Simulations of the net biospheric carbon emissions of management peatlands: the evaluation of the impact of management strategies for meeting a carbon neutral point, and net zero targets

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August 2024

A thesis submitted to McGill University in partial fulfillment of the requirements of the degree of Master of Science

Abstract

It is estimated that peatlands cover ~3 % of the global terrestrial surface and account for 11 – 14 % of Canadian land cover. Peatlands form and grow over millennia, taking up carbon (C) from the atmosphere. Canadian peatlands store ~ 150 Pg C but are subject to disturbances that disrupt their C store. 350 km^2 (0.03 %) of peatlands in Canada are disturbed through peat extraction for horticulture. While the area of peatlands disturbed for horticulture is small, the emissions caused by extraction are not insignificant.

I develop a systems model to look at the impact of peat extraction management, as well as the management of the fate of extracted peat, on net biospheric C emissions. The model was based on previous peatland simulation models and was evaluated using field measurements from Rivière-du-Loup in eastern Québec, Canada. Sensitivity analysis showed that for each average year of extraction, the emissions from the field required up to 10 years of post-restoration uptake to offset. For every 1 kg C emitted per square metre as part of downstream emissions, an average of ~ 50 years would be needed to take up the biospheric C by the restored peatland.

Scenarios that vary field management parameters suggest that cumulative field biospheric C emissions will be offset by restoration within 120 to 220 years. However, extracted peat remains in the biosphere until it is decomposed. The inclusion of downstream emissions suggests that it will take many millennia after successful restoration for the biosphere for cumulative C emissions to return to zero. I conclude that while peatlands are renewable on a short geological timescale, the emitted C is not recoverable on anthropogenic policy timescales.

Résumé

Les tourbières couvrent environ 3 % de la surface terrestre mondiale et représentent entre 11 à 14 % de la couverture terrestre canadienne. Les tourbières se forment et se développent au fil des millénaires, absorbant le carbone de l'atmosphère. Les tourbières canadiennes stockent ~ 150 Pg C, mais sont sujettes à des perturbations qui troublent leur stockage de carbone. 350 km2 (0,03 %) des tourbières au Canada sont perturbées par l'extraction de la tourbe à des fins horticoles. Meme si la superficie des tourbières perturbées pour l'horticulture est petite, les émissions causées par l'extraction ne sont pas négligeables.

Je développe un modèle systémique pour examiner l'impact de la gestion de l'extraction de la tourbe, et la gestion de devenir de la tourbe extraite, sur les émissions nettes de carbone *biosphérique*. Le modèle était baser sur des modèles de simulation de tourbières anciennes et était évaluer à l'aide des mesures terrestre de Rivière-du-Loup dans l'est du Québec, au Canada. L'analyse de sensibilité a montré que pour chaque année d'extraction moyenne, les émissions du champ nécessitaient jusqu'à 10 ans d'absorption après la restauration pour être compensées. Pour chaque kilogramme de carbone émis par mètre carré dans le cadre des émissions en aval, il faudrait en moyenne ~ 50 ans pour absorber le carbone *biosphérique* par la tourbière restaurée.

Les scénarios suggèrent que les émissions cumulatives de carbone biosphérique sur le terrain seront compensées avec 120 à 220 ans de restauration. Cependant, la tourbe extraite reste dans la biosphère jusqu'à c'est décomposée. L'inclusion des émissions par la suite suggère qu'il faudra plusieurs millénaires après la restauration de la biosphère pour que les émissions de carbone cumulées reviennent à zéro. Je conclus par dire que meme si les tourbières sont renouvelables à une courte échelle de temps géologique, le carbone émis n'est pas récupérable à des échelles de temps politiques anthropiques.

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List of abbreviations

BGM → Bog Growth Model

CaMP → Canadian Model for Peatlands

CC → Carbon Content

CNP → Carbon Neutral Point

CNZEAA → Canadian Net Zero Emissions Accountability Act

ET → Evapotranspiration

GMH → Groundwater Mound Hypothesis

HPM → Holocene Peat Model

LORCA → Long term rate of carbon accumulation

NEE → Net Ecosystem Exchange

NPP → Net Primary Productivity

P → Precipitation

PAM → Peat Accumulation Model

PDM → Peat Decomposition Model

PET → Potential Evapotranspiration

r → random

Contributions of Authors

Professor Nigel T. Roulet of McGill University was my supervisor and provided consistent support throughout the development and writing of my thesis. He introduced me to *Stella Architect,* the modelling software, and encouraged the development of my modelling and critical thinking. Consequently, he was active part in all thesis chapters.

Dr. Hongxing He gave suggestions for model development (Chapter 3.1) and presented alternative approaches to simulation difficulties.

Dr. Bidhya Sharma analysed some of my core samples at the University of Münster for FT-MIR (Chapter 3.2, Appendix iii).

Nicolas Perciballi, helped to gather core samples in Rivière-du-Loup, QC (Chapter 3.2).

Acknowledgements

Travelling across an ocean, to an unfamiliar city in an unfamiliar country is daunting. As with any thesis, my research has had its highs and lows, but I cannot emphasise enough the quality of my support in Montréal.

First, I would like to express my gratitude to Nigel Roulet. As a supervisor, Nigel has been always 'in my corner', encouraging my intellectual development and fostering critical thinking skills. He has supported me financially, academically, and emotionally throughout my time at McGill, fostering my newfound appreciation for satirical news comics and Benelux beer. Thank you for your unwavering trust in me and for acting as a catalyst for a passion in peat carbon science!

My committee, Tim Moore and Graham MacDonald have also ignited high levels of curiosity and expanded my perspectives. Tim has always asked difficult questions and forced me out of my comfort zone encouraging me to always ask why. He has also ensured that I'm up-to-date with any England-vs-Wales sports events, and I enjoy every sassy email he and Nigel CC me on. Graham has consistently given the outside perspective, urging me to truly understand the facets and implications of my work so that I think twice before presenting. He has taught me the value of clear and succinct communication. Thank you for your time, support, and patience!

This research was only possible through financial support from the Natural Sciences and Engineering Research Council (NSERC) of Canada, and the Canadian Sphagnum Peat Moss Association (CSPMA). Without NSERC or the CSPMA, the completion of this thesis would not have been possible.

Meetings with the CSPMA have been invaluable throughout the conceptualisation, development, and execution of this thesis. I would especially like to thank Stéphanie Boudreau and Asha Hingorani for making time to discuss my project and consistently expressing their enthusiasm for my work. I must also express my gratitude to Premier Tech and the Rivière-du-Loup peat extraction site team, who facilitated my collection of peat samples for analysis.

Postdoc Hongxing He helped me with modelling, especially with troubleshooting frustrating model feedbacks. Bidhya Sharma analysed my samples at the University of Münster for FT-MIR and provided invaluable insight into the fate of extracted peat. The peat corer used was provided by Julie Talbot and her student Émilie Jolin (Université de Montréal). Thank you also to Michael Ruppert (Whalen Lab, McGill MacDonald Campus), for your help with the carbon and nitrogen evaluation of my samples, and the team at the André E. Lalond Accelerator Mass Spectrometry (AEL AMS) lab for ^{14}C dating analysis.

Nicolas Perciballi and Steffy Velosa were invaluable as colleagues, supporters, and friends. Nicolas acted as field manager during peat core collection. Thank you for your patience, and for saving me from temperamental peat corers (sorry I didn't dig 'fast enough'). Steffy has also been a constant in my work. Countless late nights at the office were only bearable due to her encouragement and shoulder to cry on. I admit you have been successful in changing my 'whilst' to 'while', but I will continue to use 's' over 'z'. I must express my deepest sympathies to both Nico and Steffy for having to deal with my antics over the last three years. In return, I will force a lifetime of friendship on them, across every ocean.

My flatmates over the past three years also deserve appreciation of the highest caliber. Claire and Carina especially have seen me on the home-run stretch, for longer than we thought the run would take. Thank you for the endless support, encouragement, and mental-health-day bike rides.

Finally, thank you to my family. Even an ocean away and time zones between us, you were always supportive. Thank you for shaping my curiosity and letting me go on the occasional nerdy rant.

Chapter 1: Introduction

1.1: Background Information

Canadian peatlands are extensive, carbon-rich and degraded for anthropogenic use. Representing more than a quarter of total global peatland cover (Joosten, 2009; FAO 2012; Xu *et al.,* 2018), peatlands cover ≈11% of Canadian terrestrial land surface (Harris *et al.,* 2021). Approximately 150 Pg C (Tarnocai et al., 2011), one-quarter of global terrestrial soil carbon, is thought to be stored in these peatlands (IUCN 2021), highlighting their value as more than a beautiful, biodiverse, natural environment.

Peatlands establish slowly, over millennia. A high water table causes the rate of net primary productivity (NPP) to exceed the rate of anoxic decay (Jeglum and Rydin, 2013). The characteristic slow growth rate enables peatlands to accumulate carbon, classifying them as carbon sinks. Carbon emissions and uptake in peatlands are expressed as fluxes between the atmosphere and biosphere. The peatland biospheric carbon store is defined as the net accumulation of carbon through time, in the proportion of the peatland occupied by living organisms.

Unfortunately, peatlands and peat carbon are susceptible to disturbance. Natural disturbances, such as drought or fire, lead to a significant proportion of annual carbon emissions in Canadian peat bogs (Canada Natural Resources, 2012). The negative feedback loop of this environment, typically allows the peat bogs to return to their equilibrium function after a disturbance. However, if a tipping point is passed, and degradation levels are too high, peatland function may be limited beyond return. Anthropogenic degradation is often detrimental to natural peatland reestablishment and will irreplaceably lose large quantities of carbon by causing the tipping point to be passed. Anthropogenic land use change in Canada includes the small, but significant, peatland extraction for horticulture.

Peat is a valuable substrate due to its ability to limit nutrient leaching, improve soil buffering capacity, and stimulate root development and plant growth (Paleckiene *et al.,* 2021; PeatMoss, 2022). Export is also a benefit of extracted Canadian peat. In 2016, 87% of Canadian horticultural peat production was exported to the USA, representing a total economic output of CAD $335.4M in direct benefits in 2019 (PeatMoss, 2022, 2023).

350 km^2 of Canadian peatlands are extracted for horticultural peat. The peat is prepared for harvesting by lowering the water table and removing surface vegetation. The peat column is aerated, increasing the proportion exposed to aerobic peat decomposition and reducing NPP to zero. Aerobic (oxic) decomposition occurs at a faster rate than anaerobic (anoxic) decomposition (Säurich *et al.,* 2019), so emissions are subsequently increased.

Harvesting also disturbs capillary gas migration in the peat column, reducing gas residence time and limiting gas interaction with nutrient fixing microbes (Rydin and Jeglum, 2013). Shorter gas residence time and less microbe interaction limit the fixing process that would have otherwise reduced atmospheric potency of emitted gases, such as CH_4 and CO_2. Land use change to harvest peat for horticulture consequently results in peatland transition from carbon sink to carbon source (Maljanen *et al.,* 2010).

Despite only 0.03% of Canadian peatlands have been harvested for horticulture (PeatMoss, 2023), their large carbon store suggests that the consequent carbon emissions are not insignificant. Extracted peatlands emit an average of ~ 700g CO_2-e m^{-2} y^{-1}(Maljanen *et al.,* 2010), of which carbon-based emissions can be reduced or increased according to management practice (Waddington *et al.,* 2009; Nugent *et al.,* 2021). Restoration immediately after extraction can begin to offset prior emissions, while abandonment will continue to contribute to emissions (Nugent *et al.,* 2019, Humpenöder *et al.,* 2020). Canadian peatlands are no longer at risk of abandonment due to legislation from 2016 (CSPMA, May 2022, *pers comm*) and restoration usually occurs between 3 and 6 years after field closure. Yet, every year a peatland is awaiting restoration results in positive radiative forcing more powerful than post-restoration carbon uptake (Nugent *et al.,* 2019). As well as restoration delay, management practices such as extraction intensity and duration, and the fate of extracted peat, will also influence the net biospheric carbon-based emissions from the peatland.

Unlike peat extraction for fuel, horticultural peat carbon will not be entirely returned to the atmosphere. The fate of the peat, itself, will determine the mass of carbon that is either emitted or stabilised, and therefore reduce net biospheric carbon emissions. The uses of the extracted peat, storage duration and decomposition rate after burial in mineral soil are considered the 'fate of peat', post-extraction. Stored peat may function differently than catotelm peat, regarding its carbon emissions, so peat storage duration before or after use impacts emissions. Similarly, mixing peat with different growing substrates and mineral additions will change the decomposition rate of the mixture, but also the proportion of the mixed peat carbon that is stabilised. Stabilised peat carbon is no longer available for decomposition, therefore reducing the proportion of the carbon store that could be lost to the atmosphere.

Biospheric carbon emissions are known to contribute to global warming (Lapveteläinen *et al.,* 2007; Scharlemann *et al.,* 2014). Climate law is an increasingly popular method of reducing this risk, through the introduction of climate targets (Hilson, 2020). Various governments have worked together and individually to develop climate targets that aim at reducing the atmospheric temperature increase relative to the industrial revolution to 1.5˚C (Höhne *et al.,* 2021). The recent COP26 has resulted in multinational net-zero target pledges (UNCCC, 2021). However, while some hail this as a huge advance in politics (Sharma, 2021), others report its lack of a clear net-zero definition (Nature 2021).

The Canadian government defined its targets as a 40% emissions reduction by 2030, and net-zero carbon emissions by 2050 (ECCC 2020, 2022). Peatlands are included in Canada's net-zero plan to mitigate net emissions through nature-based solutions. However, anthropogenic peatland use directly negates the inclusion of peatlands to reduce carbon emissions, by causing more carbon emissions. Quantifying net biospheric carbon emissions of peat harvesting will, therefore, benefit the Canadian Sphagnum Peat Moss Association (CSPMA), to assess the offsets required to meet net emissions targets, and outline best management practices.

Peatland carbon storage and emissions have been assessed in environmental systems models, covering temporal scales from decades to millennia (Clymo 1984, Hilbert *et al.*, 2000, Frolking *et al.*, 2010). Previous models have identified sensitivities to climatic variation that may impact NPP, water table depth and consequent peat deposition and carbon accumulation rates. By treating peat extraction, and extraction management strategies, as disturbance phenomena, it is possible to introduce peatland harvesting to environmental systems models. Similarly, the addition of the fate of extracted peat to an environmental systems model will further account for the net emissions of the biospheric carbon in the peat extraction for the horticulture industry.

1.2: Thesis Structure:

In this thesis, I developed an environmental systems model that considers the biospheric carbon before, during and after extraction in a simulated peatland, to meet three main aims. First, to learn how long it takes the peat carbon store to recover after peatland disturbance and restoration, according to different management practices of peat extraction. Second, to assess both annual and cumulative biospheric carbon emissions pre-, during and post-extraction, and use these values to determine the offset of irreducible emissions that are required to meet Canada's 2050 net-zero emissions targets. And third, to compare results that consider Scope 1 only, and Scope 1 and Scope 3 inclusive emissions scenarios. Scope 1 emissions are directly a consequence of disturbance to the peatland, and scope 3 concerns downstream emissions during the fate of the extracted peat.

I expect that, while including Scope 3 in carbon accounting will increase annual and cumulative emissions in the short term, it will reduce the total time taken for the biosphere to recover lost carbon, as not all peat carbon will be assumed to be lost from the system.

Chapter 2: Literature Review

2.1: Peatlands in the carbon cycle

Peatlands cover ~3% of the global terrestrial surface (Xu et al., 2018), yet contain ~612 GtC (one giga-ton (Gt) is equal to one peta-gram (Pg), or 10^{15} g), equalling ~30% of the global terrestrial carbon store (Gibbs and Ruesch, 2008; Yu 2011). Historically, peatland research has focused on the northern hemisphere, but this bias is partly related to global peatland distribution (van Bellen and Larivière, 2020). Peatlands in the northern hemisphere store approximately 90% of global peat carbon (Yu, 2011). Many of these peatlands established and grew throughout the Holocene (MacDonald *et al.,* 2006).

Peatland abundance in the northern hemisphere can be split with a 44% and 56% distribution between North America and Eurasia, respectively (Loisel *et al.,* 2017). It is well documented that many western and northern European peatlands have experienced significant disturbance, and little is known about the peatlands of eastern Russia. Historical degradation, along with differences in soil classifications, suggests uncertainty in Eurasian peat soil carbon store assessments (Panagos *et al.,* 2013). Research suggests that around 163 Pg C is stored in North American peatlands (Gorham *et al.,* 2012), representing an estimated ~40% of northern hemisphere peat carbon (Bridgham *et al.,* 2006).

Unlike Europe, Canadian peatlands have not been significantly disturbed. Approximately 11% to 14% (~1,136,000 km^2) of the Canadian terrestrial surface is classified as peatlands (Tarnocai *et al.,* 2011; Xu *et al.,* 2018), which represents ~25% of global peatland cover (Hugelius *et al.,* 2020). Peatlands in Canada store between 147 and 190 Pg C (Turunen *et al.,* 2003; Tarnocai 2006; Gorham *et al.,* 2012; Sothe *et al.,* 2022). Most of North America's peatlands, therefore, exist in Canada.

2.2: Peatland establishment and peat carbon accumulation

As peatlands establish and grow, their vegetation and hydrology change. Peatlands are wetlands – i.e. the soil layer is water-saturated for most of the year. Peatlands are characterised as permanently saturated environments, occupied by peat-forming vegetation (Rydin and Jeglum, 2013). The high water saturation promotes anaerobic decomposition, and peat-forming species, such as *Sphagnum*, grow. As anaerobic decomposition is a slow process, peatlands have a higher rate of net primary production (NPP) than their rate of decomposition (Rydin and Jeglum, 2013). So, peatlands grow in height and accumulate carbon.

Peatlands start as systems with plants and organic matter characteristic of minerogenic systems (Rydin and Jeglum, 2013). Over time, the peat layer will thicken, removing the vegetation from the source mineral elements (Rydin and Jeglum, 2013). The peat will then become more mineral-poor, such as mineral-poor fens. If the peatland becomes so isolated from hydrological mineral inputs that its main water sources are rainfall and snow-water melt, they are ombrogenic (Rydin and Jeglum, 2013) such as bogs. The two predominant processes by which a peatland becomes ombrogenic are infilling and paludification. In infilling, peat-forming vegetation will expand slowly over a water body. The vegetation may eventually connect, and the peat will thicken until some zones are isolated from the mineral layer (Rydin and Jeglum, 2013). Paludification occurs as the water table rises, and peat-forming vegetation establish. The peat-forming vegetation, particularly *Sphagnum*, will decrease the local pH level, reduce nutrient availability, and retain the high water table (Eppinga *et al.,* 2009). The peat will continue to thicken and may be isolated from the mineral layer to become ombrotrophic. Most peat bogs in Canada are thought to have established by paludification (Vitt *et al.,* 2011). Peatland growth is slow by anthropogenic standards. It can take millennia until the increasing depth of the peat column isolates the peatland from mineral elements, and will take millennia for the peatland to reach an equilibrium state (Clymo, 1984; Frolking *et al.,* 2014; Loisel *et al.,* 2017).

Ombrogenic peat bogs are usually *Sphagnum* dominant (Rydin and Jeglum, 2013) so while peatlands can be comprised of woody- or *Carex*-peat, peat bogs produce denser *Sphagnum*-peat (Anderson *et al.,* 2003)**.** *Sphagnum* has a more uniform NPP over the growing season than *Carex* or woody-species (Anderson *et al.,* 2003). Peatbogs demonstrate water-table depths that can fluctuate between 5 cm and 25 cm beneath the surface (Price and Whittington; Howie and van Meerveld, 2013; Peros *et al.,* 2016). The slow decomposition rate due to a high water table, combined with *Sphagnum* NPP and denser sphagnum-peat, means that peat bogs can accumulate a large volume of carbon over millennia. The long-term rate of carbon accumulation in Canadian peatlands typically rests between 20 and 30 g C m^{-2} y^{-1} (Kelly *et al.,* 1997, Roulet 2000, Roulet *et al.,* 2007).

Field measurements from peat cores can demonstrate peat growth rates and exhibit any transitions between peatland and peat type over time through peat matrix, colour and macrofossil analyses (Anderson *et al.,* 2003). Core samples also show that all peat types accumulate organic matter and consequently, are rich in carbon. Peatland complexes function as carbon sinks as they establish and grow over millennia, therefore a mature peatland is a significant carbon store (Turunen *et al.,* 2003: Turunen *et al.,* 2004; Yu *et al.,* 2011; Frolking *et al.,* 2014).

Peatland function can be simplified to focus on the inputs and outputs to the ecosystem, and peatland growth modelled. The resulting simulations can demonstrate assessments for peat accumulation, peat decomposition and peat growth over millennia or, more appropriately, from the Holocene to today (Hilbert *et al.,* 2000; Frolking *et al.,* 2001; Frolking *et al.,* 2010).

2.3: Disturbance and the peat carbon store

Throughout the Holocene, peatland ecosystems have experienced disturbances that impact their inputs, outputs and feedbacks (e.g. the Little Ice Age, the Medieval Warm Period, etc.). Despite these perturbations, peatlands are examples of incredibly resilient ecosystems that respond to climatic variations.

Peatlands are resilient because of their ability to self-regulate (Basiliko *et al.,* 2006; Morris *et al.,* 2011; Rydin and Jeglum 2013). Self-regulation in peatlands can be attributed to a series of feedbacks that facilitate their growth and continued function (Eppinga *et al.,* 2009). That is, peatlands, and to a stronger extent peat bogs, are negative feedback systems that naturally compensate for climatic variations. To maintain stability during a disturbance, the peatland may respond as a short-term carbon source and behave as a stronger carbon sink following self-regulation (Belyea, 2009; Frolking *et al.,* 2010).

Fires, droughts and floods are all examples of disturbance. A peat bog experiencing a drought will have a decreasing water table. Surface peat and vegetation, exposed to aerobic decomposition, will not grow more than it decays which reduces peat mass

(Rydin and Jeglum, 2013; Frolking *et al.,* 2010). Consequently, the surface layer of the peat bog will not increase relative to the water table despite the water table reducing, allowing for recovery when the drought finishes. Conversely, a period of flooding would lead to a higher water table. Some *Sphagnum* species increase productivity in wetter conditions, leading to more growth and carbon input (Belyea 2009; Frolking *et al.,* 2010). NPP increases and wetter conditions reduce decomposition leading to an eventual decrease in water-table depth relative to the surface.

Nevertheless, there is a threshold for disturbance from which a peatland may not recover (Eppinga *et al.,* 2009; Luo and Weng, 2011; Drever *et al.,* 2021; Harris *et al.,* 2021). An exact tipping point for peatland recoverability is not known, but water table depth, nutrient availability, pH, light availability and temperature all influence the *Sphagnum* to vascular plant ratio (Eppinga *et al.,* 2009), which in turn influence decomposition and NPP. Anthropogenically induced disturbances can knock a peatland ecosystem out of its range of control, and impact its ability to self-regulate (Frolking *et al.,* 2010; Moomaw *et al.,* 2018).

Peat mining and extraction forces peatlands out of their range of control by significantly lowering the water table and removing all surface vegetation. As such, the decomposition rate, that is the carbon leaving the biosphere to the atmosphere, is far greater than the uptake of carbon from the atmosphere. Often, the complete removal of vegetation occurs, and NPP is reduced to 0. Past this tipping point, peatlands are pushed completely to disequilibrium and cannot recover without intervention (Davidson and Janssens, 2006; Lou and Weng 2011).

2.4: Disturbance management, peatland restoration and peat use's influence on CO_2

Peatlands are extracted for horticulture because peat improves water buffering capacity, soil porosity and nutrient fixing capability, making peat a valuable resource (Paleckeine *et al.,* 2021; CSPMA 2023). Less than 0.05% of Canadian peatlands have been extracted, 350 km^2 (Harris *et al.,* 2021), but this carbon is irrecoverable within our lifetimes.

Irrecoverable carbon refers to carbon emissions that cannot be naturally recovered before target years (Goldstein *et al.,* 2020), such as the politically relevant 2050 net-zero emissions target year. By this definition, peat carbon loss due to disturbance is irrecoverable on anthropogenic timescales. However, on an ecological timescale, a disturbed peatland will recover its lost carbon after successful restoration, pending millennia.

Net emissions are the difference between the carbon uptake by the biosphere from the atmosphere, and the carbon emitted to the atmosphere from the biosphere (Fankenhauser *et al.,* 2022). Extraction management practices have an impact on the biospheric carbon store and net carbon emissions (Cleary *et al.,* 2005; Maljanen *et al.,* 2010; Wilson *et al.,* 2015; Bieniada and Strack 2021; Holmberg *et al.,* 2021; He and Roulet, 2023).

Before active extraction, drainage ditches are dug and surface vegetation is removed. Ditch depth and spacing are determined by practice. Changes to the hydrology inhibit the re-colonisation by *Sphagnum* and other peat-forming species (Ketcheson and Price, 2011). The vegetation removal and delay period between ditch-digging and active extraction aerates surface peat. With no NPP and more aerated peat increasing decomposition, the peat extraction phase is a period of net-positive carbon emissions. Extraction consists of heavy machinery, including peat conditioners and vacuum harvesters, that remove between 2 and 10 cm of peat per year (CSPMA, March 2023, *pers comm.*). Extraction continues until ~1 m of peat remains. Any depth less than 1 m is not sufficient to isolate the surface material from the underlying mineral soils, so 1 m is important for peatland ecological restoration with *Sphagnum* to be effective (Quinty and Rochefort, 2003). It is important to note that extracted peat does not disappear from the biosphere and that it has a ‘fate’ beyond extraction. The extractive peatland will also continue to emit carbon until restoration occurs. Accordingly, extraction intensity (depth per year), extraction duration (years) and height of residual peat are important management foci for the extraction phase.

In Canada, restoration must be carried out within 3 years of extraction ending as part of the extraction licencing certification (SCS Global Services, 2019; CSPMA *pers comm.*)

and following *The Peatland Stewardship Act* (Ministry of Justice, C.C.S.M. c. P31, 2015). It is not uncommon for this delay to be extended to six years as restoration requires favourable climatic conditions, and occasionally peat fields are re-opened for another year of extraction. Prompt restoration of previously extracted peatlands is favourable (Rankin *et al.,* 2018; Nugent *et al.,* 2019), as the system will remain in net positive carbon emissions until effectively restored. The mechanisms for restoration in Canada include ditch blocking and ecological restoration via the moss layer transfer (moss spreading) technique (Graf and Rochefort, 2016). Raising the water table is critical for restoration, as the surface peat needs to be saturated enough to encourage *Sphagnum* colonisation after moss spreading (Quinty and Rochefort, 2003). The higher water table also reduces the decay rate by re-introducing anaerobic decomposition. Usually within ten to twenty years after the start of restoration, net-carbon uptake (through greater NPP than the rate of residual peat decomposition) returns the bog to a carbon sink (Wilson *et al.,* 2016; Nugent *et al.,* 2018). Species diversity and biospheric structure will not be restored within the same timeframe (Minayeva *et al.,* 2017). Depending on the restoration target (i.e. specific flora or fauna re-encouragement), different vegetation species will need to be introduced after successful moss spreading (Hugron *et al.,* 2020). The vegetation matrix's community maturity is complex and will have different timescales of vegetation succession (Daza Secco *et al.,* 2016). Vegetation maturity, diversity and relative abundance will likely mimic pre-extraction levels on a similar time frame to acrotelm maturity, though this is not well researched.

While the peatland is restoring, the extracted peat is being used. Extracted peat in Canada is not used as a fuel, therefore, the carbon returns to the atmosphere slowly as the used peat decomposes. A proportion of the peat carbon is likely to remain in other soil in another ecosystem after use, not in the peatland itself. Little is known about the fate of peat, other than that emissions due to decomposition will continue. Thus, the fate of peat phase will exhibit net-positive carbon emissions (Tubellio *et al.,* 2022). A key item when considering the impact of the fate of peat's emissions includes the duration of the use of peat, as well as the produce grown in peat (Sharma, 2024), and any secondary or tertiary peat uses. After peat is used, it is likely stocked piled and not used, where it will continue to decompose. Peat is rarely used alone, however. Peat is very acidic and is mixed with lime or another substrate to neutralise pH before use (Sharma, 2024). A different decomposition rate of the peat soil carbon is, therefore, experienced during use compared to peat alone (Sharma, 2024). After peat use, the peaty organic matter can be mixed with mineral soils, which I expect will stabilise a proportion of the peat carbon. That is, some peat carbon will become unavailable for decomposition after mixing with mineral soils. The carbon emissions during each sub-management phase for the fate of extractive peat will vary depending on the management.

2.5: Modelling peatland land-use change

A potentially valuable method for comparing the impact of scenarios on an environment is through environmental systems modelling. Peatlands, as ecosystems that establish and mature over millennia, must first be modelled to consider peatland growth and function over long time frames before scenarios can be introduced.

Clymo (1984) developed one of the first peatland growth models. The relationship between acrotelm (oxic layer) and catotelm (anoxic layer), and the parameters that will influence peat accumulation, are characterised in the Bog Growth Model (Clymo, 1984). The BGM assumes an NPP, has a constant peat density and has a fitted peat decomposition rate based on peat core measurements (Clymo, 1984). There is no physical acrotelm in the BGM, but it is assumed that only 10-20% of peat biomass is transferred to the catotelm, the rest lost during acrotelm decomposition (Clymo, 1984). The BGM is later expanded to reconsider some catotelm relationships, namely assumed constants, as not always true (Clymo, 1993). Namely, these adaptations were to account for peatland parabolic shape based on the groundwater mound hypothesis (GMH) (Ingram, 1982). Both BGM and the Groundwater Mound Hypothesis (GMH) assume homogeneous properties in the peat columns and do not consider multiscale hydrological and ecological process coupling (Belyea and Baird, 2006). By including groundwater flow dynamics in the BGM, the BGM effectively reduces peat bog relationships to include only the most important drivers, limiting variability through the constants. Drivers of peat production and growth are identified as NPP input, and peat decay relating to the acrotelm or catotelm layer (Clymo, 1993). The sensitivity of bog growth to parameters and relationships was assessed in the BGM (Clymo, 1992; Belyea and Baird, 2006), and the building blocks for basic peat bog modelling were identified. Subsequent models have used the BGM base to expand peatland simulation questions and test other hypotheses.

The peat accumulation and peat decomposition models, PAM and PDM respectively, were developed to integrate the non-linear relationships between peat accumulation, decomposition and hydrology, and consider the impact of vegetation types (Hilbert *et al.,* 2000; Frolking *et al.,* 2001). Building on Clymo's work, the PAM serves as a generalised peatland dynamics model that allows for the analysis of simple but realistic assumptions for the long-term dynamics of peatlands (Hilbert *et al.,* 2000). The PAM developed the relationship between water-table depth, NPP and decomposition, varying the hydrologic regime to suggest peatland sensitivity to climatic variability (i.e. precipitation). Subsequent outcomes suggested that a shift from equilibrium as a response could lead to the peatland becoming a carbon sink or source within a short time frame (Hilbert *et al.,* 2000). Thus, the idea of peatland tipping points, and range of control, emerged. Conversely, the PDM uses plant vascularity as an indicator for decomposition rate, modelling the transition between fen- and bog-type peatlands (Frolking *et al.,* 2001). The PDM highlights similarities and variability between modelled and measured data through comparisons with sites in Eastern Canada and notes the relationship between productivity, decomposition and long-term peat accumulation in a dynamic, frozen model (Frolking *et al.,* 2001).

Later, the Holocene Peat Model (HPM), merged the ideas in PAM and PDM, introducing twelve functional plant types. The HPM addresses the simulated implications of vegetation composition and NPP, and water-table depth (Frolking *et al.,* 2010). The HPM presents the complex nature of the coupling between peat accumulation and water dynamics and reiterates the implications of climate variance on peatlands (Frolking *et al.,* 2010). Peat accumulation over decades to millennia is modelled to account for NPP-decomposition-water feedbacks and evaluated with eastern Canadian peatlands. While model outputs did not exactly match the reference site, *Mer Bleue*, the HPM simulated age and peat accumulation rate followed a similar trend to peat core data. Model outputs were noted to be sensitive to century-scale anomalies, representative of 100-year climatic events, as defined by precipitation variability even when productivity through NPP did not experience the same variations (Frolking *et al.,* 2010). In some scenarios, the HPM demonstrated that short periods exist when peat-mass loss occurred as decomposition was greater than NPP (Frolking *et al.,* 2010), as part of peatland self-regulation.

Millennia-spanning simulations are useful to outline model establishment, equilibrium, and the relationships between NPP, decomposition and hydrology (Clymo 1992; Hilbert *et al.,* 2000; Frolking *et al.,* 2001; Frolking *et al.,* 2010). These models did not specifically simulate carbon dynamics, but the accumulation of organic matter. However, with some knowledge of density and the relatively narrow range of the carbon content of peat, it is relatively easy to convert organic matter accumulation into carbon accumulation.

Building on the GMH framework for ecohydrological feedbacks and with peat properties (Ingram, 1982), Digibog develops the frameworks to consider the impacts of peatland development and carbon accumulation (Baird *et al.,* 2012). Multiple dimensions of peatland development inform the model, as it simulates theoretical peat columns that develop over millennia, and then uses shorter time-steps for other variations. Digibog considers time-step as indicative of feedbacks and therefore varies timestep to mirror ecological and hydrological cycles, or else follow annual patterns (Morris *et al.,* 2012).

Climatic variability has a potential effect on the patterns of peat growth and decomposition, thus the future of the terrestrial carbon sink is uncertain (Keenan and Williams, 2018). The coupling of relationships within models, as well as the impact of disturbance events, must, therefore, be important considerations in modern model development (Keenan and Williams, 2018).

Environmental systems models can be used to simulate pristine peatland systems as they establish and mature over millennia (Hilbert *et al.,* 2000; Frolking *et al.,* 2001; Frolking *et al.,* 2010). The models show that peatlands have net-negative carbon emissions until they reach equilibrium, and ultimately demonstrate the size of the peatland carbon sink. The impact of land use change through disturbances can also be modelled by using shorter time scales, simulating carbon and nutrient dynamics (Baird *et al.,* 2012; He *et al.,* 2021).

Peatland land-use change has been modelled for tropical drained sites to show that anthropogenic peatland disturbances cause net-positive carbon emissions and take millennia to recover (Dommain *et al.,* 2018). In Canada, peatland recovery simulations can determine the further millennia required for a restored peatland to uptake the equivalent carbon lost during extraction back into the biosphere. Thus, we can use environmental systems models to break up the phases of peatland land use change, using parameters that can be independently varied, as phenomena, to account for extraction and fate of peat management practices pre-, during and post-extraction. In this way, not only will the millennia over which peatlands establish and mature be considered, but so will the decades within which the greatest anthropogenic influence is felt.

Carbon accounting models could also be used to assess the carbon lost to the atmosphere from peatland disturbance. To understand peatland carbon, develop dynamics in Canada and propose a structure for large-scale spatial and temporal emissions, the Canadian model for peatlands (CaMP) was developed (Bona *et al.,* 2020). CaMP was designed to work alongside the Generic Carbon Budget Model and is incredibly fit for purpose as a module that accounts carbon in Canadian peatlands as approximations (Bona *et al.,* 2020). CaMP has experienced significant overestimation of methane and net ecosystem exchange, for some of the comparative sites. Subsequent revisions aim to consider re-calibrated peat decomposition rates and NPP parameters, as well as natural and anthropogenic disturbances (Bona *et al.,* 2020). The large scale of the CaMP also requires large generalisation, or else there exists a risk of overcomplication of processes. Still, CaMP generalises and makes assumptions to inform areas for further research and identify uncertainty in Canadian carbon accounting over time. Thus, CaMP highlights that model critiques must consider a model's strength for its purpose, and as informative for future research developments, rather than as applicable to a different system. In the case of CaMP, Canada-wide models must generalise to an extent due to the sheer size of the country, meaning CaMP outputs, while showing uncertainty, are very effective at their task.

To consider the intricacies of peatland complexity, highly detailed coupled-relationship models should be used. CoupModel, a coupled heat and mass transfer model for the soil-plant-atmosphere system, was originally developed with a focus on soil physics and soon coupled the relationship with hydrological dynamics (Jansson, 2012). More recently, the CoupModel has been adapted for peatlands, with models for vegetation and cycling of nitrogen and carbon (He *et al*., 2021). CoupModel can assess the impact of seasonal and inter-annual climatic variability on peatlands disturbed for peat extraction and simulate net-carbon emissions (He and Roulet, 2023; He *et al.,* 2023). The short annual-to-decade time scales with a daily time-step, however, mean that CoupModel is not an appropriate instrument for long-term carbon store assessments.

Peatland models can be used to calculate approximate carbon stores on sub- and inter-annual scales, including millennia, making them useful for recent policy carbon emissions targets.

2.6: Relevance of Policy in the Canadian context

The interest of the government in peatlands in Canada is demonstrated by the introduction of the *Peatlands Stewardship Act* regarding peatland restoration post-extraction at the provincial level. Federally, Canada is one of the many countries that have implemented net-zero emissions targets in a bid to mitigate the effects of climate change (UNFCCC, 2015; S. C. 2021, c.22).

2050 net-zero emissions targets, however, are often poorly defined (Nature, 2021) despite representing a '*milestone in… law and policy'* (Wright, 2023). Although legislation is expected to be vague to allow for detailed development in policy documents, the *Canadian Net-Zero Emissions Accountability Act* (CNZEAA) risks a wide '*implementation gap'* due to the vague nature and lack of clear direction in the writing itself (Wright, 2023). The complex Canadian legislative and constitutional system that attempts to balance federal, provincial and territorial governments does not lend itself to binding, detailed and prescriptive net-emissions legislature (Wright, 2023). Resources and their management, including land, are provincial responsibilities, while international agreements and obligations are under federal jurisdiction. Consequently, the responsibility of providing and implementing mechanisms to mitigate greenhouse gas emissions and reduce the risk of climate change falls on the industries themselves.

In response to CNEZAA the *Canadian Sphagnum Peat Moss Association* (CSPMA), a group of Canadian peat producers that promote and improve upon the responsible management of peatland extraction (CSPMA, 2024), are working towards mitigating current carbon emissions and improving peat extraction management practices to reduce future emissions. Still, a lack of definition in CNEZAA delegates emissions definitions and protocol to the CSPMA and its participant producers.

The CSPMA divides its emissions into mechanical and non-mechanical emissions (Boudreau, May 2022, *pers. comm.).* Whereby mechanical emissions account for the carbon emissions relating to the machinery that prepares the peatland, extracts peat, and processes peat for use, and non-mechanical emissions consider the emissions from the peatland, consequent of extraction (CSPMA *pers. comm.*).

Across industries, these emissions 'fit' into boxes of 'Scope', according to the emission sources (EPA, 2023). Scope 1 is defined as the direct emissions relating to the industry processes and the machinery controlled or run by said industry (EPA, 2023). For peatland extraction, Scope 1 consists of the greenhouse gas emissions relating to the machinery and operations used leading up to, during and immediately after, peat extraction, as well as the biospheric emissions from the peat field as a result of peat extraction. Scope 2 emissions refers to the indirect emissions resulting from purchased material required for the industry process to take place (Sotos *et al.,* 2015). Peat industry Scope 2 emissions can be debated to consider purchased fuel, electricity and other materials required for processing the extracted peat. Finally, Scope 3 emissions consist of the greenhouse gases produced up or downstream as a result of transport, waste, product use and disposal (Bhatia *et al.,* 2011). Similarly, Scope 3 greenhouse gas emissions include the transport of the peat product, as well as the fate of extracted peat.

Mechanical emissions for each scope level have already been reported to the Canadian government as part of CZNEAA; however, the biospheric emissions from the extraction sites and downstream, have not been reported. Canada is obligated as a partner to the UNFCCC to report its biospheric emissions from land-use change, including land-use change related to the drainage and excavation of organic soils (UNFCCC, 2013).

Therefore, the peat extraction industry must consider the biospheric emissions from the peat fields related to extraction and restoration, for Scope 1 accounting. In the same way, for Scope 3 emissions, emissions accounting must follow the peat and consider the biospheric emissions relating to the fate of extracted peat. Management on these levels will impact net annual and cumulative carbon emissions. While it is better to not extract peat at all, the peat industry does exist and causes greenhouse gas emissions (Moomaw *et al.,* 2018). The peat industry also serves a need and produced peat has had a mean shipment value of $340.8 M (CAD) over the past five years (Natural Resources Canada, 2023) and employs over 3000 people in direct and indirect jobs (CSPMA, 2024).

The likelihood of meeting CNZEAA targets using mitigation alone is small, so offsets will need to be considered. The quantity of emissions that must be offset at a specific target year is related to management strategies and mitigation practices employed by the peat extraction industry. Still, biospheric peat and peatland emissions must be considered if we intend to meet 2050 CNZEAA targets and attempt to move the industry to greater sustainability.

Chapter 3: Methodology

3.1: Model Development

I aimed to develop a model that would simulate the biospheric carbon emissions of a peatland that experiences land use change due to peat extraction. Biospheric carbon fluxes, as defined for this work, include carbon inputs through the proportion of growing biomass that is carbon and output as carbon from decomposing material in the peat column. Anthropogenic or mechanical emissions are not accounted for in the model since they are already reported to the federal government by the industry. My model does not differentiate carbon emission types and allows for conversion into CO_2 equivalent; methane is not explicitly simulated as its short life cycle suggests that its total impact on net biospheric carbon emissions would be minimal over the millennia. I use a 1-year time step, with a delta-time of 0.25 years, meaning that my model is integrated four times per time-step for all runs. The model was developed in Stella Architect and the code (appendix I) can be adapted for other software (Babak and Alexey, 2012).

3.1.1: Basic Clymo model

The Clymo model (Clymo, 1984) simulates peat accumulation as the fraction of net primary productivity (i.e. biomass production, *NPP*) passed to the catotelm minus the mass of peat decomposed in the acrotelm. This model determined that the maximum depth of a peatland is limited by the rate of input to the catotelm at the bog's centre, and the rate of catotelm decomposition (Clymo, 1984).

Peatland NPP produces 400 to 800 g m^{-2} y^{-1} of biomass (Clymo 1984; Frolking *et al.,* 2001; Moore *et al.,* 2002; Basiliko *et al.,* 2006; Frolking *et al.,* 2010). To represent an eastern Canadian continental bog, the midpoint of the peatland NPP range was used, 600 g y^{-1}. Input to the catotelm is immediately converted from peat mass to peat carbon. Between 42.8% - 51.8% of accumulated peat is carbon (Vitt *et al.,* 2000; Turunen *et al.,* 2004; Bridgham *et al.,* 2008). I use a 50% peat carbon content, which is within the 42.8% - 51.8% range and simplifies carbon content to be half of the biomass. The catotelm decomposition rate is roughly between 0.01% and 0.03% per year (Hilbert *et al.,* 2000; Frolking *et al.,* 2001; Loisel and Yu, 2013). A 0.25% y^{-1} rate is commonly used in modelling (Clymo 1984; Hilbert *et al.,* 2000; Frolking *et al.,* 2001). It is assumed that only 10% to 20% of peat reaches the catotelm from the acrotelm (Clymo, 1984). Peat carbon mass (M_P, g C) in the Clymo model is calculated as:

$$M_{P,t} = (NPP \cdot cc \cdot (0.1)) - (M_{P,t-1} \cdot \alpha_1)$$

Equation 1

Where *t* is time after establishment on an annual timestep, *cc* is carbon content, 0.1 represents the 10% of acrotelm peat reaching the catotelm and α_1 is the catotelm decomposition rate.

3.1.2: Adding an acrotelm to the basic Clymo model

The Clymo model was adapted to include acrotelm decomposition in the peat accumulation model (PAM) (Hilbert *et al.,* 2000). To determine the acrotelm decomposition rate, Hilbert *et al.* (2000) first calculated acrotelm thickness. The water table defines the acrotelm-catotelm boundary, whereby the peat above the long-term mean water table depth is considered acrotelm and below it is catotelm (Hilbert *et al.,* 2000). Acrotelm decomposition has an approximate rate of 2.5% y^{-1} (Clymo, 1984; Hilbert *et al.,* 2000; Frolking *et al.,* 2001). In observations, the acrotelm-catotelm division is not defined as a singular boundary, but instead as a transition zone. The peat decomposition model (PDM) assumes a transition zone from acrotelm to catotelm between 0.30 and 0.35 m depth and models the acrotelm and catotelm differently (Frolking *et al.,* 2001). The annual transfer from acrotelm peat to catotelm peat across the transition zone is between 10% and 20% (Clymo,1984; Frolking *et al.,* 2001). The sum of the acrotelm and catotelm carbon masses (M_A, M_C respectively) is equivalent to the total peat carbon mass:

$$M_P = M_A + M_C$$

Equation 2

$$M_{A,t} = (NPP \cdot cc) - \left(\alpha_2 \cdot M_{A,t-1}\right)$$

Equation 3

$$M_{C,t} = \left(M_{A,t-1} \cdot p_c\right) - \left(\alpha_1 \cdot M_{C,t-1}\right),$$

Equation 4

Where α_2 is the acrotelm decomposition rate and p_c is the annual mass transfer across the acrotelm-catotelm boundary.

The two-layer model is necessary for my model development because the acrotelm and catotelm behave differently during and after extraction and restoration. The acrotelm is first to establish, and first to re-establish after restoration (Taylor and Price, 2015). It also has a lower density than the catotelm (Rydin and Jeglum, 2013). The catotelm is more humified and its density increases with compression due to heavy machinery in degraded sites (Drollinger *et al.,* 2020). When the water table is lowered during extraction, the catotelm decomposition rate will change (He *et al.,* 2023). One meter of catotelm peat must also remain for restoration to be successful (Graf and Rochefort, 2016). Thus, the two-layer model is important for peatland extraction and restoration scenario simulation.

Once coupled with the water table, the equation for the acrotelm becomes:

$$M_{A,t} = (NPP \cdot cc) - \left(\alpha_2 \cdot M_{A,t-1} \cdot f(Z)\right)$$

Equation 5

Where *f(Z)* represents the multiplier for acrotelm decomposition with fluctuating water-table depth (*figure 1*). The mean water-table depth in my model is approximately between 20 and 25 cm, below the surface, which corresponds to a multiplier of ~1 in this figure.

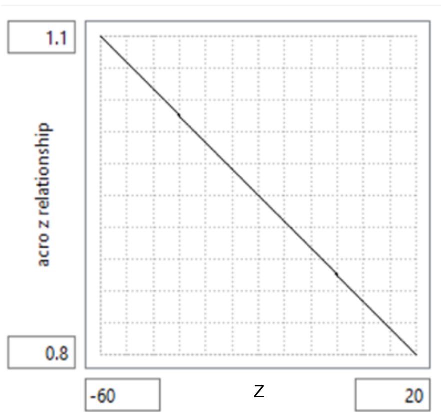

Figure 1: The relationship between acrotelm decomposition (dimensionless) and Z, water table depth (cm).

Peat height (H_P) is also calculated in this iteration, as a function of the peat mass and density. Peat is usually lighter and less dense closer to the peat column surface. Typically, the acrotelm has a density between 50 and 70 kg m^{-3}, while the catotelm has a density between 90 and 120 kg m^{-3} (Frolking *et al.,* 2010). I use 70 kg m^{-3} for the acrotelm and 120 kg m^{-3} for the catotelm densities.

$$H_P = H_A + H_C$$

Equation 6

$$H_A = M_A \cdot \rho_A$$

Equation 7

$$H_C = M_C \cdot \rho_C$$

Equation 8

Where H_A and H_C are peat thicknesses for the acrotelm and catotelm respectively, and ρ_a and ρ_c are the respective acrotelm and catotelm densities.

3.1.3: Describing the water-table position

Thus far, the acrotelm-catotelm interface has been defined by a transfer function (*equation 4)*. The acrotelm and catotelm are assumed to be bounded by the long-term average water-table depth (Ingram, 1982; Clymo, 1984; Hilbert *et al.*, 2000), but structural and functional peat layers are not the same. Peat column structural layers are consistent and defined as the less decomposed peat above the water-table '*litter-peat'*, the transition zone '*collapse'* and the more decomposed peat below the water-table '*peat proper'* (Clymo, 1992). Peatland functional layers consider the different decay rates of peat zones according to water-table depth and residence time with seasonal variations over an annual cycle (Clymo, 1992). It also mirrors the PAM (Hilbert *et al.,* 2000) two-layer structure and does not have a set transition zone.

I developed a hydrological sub-model to couple with the peat carbon store model to adjust my acrotelm-catotelm proportions. As my model simulates an ombrogenic peat bog, the only water input is precipitation. In eastern Canada, precipitation rates vary over the year as an environment experiences cold, snowy winters, and warm, humid summers, but the precipitation rate is consistently greater than the evapotranspiration rate. Annual precipitation near the Rivière-du-Loup evaluation site was a mean 1,100 mm y^{-1} over 15 years (Climate-Data, 2023). Many eastern Canadian peatlands experience lower precipitation than 1100 mm y^{-1}, so my annual precipitation input rests at 900 mm y^{-1}, with a random 10% fluctuation each dt.

$$P = P_0 \cdot r$$

Equation 9

Where *P* is actual precipitation, P_0 is annual mean precipitation, and *r* is the randomisation function.

Mean annual evapotranspiration at water-table class midpoints ranged between 200 mm y^{-1} and 400 mm y^{-1}, based on Mer Bleue (Lafleur *et al.,* 2005). I adapted this function for the simulated peatland, as Mer Bleue is much drier than our Rivière-du-Loup evaluation site (*figure 2*). Mean evapotranspiration was set to 250 mm y^{-1} and varied by a function based on Lafleur *et al.,* (2005) to account for potential evapotranspiration with change in water-table depth.

$$ET = ET_0 \cdot r \cdot ET_Z$$

Equation 10

Where *ET* is actual evapotranspiration, ET_0 is annual mean evapotranspiration, *r* is the randomisation function of 10%, and ET_Z is the potential evapotranspiration multiplier based on Lafleur *et al.* (2005).

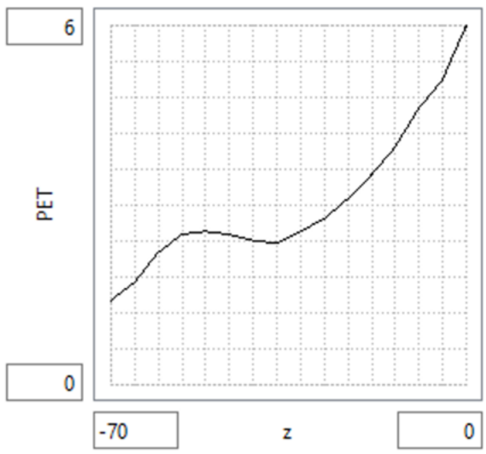

Figure 2: the potential evapotranspiration (dimensionless) with water-table depth (cm), based on Lafleur et al. (2005).

Surface and subsurface water flow are grouped as discharge (*D*) in the model. Discharge is determined by the total water store (in height equivalent) and a discharge rate:

$$D = q \cdot W$$

Equation 11

Where *q* is the discharge rate and *W* is the total water store.

The total water store is then a sum of its inflows (precipitation) and outflows (evapotranspiration and discharge).

$$W = P - (ET + D)$$

Equation 12

The discharge rate (*q*) is a function of a hydraulic gradient and the thickness of the peat. The hydraulic gradient is fixed by the assumption that a growth of 1 m height in peat equates to a 1000 m radius following the trend to 5 m height and 5000 m radius. The hydraulic gradient used is 0.001.

$$q = K_W \cdot \lambda$$

Equation 13

Where K_W is the hydraulic gradient and λ is the peat thickness.

To calculate peat thickness, it is assumed that the peat has a porosity that reduces space available for sub-surface water. Peat porosity is a dimensionless value between 0.71 and 0.95 (Rezanezhad *et al.,* 2016), with 0.887 and 0.919 calculated for peat bog porosity (Liu and Lennartz, 2019). My hydrology model uses a rounded 0.9 porosity for simplicity. The water-table depth is then removed to calculate the peat thickness (cm):

$$\lambda = \left(\frac{W}{\phi}\right) - Z$$

Equation 14

Where ϕ is peat porosity, and *Z* is water-table depth (cm).

To determine the water-table depth, I considered the peat column similar to a hypothetical cylinder with porosity, that was filled with water from the water store. Peat height (*equation 5*) was multiplied by the porosity to calculate the space available for water and that space was 'filled' by our water store.

$$Z = (H_P \cdot \phi) - W$$

Equation 15

The simulated water table rested between 25 and 30 cm below the peat surface, with variation each dt due to the random functions in both precipitation and evapotranspiration. The sub-components of the hydrological sub-model were closely linked due to the impact that each parameter had on the next (*figures 3, 12*).

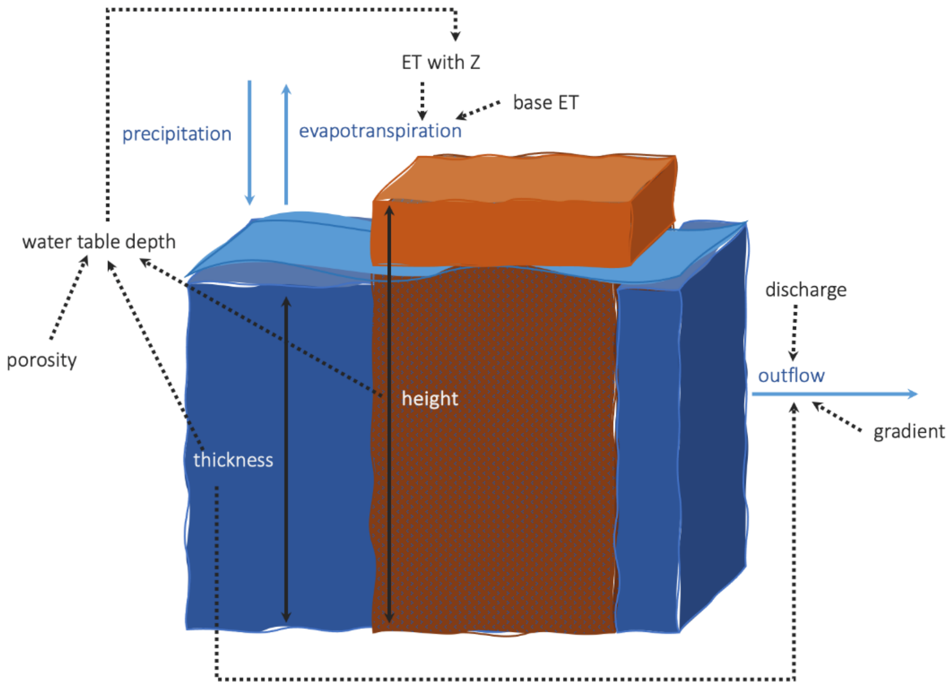

Figure 3: A schematic of the hydrological model as it couples with the peat column, which has a surface area of 1 m^2.

3.1.4: Addition of the litter layer

While the coupled peat-hydro version functioned, we identified that the accumulation was too high in the first few years of the simulation. The problem arose because too much of the annual NPP entered the acrotelm stock. We therefore introduced a virtual litter layer that decomposed at a rate of 30% per year (Moore *et al.,* 2007), and the remaining litter biomass then entered the acrotelm. During peatland establishment, the litter decomposition rate was delayed by a function. The function helps to simulate the establishment of vegetation, and that a 30% decomposition rate will not be met before the litter mass (M_L) and acrotelm layers have stabilised.

$$M_{L,t} = \left(M_{L,t-1} \cdot \alpha_3 \cdot f(t)\right) - \left((1 - \alpha_3) \cdot M_{L,t-1}\right)$$

Equation 16

Where α_3 is the decomposition rate of the litter layer and f(t) represents the multiplier function for litter decomposition with time.

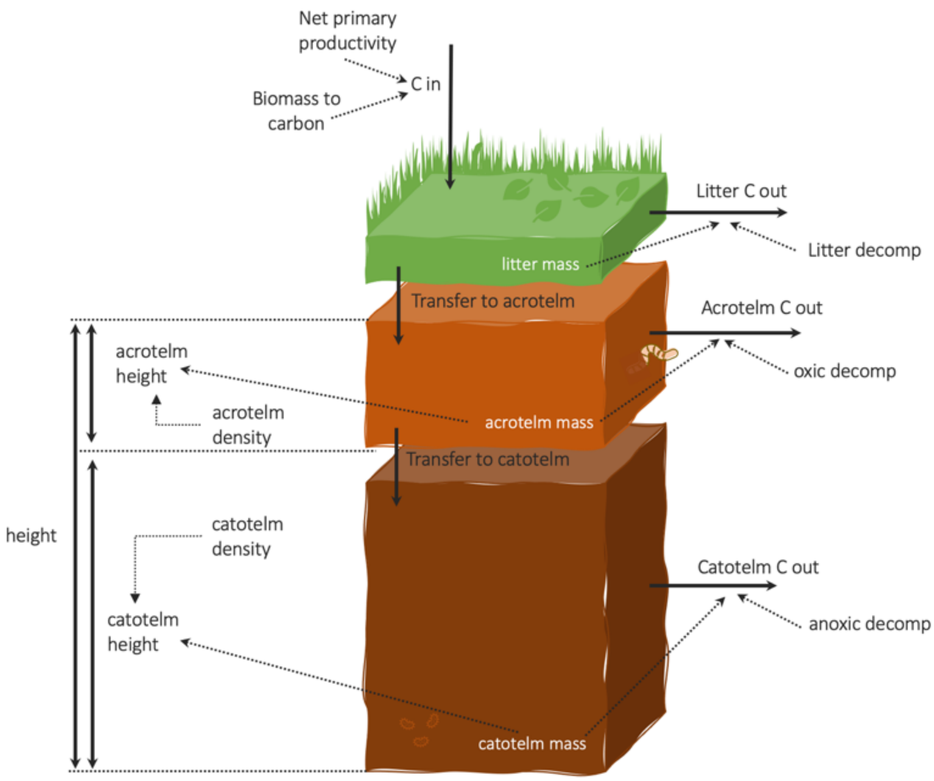

Figure 4: a schematic of peat column in peatland simulation, as divided into Clymo (1992) litter, acrotelm and catotelm structural layers.

Coupled with the hydrological sub-model, water table position helped to determine the transition between the acrotelm and the catotelm. As the water table varied annually, this implicitly introduced a mesotelm. Peat organic matter passes through the acrotelm after approximately 100 to 250 years (Turunen *et al.,* 2004; Robinson, 2006; Loisel and Yu, 2013; Bunsen and Loisel, 2020). I represented the acrotelm as dry, with a stock with a transit time of 150 years and a leakage of 2.5% per year, reflecting oxic decomposition.

The introduction of the litter layer to the peat carbon model and coupled with the hydrological sub-model resulted in a mean carbon accumulation rate between 20 and 30 g C m^{-2} y^{-1}, which is similar to eastern Canadian peat bogs (Turunen *et al.,* 2003).

3.1.5: Coupling water into the base carbon model for the extraction disturbance

Once the water table and peat growth were established as stable and peat height had neared its equilibrium, I introduced an extraction disturbance in the form of additional outputs. In practice, drainage ditches are dug to lower the water table prior to extraction. In the model, drainage is limited to the time between when the drainage ditches are dug (two years before extraction) and when restoration begins. A drainage rate replaces the discharge rate from *Equation 10*. Inflow and evapotranspiration maintain their equations. The drainage outflow (D_{Ex}) is described as:

$$D_{Ex} = W \cdot d$$

Equation 17

Where *d* is the drainage rate due to extraction and overwrites the discharge rate (*q*) in equation 11.

During extraction, vegetation is removed from the surface of the peat column, reducing NPP to zero. There is no carbon input to the system during this time.

My model simulates peat extraction as a function of an extraction rate, the remaining peat depth and minimum peat depth. A mean residual peat after extraction is not reported in the literature or by peat producers. Research of peatland restoration in eastern Canada usually occurs on peat fields abandoned by peat producers due to peat quality or difficulty in extracting (e.g. Bois-des-Bel and Cacouna, QC). Residual peat thickness does impact restoration effectiveness (Girard, 2000; Lavoie *et al.,* 2003). At least 1 m of peat is needed to isolate the surface layer from mineral elements and ions that could diffuse from the parent material below (Fraser *et al.,* 2001). To reflect that my simulated peatland restoration is effective, I use the conservative 1 m residual peat to limit maximum extraction. I assume a peat density of 120 kg m^{-3} during extraction, due to peat compression related to peatland degradation (Drollinger et al., 2020). The extraction rate (g C m^{-2} y^{-1}) is a function of the peat density, and the extraction depth (h_{Ex}, m) per year:

$$\frac{Ex}{dt} = \begin{cases} 0, & t < t_{Ex,S} \\ \rho_{ex} \cdot \frac{h_{Ex}}{dt}, & t \geq t_{Ex,S}, t \leq t_{Ex,E}, h_r \geq 1 \\ 0, & t > t_{Ex,E}, \end{cases}$$

Equation 18

Where ρ_{ex} is peat density during extraction, h_{Ex} is the extraction depth and h_r *is the peat thickness remaining*. The time limits *Ex,S* and *Ex,E* refer to the extraction start year, and extraction end year.

The lowered water table exposes more of the peat column to oxic decomposition. In the catotelm, I assume that the decomposition rate is constant until there is an extraction disturbance. When extraction occurs the CO_2 flux is considered a function of the water table (He *et al.,* 2023), so I used an adapted equation from He *et al.* (2023) to develop a decomposition factor to reflect the increase in decomposition rate for catotelm peat during extraction. The adjusted equation includes a conversion from CO_2 to C-equivalent and the catotelm mass.

$$y = \frac{-2.4 \cdot Z - 0.94}{b} \cdot \frac{1}{M_C}$$

Equation 19

Where *y* is the decomposition factor, *b* is the conversion from CO_2 to C, and Z is the depth of the water table.

The decomposition factor was then multiplied by the catotelm decomposition rate of 0.25% y^{-1} (p. 18) to give the adjusted catotelm decomposition rate during extraction.

The sub-components of the hydrological sub-model continue to be closely linked with only a few changes from pre-extraction (*figure 5*).

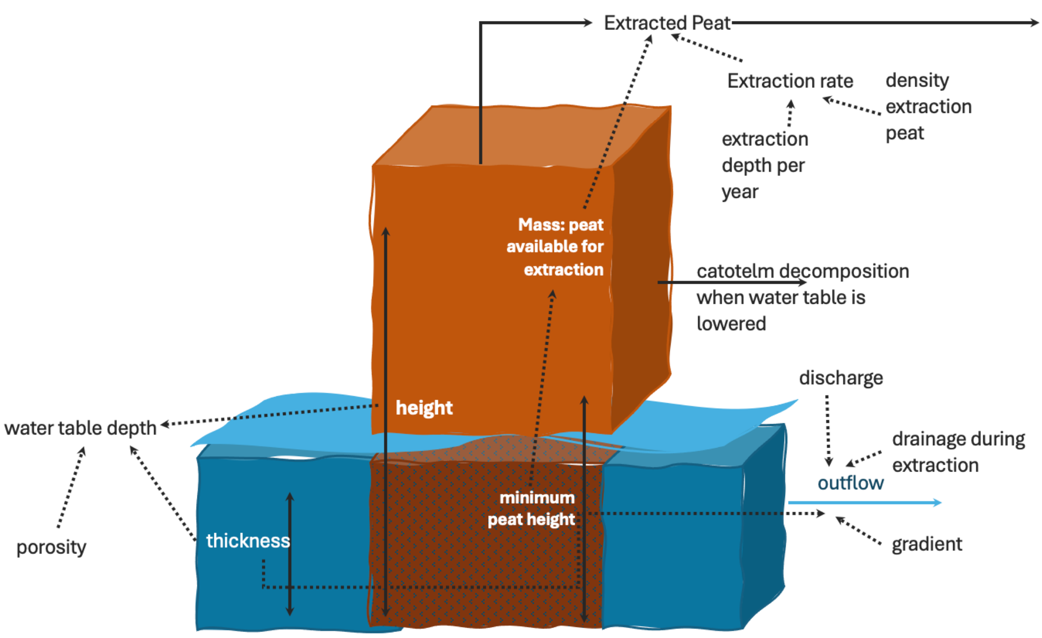

Figure 5: A schematic of hydrological sub-model as it couples with the peat column and responds to an extraction disturbance.

Once restoration begins, the hydrological sub-module returns to the pre-extraction functions (*figure 3)*.

3.1.6: Multi-layered 'restoration' module

After extraction, the peatland would either be restored immediately or restored after a delay. For the creation of a new acrotelm on a restored peatland, I used a different stock configuration. I filled the new acrotelm using a negative distribution as it effectively replicated field observations of acrotelm accumulation in literature (Taylor and Price, 2015). The new litter and acrotelm layers are established directly on top of the remaining catotelm peat (*figure* 6). A proportion of litter removed prior to extraction is available to aid restoration. Again, I introduced a new litter layer to reduce the input of all NPP to the new acrotelm.

The litter layer removed a proportion of mass from the acrotelm, so acrotelm decomposition only needed to account for its peat mass. The peat regrowth rate in the acrotelm was then comparable to the observed growth of similar eastern Canadian peatlands (Taylor and Price, 2015). Peat carbon accumulation was lower during restoration than during establishment because a large mass of catotelm peat was still decomposing during restoration and I adjusted NPP to reflect post-restoration *Sphagnum* re-establishment.

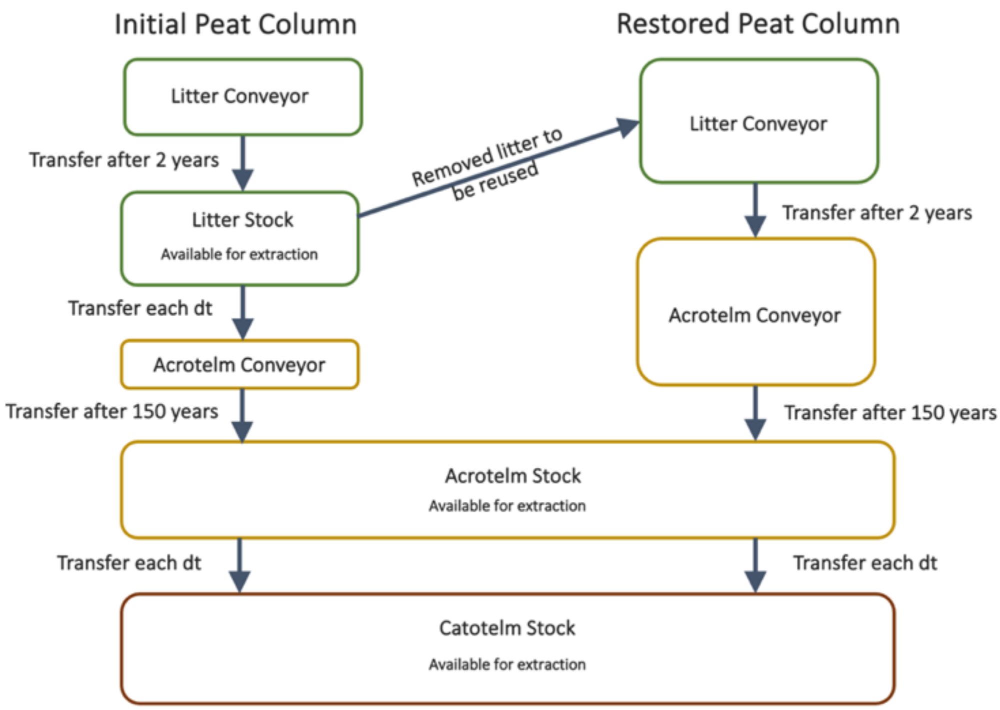

Figure 6: The peat column as split by structural carbon stores, both initially and after restoration.

3.1.7: Net primary productivity adaptation

Because our simulated peatland experiences different conditions as it establishes, after establishment, reestablishment during restoration, and after restoration, the actual NPP was not constant.

The mean 600 g m^{-2} y^{-1} NPP rate, as used in the basic Clymo model, was impacted during each phase. During initial establishment, NPP was affected by the water table and the relationship between vegetation when establishing and potential NPP (*figure 7)*.

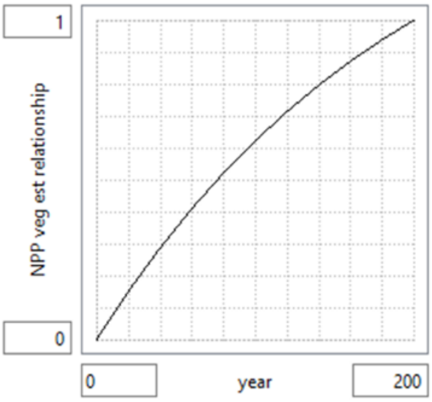

Figure 7: The relationship between NPP (dimensionless) and the time taken for vegetation to establish (years).

After the 200-year establishment phase, NPP was only influenced by the water table (*figure 8)*.

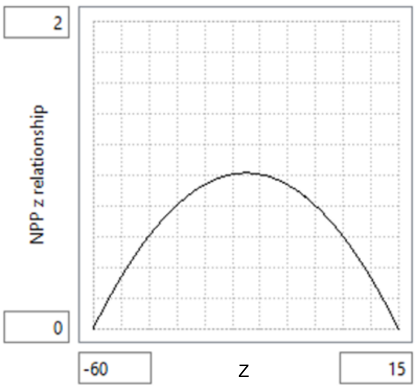

Figure 8: The relationship between NPP (dimensionless) and water-table depth (cm).

Two years prior to extraction, when drainage ditches were dug, NPP was reduced to 0 to reflect litter vegetation being 'removed'. Post-extraction ecological restoration is simulated on the remaining catotelm peat. A peatland is not considered functionally restored until its net ecosystem exchange (NEE) is similar to its state before extraction.

After ecological restoration via moss spreading, it will take 15-20 years to return to NEE function (Nugent *et al.,* 2018). The initial pioneering *Sphagnum* will establish over this 15-20-year period. I have introduced a multiplier for NPP during restoration, to combine with the relationship to the water table for actual NPP (figure 9). The potential NPP available during the reestablishment phase is also reduced, as it takes approximately 200 years for the peatland vegetation matrix to stabilise, and the acrotelm to reach equilibrium. Another multiplier accounts for the slow increase in potential maximum NPP (*figure 10).*

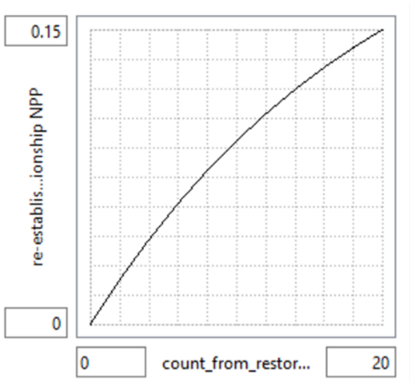

Figure 9: The relationship between NPP (dimensionless) and the time taken for vegetation to establish during restoration (years).

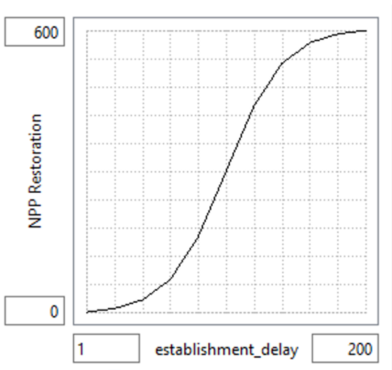

Figure 10: The NPP of the ecosystem as it restores (g m^{-2} y^{-1}), over a 200-year establishment period as Sphagnum stabilises (years).

Once ecological restoration is considered effective, after 20 years, NPP is influenced by the water table, the NPP maximum available multiplier (*figure 10*) and the relationship between vegetation when establishing and potential NPP. This version of NPP continues until the acrotelm and peatland vegetation matrix are stabilised (after 200 years) (figure 11).

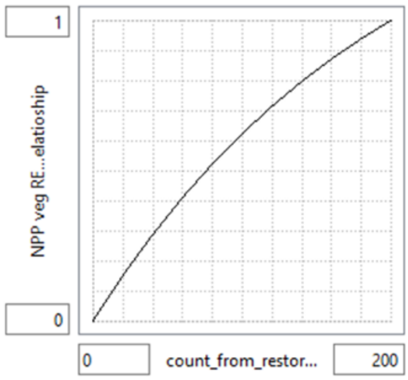

Figure 11: The relationship between NPP (dimensionless) and the time taken for vegetation to establish after restoration (years).

Then, the mean 600 g m^{-2} y^{-1} NPP rate is only impacted by its relationship to the water-table depth. The equation for NPP can be described as follows:

$$NPP = \begin{cases} NPP \cdot f(Est) \cdot f(Z), & t \leq t_{s+AcroDelay} \\ NPP \cdot f(Z), & t > t_{\,s+AcroDelay} \quad t < t_{\,Ex,S}, \quad t > T_{R,E+AcroDelay} \\ 0, & t \geq t_{\,Ex,S}, \quad t \leq t_{Ex,E} \\ NPP_{Rest} \cdot f(Rest) \cdot f(Z), & t > t_{R,S}, \quad t \leq t_{R,E+AcroDelay}, \\ NPP_{rest} \cdot f(Rest_{est}) \cdot f(Z), & t > t_{R,E+AcroDelay}, \quad t \leq T_{R,E} \end{cases}$$

Equation 20

Where *f* refers to a graphic function, with f(est), f(z), f(rest) and f($rest_{est}$) corresponding to figures 7, 8, 9 and 11. NPP_{rest} refers to NPP according to Figure 10. The time limits *S, R,E, and R,S* refer to the model start year, the restoration start year and the restoration end year. AcroDelay notes a 200-year addition to the respective time limits according to the time required for the acrotelm to establish and reach equilibrium. NPP is then multiplied by the carbon content of 50% (*cc*, equation 5) for the carbon in flow.

In this peatland disturbance model, the connectedness between each peat layer and its parameters, and the hydrological sub-model is emphasised by the feedbacks between them. Relative feedback strength varies depending on the model phase, but the key positive and negative feedbacks are summarised in *Figure 12*.

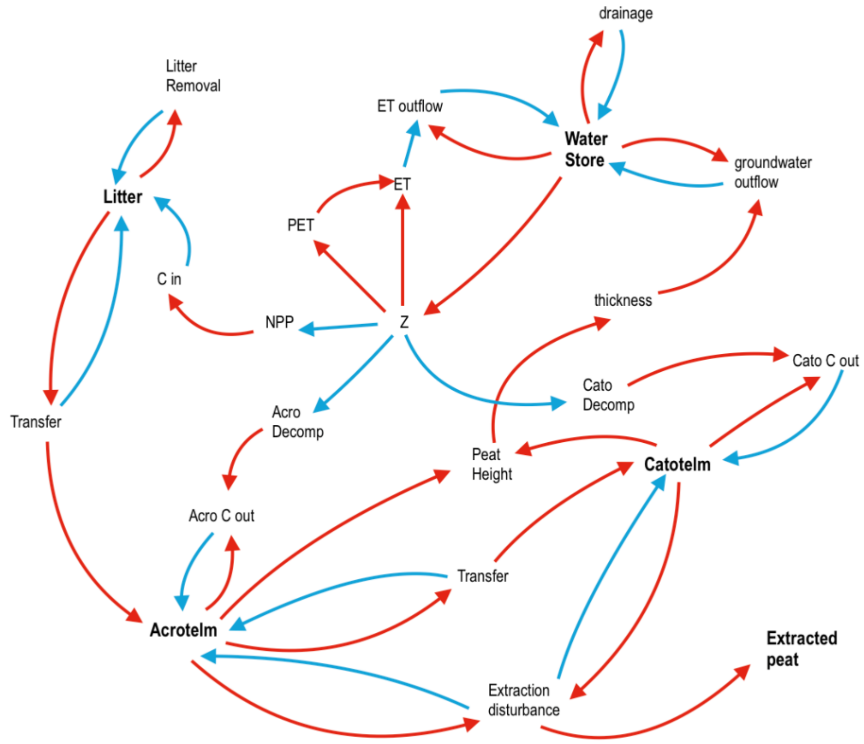

Figure 12: The key positive (red) and negative (blue) feedback loops in the model simulation. Key stores are in bold.

3.1.8: Module on the fate of peat

Extracted peat carbon, used for horticulture, is not immediately lost from the biosphere to the atmosphere after its removal from the peatland. To represent the fate of peat carbon once the peat has been extracted, I introduced a ‘fate-of-peat’ module to the coupled peatland-hydrology simulation.

The fate of peat carbon is controlled by its management. The proportion of carbon masses that are not decomposed then transfer to subsequent stores. We assume that once peat has been extracted, it has a decomposition rate of 5% per year (Sharma *et al.*, 2024). Peat use and after use are defined by prescribed lengths of time and represented as mass stores (M_U and M_{AU} (g C m^{-2}) respectively).

$$M_U^t = D_{EX} - (\alpha_4 \cdot M_U^{t-1}) - p_U$$

Equation 21

$$M_{AU}^t = p_U - (\alpha_4 \cdot M_{AU}^{t-1}) - p_{AU}$$

Equation 22

Where D_{EX} is the extracted peat, α_4 is the decomposition rate, and p_U and p_{AU} are the transfers out of the use and after-use stores, respectively.

To augment the peat, and improve yield during use, mineral soils are mixed into the peat. After peat use, the soil mixture is considered 'waste' organic matter. For the peat organic matter mixed with mineral soils, I vary the decomposition rate between 1% and 6% per year. There is very little published on the decomposition rate of organic matter in mineral soils; therefore, my values are largely speculative and the simulated carbon output back to the atmosphere should be treated as hypothetical scenarios. Similarly, I expect some stabilisation of carbon in the residual organic-matter-mineral-soil mixture, but again little is published on the subject, so the proportion stabilised is unknown. I assume for the various scenarios a carbon stabilisation proportion between 10% and 50% of peat carbon mixed with mineral soils per year. Peat organic matter mixed with mineral soils, and stabilised peat carbon, are represented by their own stores in the model (*figure 13*), M_{MS} and M_s respectively.

$$M_{MS}^{t} = p_{AU} - (\alpha_5 \cdot M_{MS}^{t-1}) - (p_S \cdot M_{MS}^{t-1})$$

Equation 23

$$M_S^t = p_S \cdot M_{MS}^{t-1}$$

Equation 24

Where α_5 is the decomposition rate of the peat-carbon-mineral-soil mixture, and p_s is the proportion of peat carbon stabilised per year.

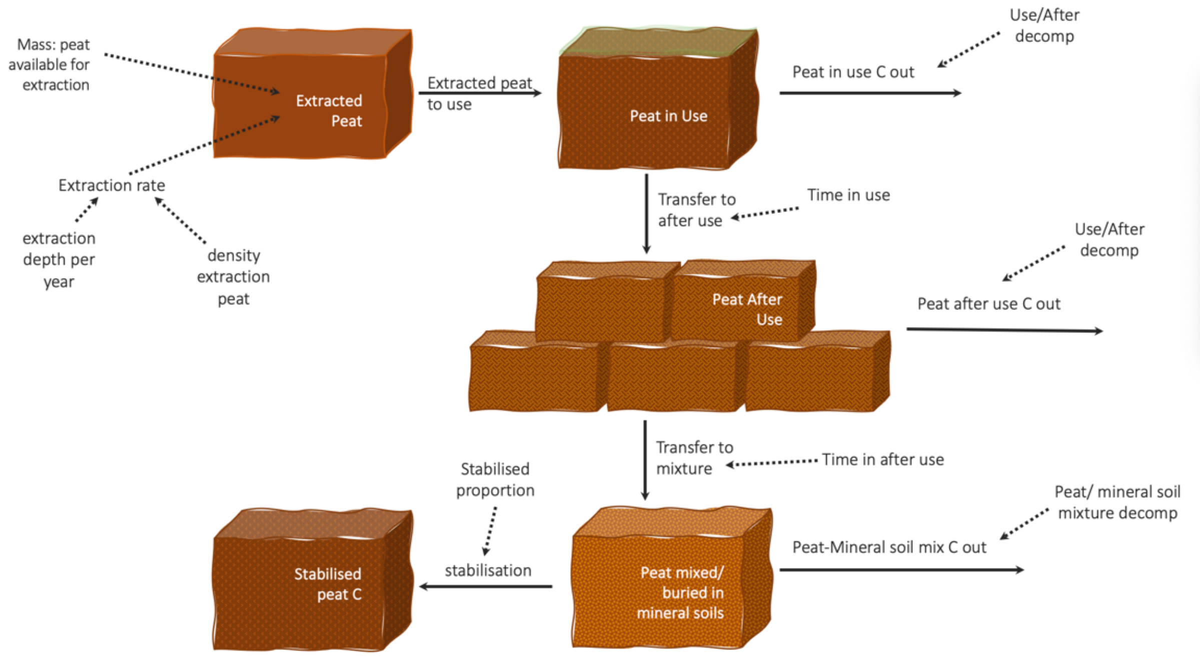

Figure 13: A schematic detailing the fate of peat after extraction, as it is used, after use, mixed with mineral soils and stabilised.

3.1.9: Frozen model and sensitivity analyses

After all the modules and the hydrological component were coupled, I froze the model and there was no further development. The frozen model is the version from which the carbon stores and biospheric emissions from the simulation were assessed through different scenarios. Sensitivity analyses were conducted to assess model stability and outline an appropriate base scenario. The chosen parameters for the frozen model base scenario were informed by industry (*table 1*) and values chosen to reflect representative management practices.

Table 1: Peat extraction management parameters, used in scenario development.

	Parameter	*Unit*
Scope 1	Extraction depth	m y^{-1}
	Restoration delay	years
	Extraction duration	years
Scope 3	Peat height remaining	meters
	Peat use time	years
	Peat after use time	years
	Peat-soil mixture decomposition rate	y^{-1}
	Peat carbon stabilisation proportion	% y^{-1}

I assumed an extraction depth of 0.04 m y^{-1}, an extraction duration of 32 years and restoration after 6 years of extraction field closure for Scope 1, peat production, management parameters. I had to make assumptions for Scope 3, fate of peat, management parameters because there is very little published, and the peat extraction industry does not track downstream practices. Extracted peat was assumed to be used for 2 years before moving to after-use. Peat would transition through the after-use use phase for 10 years. Peat organic matter mixed with mineral soil was assumed to have a decomposition rate of 6% per year, and 10% of the peat carbon is stabilised each year.

A sensitivity analysis was conducted on the response of the base scenario to variation in each management parameter. Seven additional management scenarios were developed to show the impact of a) including the fate of peat on biospheric carbon recovery time and cumulative carbon emissions and b) different peatland management strategies on biospheric carbon recovery time and cumulative carbon emissions. The sensitivity analysis and management scenarios are expanded upon in my *Results* section.

3.2: Field Observations: biogeochemical properties of peat profiles in extraction fields in Rivière-du-Loup, Québec

3.2.1: Site locations

Peat extraction for horticulture has occurred approximately 5 km southeast of Rivière-du-Loup town, QC, since the mid to late 20th century. Core samples were taken at four locations, in three peat extraction fields where extraction began in 2007, 2016 and 2020, and a fourth field, cleared of vegetation in 2022 to prepare for extraction (*figure 14*). The peatland was predominantly a partially treed ombrotrophic treed bog, with peat depths ranging from 2.4 m to 4.3 m in 1914 (Dept. of Mines, 1914) (*figure 15*).

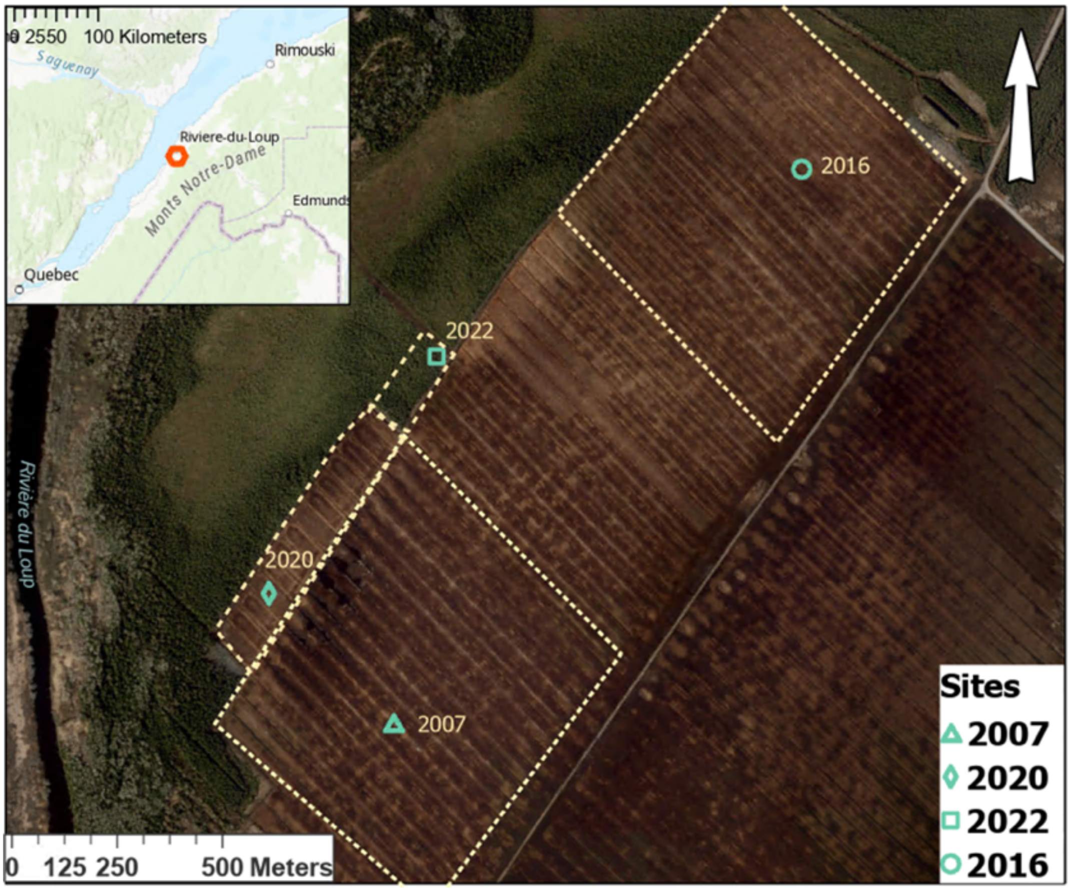

Figure 14: A map of Rivière-du-Loup peat coring sites. Fields are differentiated by extraction/ vegetation removal start year.

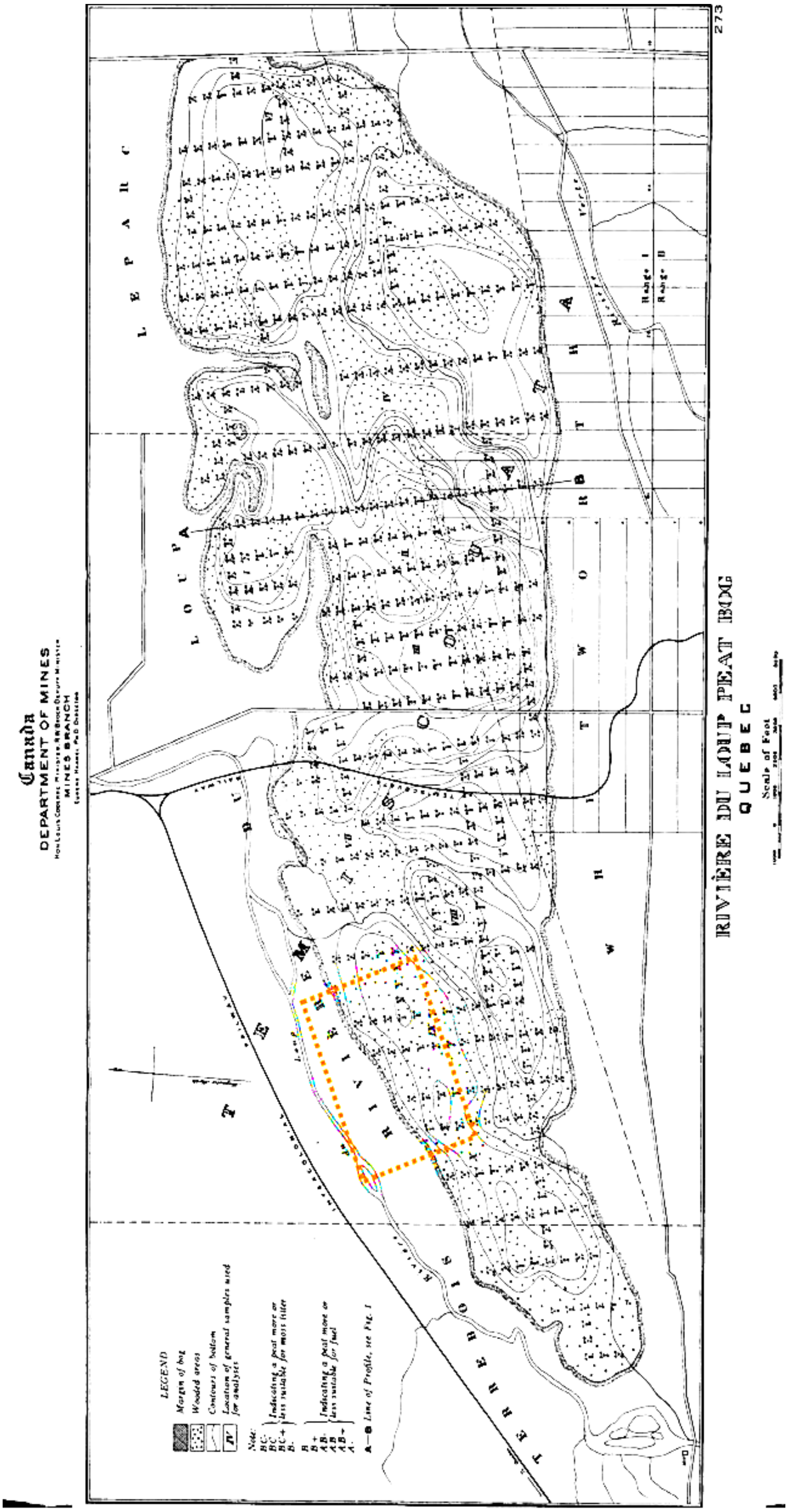

Figure 15: A 1914 aerial assessment map of Rivière-du-Loup treed bog, with approximate research location (orange) (Dept. of Mines, 1914).

The highest elevation point of the original domed bog is along the maintenance road, between the 2007 and 2016 fields. Prior to extraction, drainage ditches were dug and are present every 30 m in the fields. Lateral ditches encourage flow towards larger, field-end ditches that cumulate flow in a settling pond, lowering the water table. The 2020 and 2022 sites were more saturated than the 2007 and 2016 sites due to their location along the ditch-modified hydrological gradient of the domed peat field. Our samples were taken in early September 2022, after a wet summer relative to previous extraction years. The mean annual temperature and precipitation are ~5 ˚C and ~800mm respectively (Meteoblue, 2023).

3.2.2: Core sample analysis

A 50 cm deep pit was dug at each site with a vertical wall, and a Russian Auger was used to extract peat until the parent material was reached (*figure 16*). A surface sample of 10 cm^3 was first taken, followed by a 10 cm length of core sample, every 50 cm until the mineral clay parent material was reached. Samples were immediately placed in plastic bags, with excess air removed, and stored in a cooler. Twenty-four samples were collected.

Figure 16: (a) Pit dug for surface and 50-60 cm depth samples. Photograph taken at the 2016 site. (b) core taken for sampling at 150-200 cm depth. Photograph taken at the 2007 site. The spade of our trowel is 10 cm long.

In the laboratory at McGill University, each sample was weighed for wet mass, dried in an oven at 60˚C for 24 hours, then reweighed for dry mass. Since sample volume was recorded at the time of sampling, dry bulk density (ρ) could be calculated:

$$\rho = \frac{m}{v}$$

Equation 25

Where *m* is the sample dry mass, and *v* is the sample volume.

Each sample was separated into three parts. A subset of samples was sent to the *André E. Lalonde Accelerator Mass Spectrometry* in Ottawa for ^{14}C and age before present (BP) analysis. The remaining samples were ground using a mortar and pestle, followed by a ball mill and then run through a 500 µm sieve. Ground samples were then shipped to *WWU Münster* for Fourier Transform mid-infrared spectroscopy (FT-MIR) analyses and sent to *Whalen Lab McGill Macdonald Campus* for CN analyses.

On return of ^{14}C, C% and dry bulk density, long-term rate of carbon accumulation (*LORCA)* could be calculated.

$$LORCA = \frac{a}{d_m} \cdot \rho \cdot cc$$

Equation 26

Where a is the sample age in years before present, d_m is the depth the sample was extracted from, and cc is the carbon content in per cent.

3.2.3: CN analyses

At the *Whalen Lab,* McGill Macdonald Campus, 8-12 mg of my ground peat samples were placed in tin capsules and analysed with a *Flash1112 Elemental Analyzer*. The samples were measured for concentrations of carbon and nitrogen. They were calibrated every twelfth sample to eliminate background noise.

3.2.4: ^{14}C analyses

At the *André E. Lamond AMS* Laboratory radiocarbon analyses are performed on a *3MV accelerator mass spectrometer* (AEL AMS, 2022). The fraction of modern carbon was calculated as a ratio of ^{14}C to ^{12}C (AEL AMS, 2022). Radiocarbon ages were calculated as a function of -8033ln($F^{14}C$) and are repurposed as ^{14}C years before present (*BP*), where BP corresponds with AD 1950 (Stuiver and Polach, 1977, *as noted in AEL AMS 2022*).

Chapter 4: Results

4.1: Simulated peatland - Undisturbed

The peatland simulation began at t=0 and ran for up to 20,000 years, with a time step of 1-year. The simulated peat column reaches a maximum height at steady state of 5.35 m after 20,000 years; catotelm and acrotelm thicknesses are 4.86 m and 0.49 m, respectively (figure 17). The peatland grows fastest in the first 500 years from 0 m to 0.55 m, and the acrotelm steady-state is met at approximately 300 years.

Acrotelm growth and maximum thickness correspond with decomposition, mass, and time, with decomposition limited by the water-table depth (Clymo, 1984). Acrotelm depth often ranges from 20 to 35 cm (Clymo, 1984; Bunbury *et al.,* 2012; Bunsen and Loisel, 2020). My model omits a mesotelm. Classified as the lower part of the acrotelm (Clymo, 2015) or its own peat layer, the mesotelm can be up to 30 cm thick (Younes and Grasset 2018; St. James *et al.,* 2021) depending on variations in the water table depth. Including a mesotelm, therefore, increases the thickness above the catotelm to up to 50 to 65cm, which is consistent with our acrotelm thickness of 49 cm.

The simulated catotelm thickness and total peat depth are similar to the President's bog, near Rivière-du-Loup, an eastern Canadian continental peat bog, undergoing extraction. Historic Canadian peat depths average ~ 3 m (Tarnocai 1984), but recent peat cores suggest that Canadian peatlands could be much deeper (Southee *et al.,* 2021). Frolking *et al.* (2010) simulated the Mer Bleue bog has a soil carbon accumulation rate of 20 g C m^{-2} y^{-1}, 8,000 years after initiation.

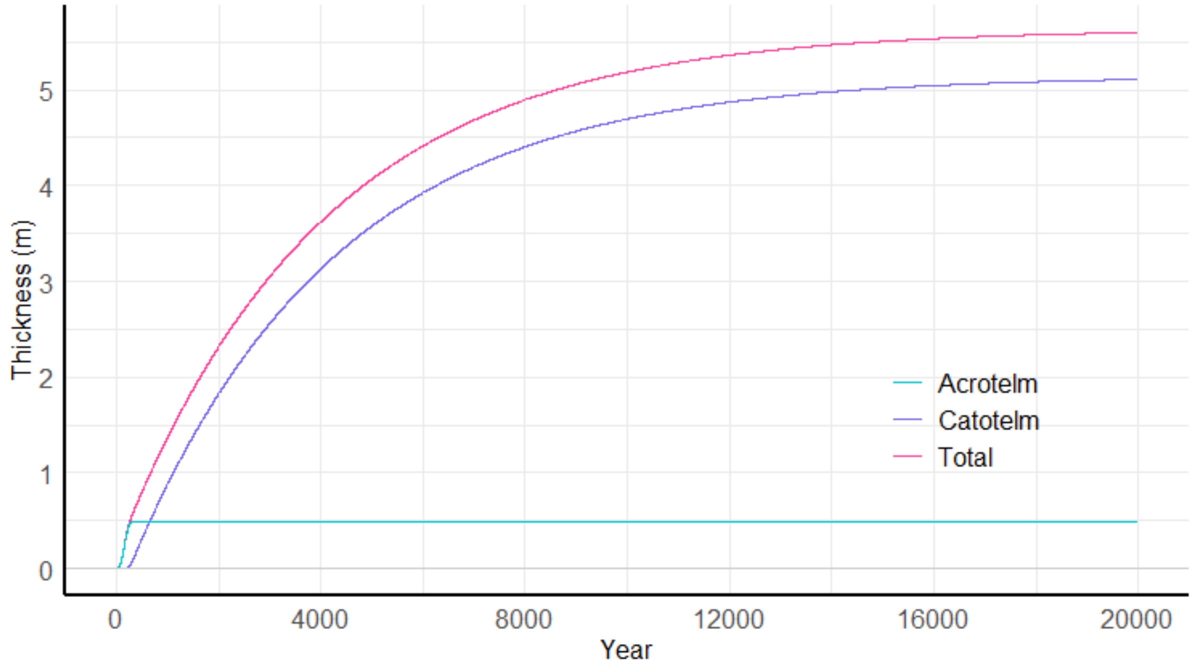

Figure 17: The peat column height over time, no disturbance. Catotelm and acrotelm heights are shown separately, and combined as total peat height.

The carbon accumulation rate in the base rates is 63.7 g C m^{-2} y^{-1} during the first 500 years of peatland establishment and then slows down as the peatland ages to 23.5 g C m^{-2} y^{-1} by 8,000 years (figure 18). In eastern Canada, ombrotrophic peat bog accumulation is usually measured between 20 and 30 g C m^{-2} y^{-1} for peatlands that established during the first part of the Holocene (5,000-10,000 years BP) (Turunen *et al.*, 2003). After the 20,000-year undisturbed run, the simulated mean is 10.7 g C m^{-2} y^{-1} (figure 19).

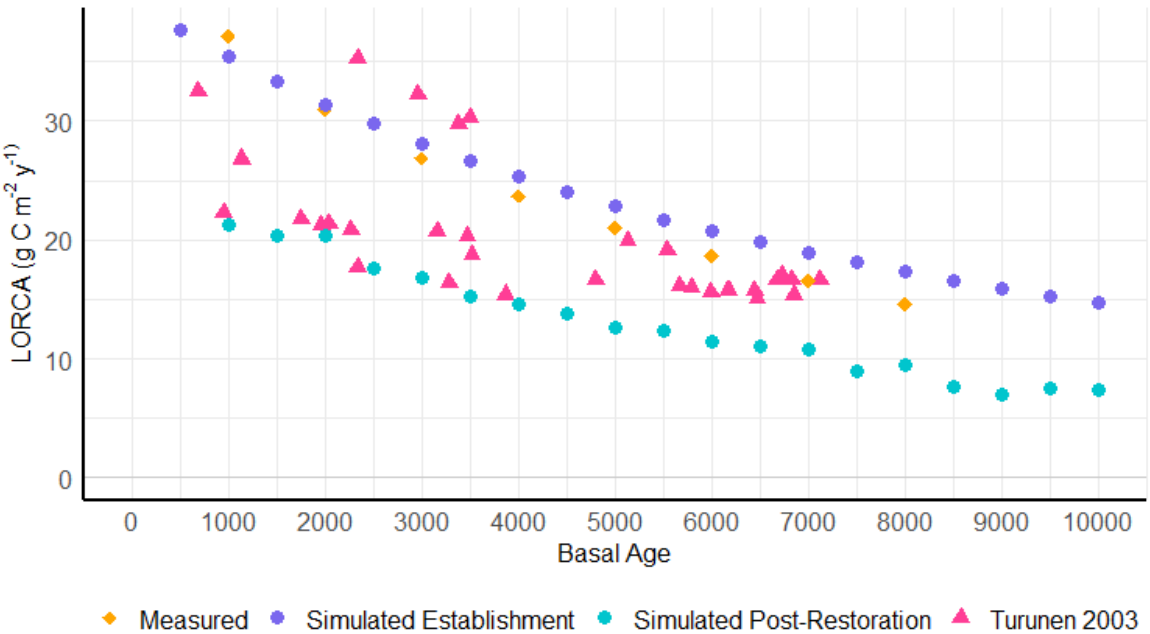

Figure 18: The long term rate of carbon accumulation. Carbon accumulation rate is shown for the simulated peatland as it established, and after restoration, at 500-year intervals. Simulated LORCA is overlain with Turunen et al. (2003) LORCA datapoints, and measured LORCA.

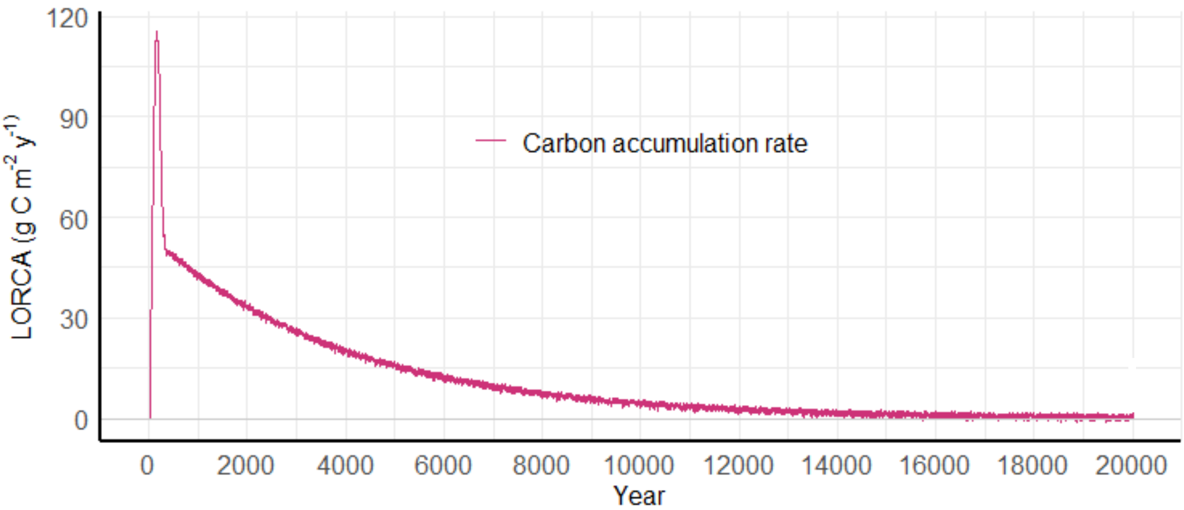

Figure 19: The long term rate of carbon accumulation for the simulated peatland over 20000 years. Mean carbon accumulation fits observations of ~20 g C m^{-2} y^{-1} between 4000 and 8000 years. After 14000 years LORCA begins to approach zero, as expected from previous works (Clymo 1984, Clymo 1992).

During establishment (0-500 years) the water-table depth has a shallower mean depth of 14.1 ± 6.4 cm below the surface. After 500 years the water-table depth has a mean of 17.9 cm ± 2.0 cm (figure 20). The water table fluctuates with fluctuating precipitation and evapotranspiration, which were varied randomly by ± 10% around a mean simulation value of 900 mm y^{-1} and 250 mm y^{-1}, respectively. At Mer Bleue, the mean daily water table varies from just below the surface to 65 cm depth (He *et al.,* 2023) and the mean annual water table varies between 20 and 50 cm (Wilson, 2016). Other northern hemispheric ombrotrophic peat bogs experience an annual average water-table depth between 20 and 30 cm (Moore *et al.,* 2002; Graf *et al.,* 2008; Bunbury *et al.,* 2012). My simulated mean water-table depth of 17.9 cm ± 2.0 cm is slightly shallower than this range, and the interannual variability is smaller than observed at Mer Bleue (Wilson, 2016).

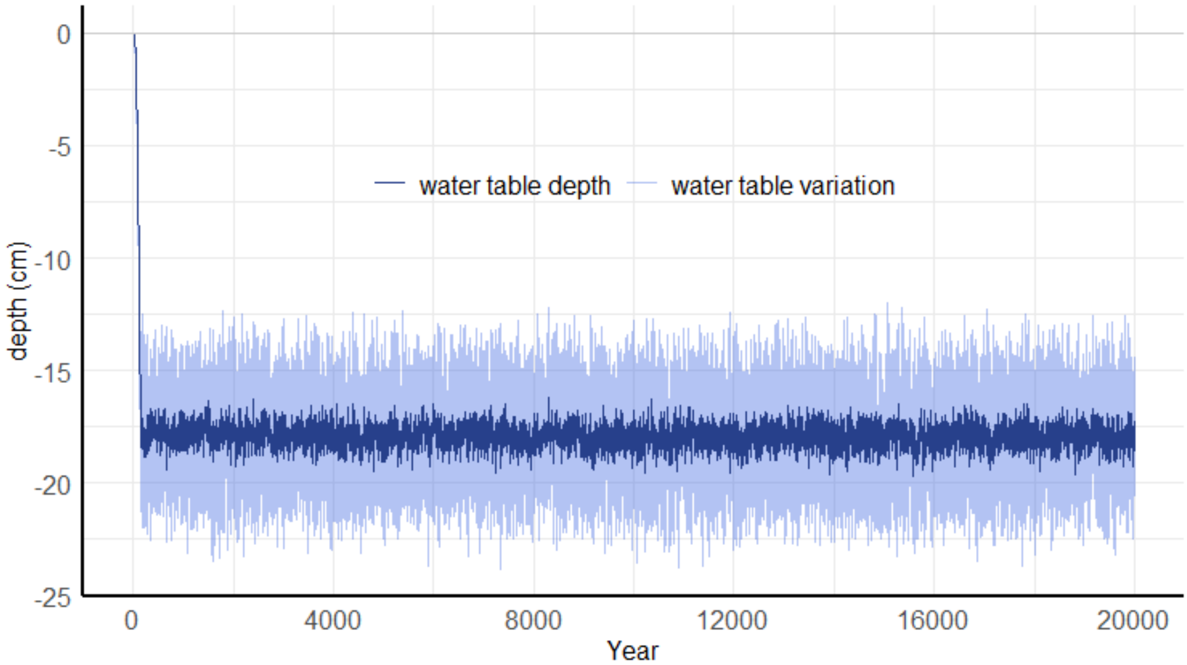

Figure 20: The water table depth over time for the simulated peatland. Light blue represents annual water table according to fluctuating precipitation and evapotranspiration parameters. Dark blue is the 5-year average of the annual water table, which is used in peat thickness calculation.

Before parameter sensitivity analysis, the maximum peat height of ~ 5.35 m was reached 18,358 years into the simulation (figure 5). The peat growth rate was consistently below 1 cm per 100 years, after 10,519 years. A sensitivity analysis of parameters to a ± 10 % variation was conducted on the model (figure 21, table 2). NPP increase by 10 % caused the maximum height of the peatland to increase to 5.88 m (+ 0.53 cm, or 9.9 %). An NPP decrease by 10 % led to a maximum height of 4.82 m (- 0.53 cm, or 9.9 %). Precipitation experiences an up to ± 10 % randomisation function during the simulation each dt as part of the coding, so for sensitivity analysis, I retained the randomisation function but increased or decreased base precipitation ± 10 %. The increased precipitation rate had the simulated peatland reaching at a maximum height of 5.50 m. The lower precipitation rate caused the simulated peatland to reach a height of 5.19 m. I also varied acrotelm and catotelm decomposition by ± 10 %. The decomposition rate increase caused the maximum height of the peatland to decrease to 3.43 m. The decomposition rate decrease led to a maximum height of 7.67 m. The model is therefore most sensitive to changes in decomposition rate.

Table 2: Peat thickness sensitivity to the rates of precipitation, decomposition (acrotelm and catotelm), evapotranspiration, and net primary productivity.

Parameter		*Peat Column Thickness (m)*	*Change in thickness (m)*	*Change in thickness (%)*
Baseline		**5.35**	**-**	**-**
Precipitation	+10%	5.50	+ 0.15	+ 2.8
	-10%	5.19	- 0.16	- 3.0
Decomposition	+10%	3.43	- 1.95	- 35.9
	-10%	7.67	+ 2.32	+ 43.4
Evapotranspiration	+10%	5.07	- 0.28	- 5.2
	-10%	5.56	+ 0.21	+ 3.9
Net Primary Productivity	+10%	5.88	+ 0.53	+ 9.9
	-10%	4.82	- 0.53	- 9.9

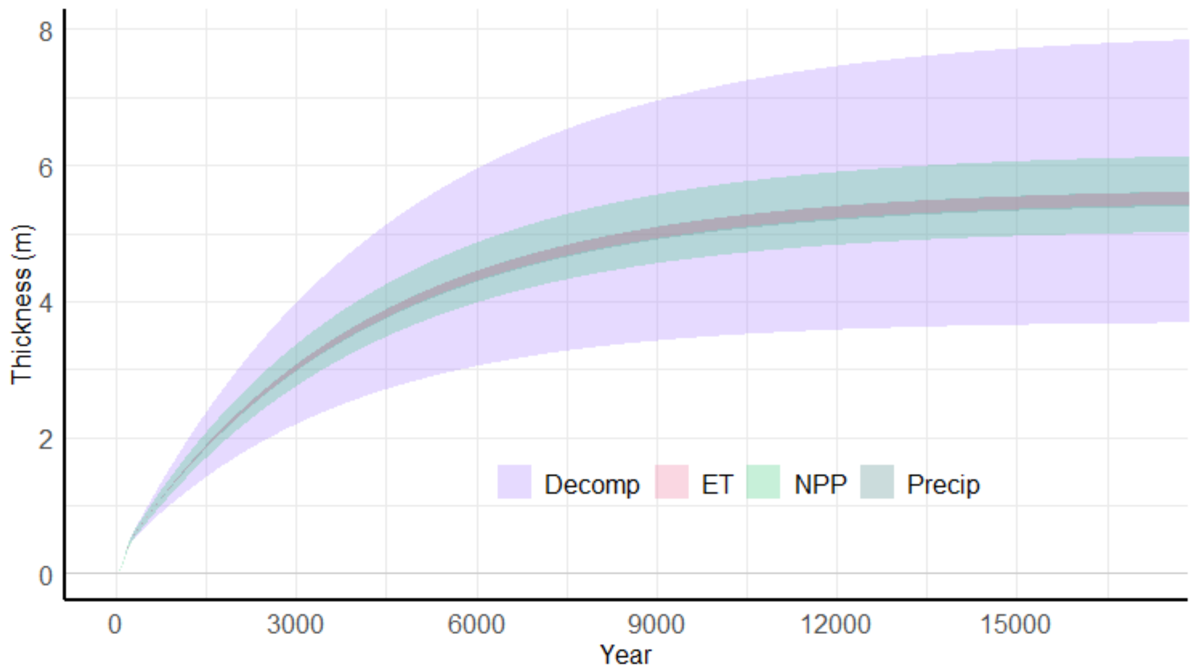

Figure 21: The change in peat column thickness according to sensitivity analysis by parameter ±10% variability.

4.2: Field results – Extracted peatland, Rivière-du-Loup, QC

I evaluated the base simulation model with field measurements. For this model, bulk density, peatland age at the time of extraction, and carbon density were calculated based on four cores taken from the field. The biogeochemical characteristics pertaining to CN ratio and FTIR humification for the cores are available in *appendix iii*.

The basal date ranged from 8,234 ± 52 to 1,862 ± 12 ^{14}C y BP (figure 23). Peatland initialisation can, therefore, be assumed to have begun mid-Holocene (Dazé *et al.,* 2022). By fitting a logarithmic function to our age-depth curve, we can normalise depth with age because the top 0- to 2,000-year-old peat has been extracted. The slope of the logarithmic curve can be used to calculate the carbon accumulation rate.

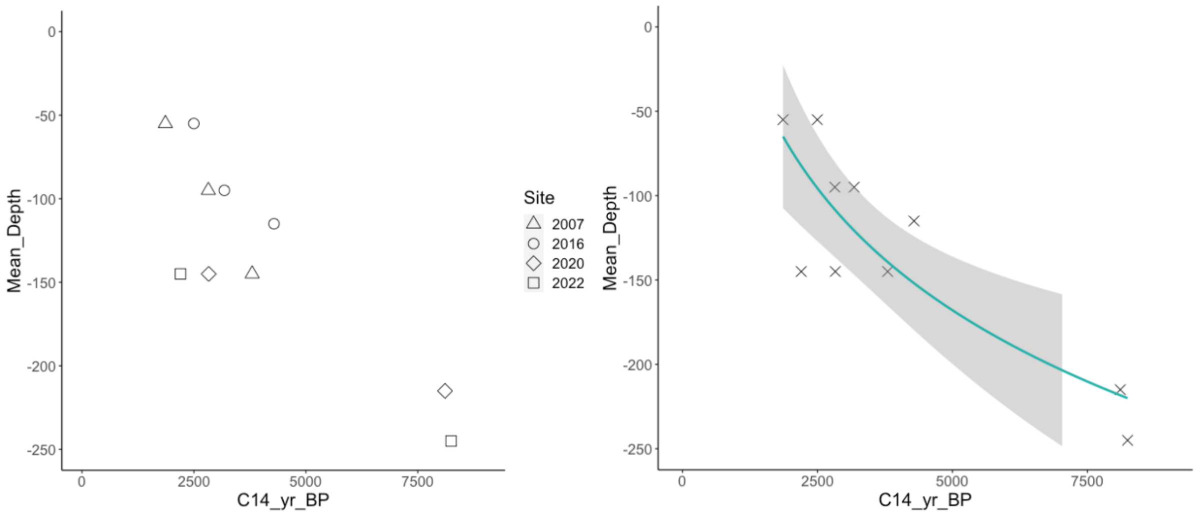

Figure 22: The peat depth and age according to core measurements. Date is shown both separated by site(left) and collectively (right).

Bulk density consistently increases with normalised age-depth (figure 23). Sites 2007 and 2016 (site year indicates when the field was first opened for production) have been extracted for longer, and demonstrate a steeper increase in bulk density than the more recent 2020 and 2022 sites. Most samples are above the mean bulk density of pristine peatlands (80 kg m^{-3}) and below 200 kg m^{-3}.

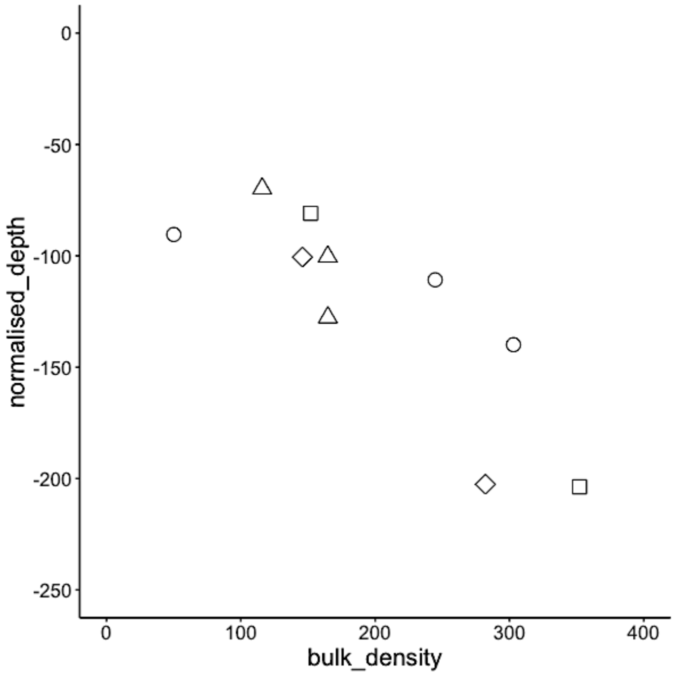

Figure 23: The peat bulk density (kg m^{-3}) with normalised-age-depth (cm).

There was little variation in carbon and nitrogen content with depth (figure 24). The mean carbon content (CC) was 46% carbon, which fits within the 42.8 – 51.8% range noted in North American literature (Vitt *et al.*, 2000; Bridgham *et al.*, 2008; Turunen *et al.*, 2004). Nitrogen percentage increased with normalised depth and is similar to that reported in the literature.

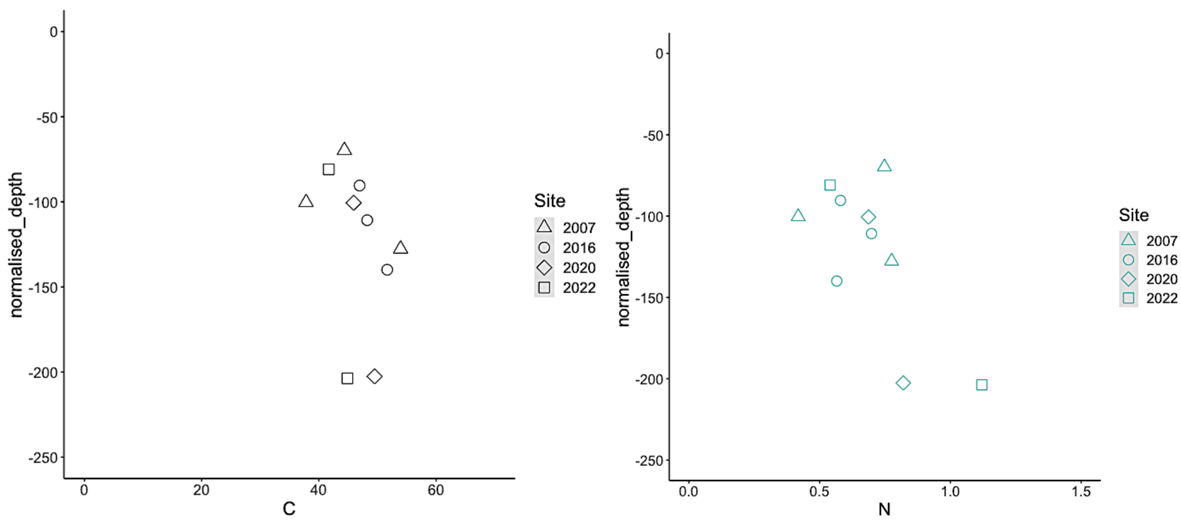

Figure 24: Macronutrient abundance in percentage by normalised age-depth for carbon (left) and nitrogen (right).

Using the measured slope of age-depth, dry bulk density and the CC, a carbon accumulation rate was calculated. The carbon accumulation rate decreases over time from ≈37 to ≈14 g C m^{-2} y^{-1}, with a mean long-term carbon accumulation rate (LORCA) of 24 g C m^{-2} y^{-1} (figure 19). Peatlands exhibit a range of 18 – 29 g C m^{-2} y^{-1} (Gorham 1991; Clymo 1998; Roulet *et al.,* 2007; Nilsson *et al.,* 2008; Yu *et al.,* 2010; Koehler *et al.,* 2011; Helfter *et al.,* 2015), while peat bogs specifically exhibit a range of 20 – 30 g C m^{-2} y^{-1} in literature (Kelly *et al*., 1997; Roulet, 2000; Roulet *et al.,* 2007). The measured mean of 24 g C m^{-2} y^{-1}, therefore, fits well within the reported ranges. The accumulation curve is similar to the Turunen *et al.* (2003) LORCA.

4.3: Simulated peatland - Disturbed

With an extraction disturbance, the peatland height and water table change, and there is no longer any C accumulation. The peatland becomes a source of CO_2 to the atmosphere as peat mass is lost by continued decomposition and removal for growing substrate.

In the simulations, disturbance begins at the peatland 8,000 years after initialisation. At this time, the total peat thickness is 4.69 m. After extraction ceases the peatland height is 1 m (this height is set to leave 1 m of residual peat in the catotelm based on best practices). After restoration begins, there is a slow growth in peatland height for ~ 200 years. At 20,000 years of simulated peatland age, 11,960 years after restoration, the peatland height is 4.77 m. At 20,000 years the acrotelm and catotelm thicknesses are 0.49 m and 4.28 m, respectively (figure 25).

During extraction, the acrotelm height is reduced to 0 m, and the total peat height is reduced to a minimum of 1 m. While restoration enables the acrotelm to begin to grow again, the catotelm layer will continue to decompose and not grow until mass passes from the acrotelm to the catotelm, which occurs after between 1 and 200 years (Clymo, 1984). After extraction, restoration occurs on the catotelm layer and is quickly encouraging *Sphagnum* coverage due to the acrotelm moss transfer technique used as part of Canadian ecological restoration (Graf and Rochefort, 2016). Consequently, peatland growth post-restoration is at a slightly slower rate than pre-extraction. The catotelm continues to lose mass as the new acrotelm develops, then grows once the acrotelm is again established.

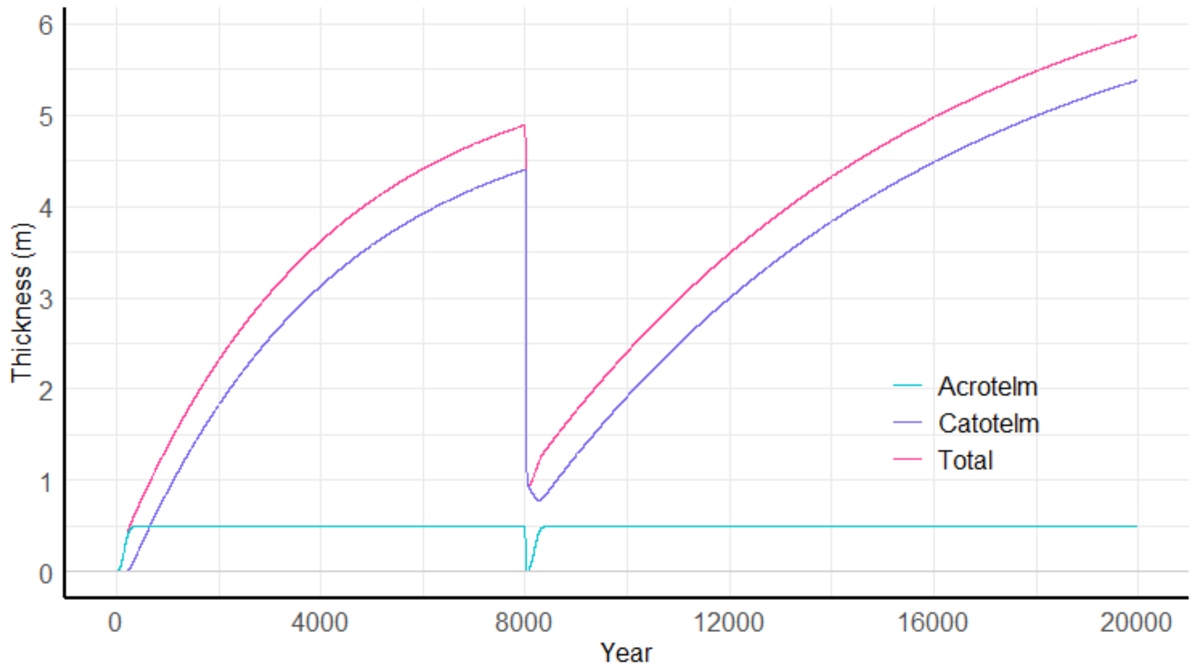

Figure 25: The peat column thickness over time, with simulated disturbance at 8000 years. Catotelm and acrotelm heights are shown both separately and combined (total peat thickness).

The water table is reduced during extraction by introducing a drainage flow from a mean of -22.6 cm ± 16.9 cm to a mean of -56.2 cm. During restoration, the drainage is removed, and water-table depth returns to -20 cm by year 8050 (figure 26). The water table fluctuates with variations in precipitation and evapotranspiration, applying the same random function for precipitation and evapotranspiration as in the initial growth of the peatland. Nugent *et al.* (2018) report post-restoration water-table depths of -0.29 m ± 0.12 m, -0.26 m ± 0.1 m, and -0.31 m ± 0.12 m, 14, 15, and 16 years after restoration.

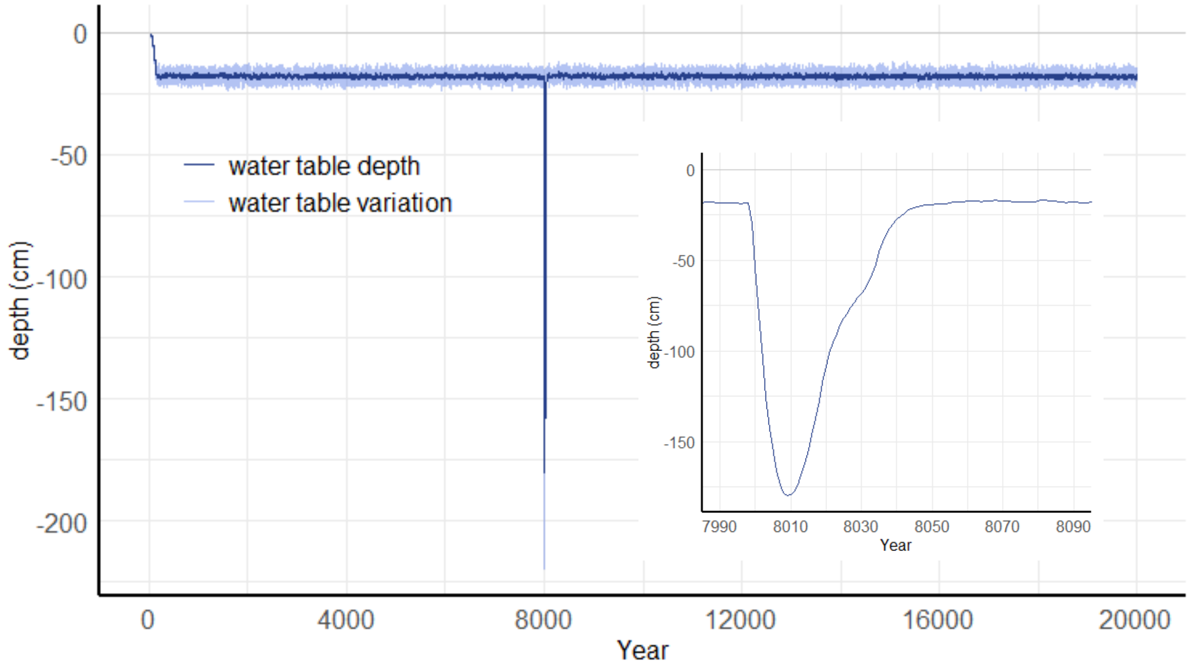

Figure 26: The water table depth over time, with extraction drainage disturbance.

Post-extraction, restoration causes the peat C accumulation rate to be a mean of 48.0 g C m^{-2} y^{-1}, from when extraction ends to 250 years after extraction, 8,000 years after extraction the rate is 15.6 g C m^{-2} y^{-1} (figure 2). By 20,000 years the mean rate of C accumulation is 12.7 g C m^{-2} y^{-1} (figure 27). The mean carbon accumulation rate is slightly lower for the restored peatland than the accumulation rate at initiation. The difference between uptake during initiation and after restoration is likely related to the 1 m of catotelm peat left in the peat column. Catotelm peat will continue to decompose as *Sphagnum* re-establishes and begins to develop the post-restoration acrotelm, so the ratio of NPP to decomposition is lower during restoration than it was during establishment. My simulated peat carbon accumulation follows a similar trend to our measured peat carbon accumulation and is also comparable to the Turunen *et al.* (2002) long-term rate of carbon accumulation (Figure 18), but there are no records of restored peatland biogeochemistry over 100 years old, and no records of peatlands restored via the moss layer transfer technique older than 20 years (Hugeron *et al.,* 2020). The oldest disturbed peatlands that show recovery are in Japan, but their disturbance relates to volcanic ash, not peat extraction (Hughes *et al.,* 2013).

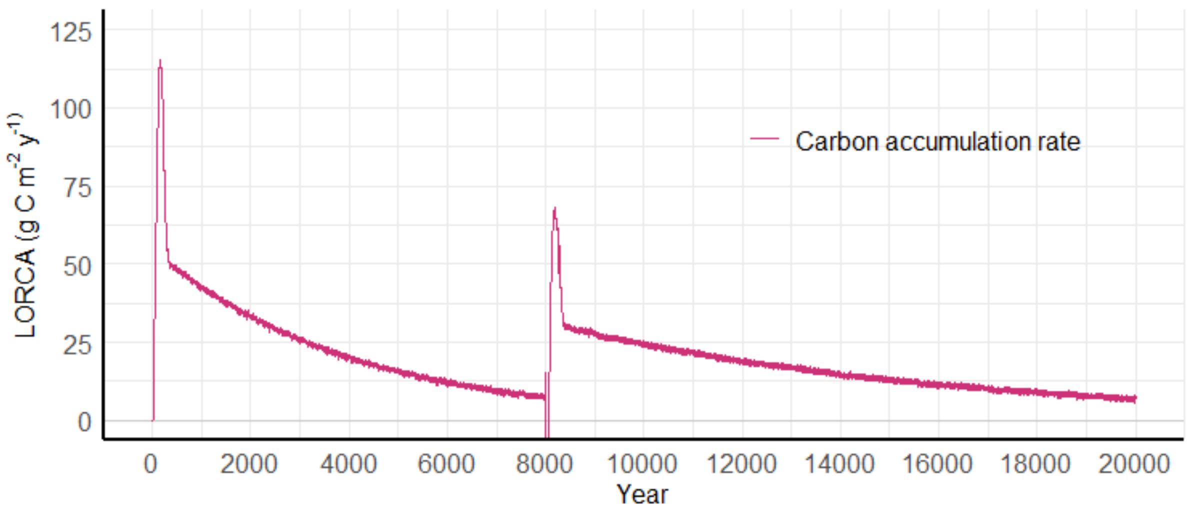

Figure 27: The long term rate of carbon accumulation, peatland disturbance occurs at 8000 years. Simulated peatland is shown with all data points.

4.4: Time to recover biospheric carbon losses after extraction

To develop management scenarios, I varied seven model parameters: three attributing to Scope 1 management, and four relating to Scope 3 management (table 3). The Scope 1 variables were extraction rate (comprised of extraction depth per year and extraction duration), and restoration delay. The Scope 3 variables were: duration for the use of extracted peat, duration for the after-use of extracted peat, the decomposition rate of peat mixed with mineral soils, and the peat carbon stabilisation proportion. Each variable had a different impact on the trajectory of peatland recovery. The scenarios demonstrated different combinations of variable values to reflect the effect of potential peatland management strategies.

Baseline 3 (scenario d+) was used for sensitivity analysis as its variable values best represent practices used by the peat industry (CSPMA *pers comm.*) and worst-case restoration delay. After extraction and effective restoration, it takes scenario *d*+ 4520 years to uptake an equivalent in atmospheric carbon as was lost from the biosphere (figure 28). I individually varied each parameter, keeping the rest unchanged, to determine which variable had the most significant impact on emissions relative to scenario *d*+.

Table 3: Scenarios modelled in the simulation. Scope 1 only scenarios are capitalised. Scenarios that assume the fate of peat is that all extracted peat is decomposed are lowercase, while scenarios that allow Scope 3, downstream, and management of the fate of peat note a + sign. The time to biospheric carbon recovery is also noted per scenario, *represents no true carbon neutrality reached as extracted peat carbon is not considered.

		Scope 1 Variables				Scope 3 Variables					Time to biospheric carbon recovery (y)
		Extraction depth (m y^{-1})	Extraction duration (y)	Restoration delay (y)	Residual peat depth (m)	Decomposition rate of extracted peat (y^{-1})	Use of peat duration (y)	After-use of peat duration (y)	Peat-mineral-soil-mixture decomposition rate (y^{-1})	Stabilisation proportion (% y^{-1})	
Scenario	A	0.10	14	0	1	-	-	-	-	-	124*
	a	0.10	14	0	1	0.05	-	-	-	-	7667
	a+	*0.10*	*14*	*0*	*1*	-	*0.25*	*1*	*0.02*	*40*	499
	B	0.08	17	3	1	-	-	-	-	-	145*
	b	0.08	17	3	*1*	*0.05*	-	-	-	-	7687.5
	b+	*0.08*	*17*	*3*	*1*	-	*0.5*	*2*	*0.04*	*30*	1174
	C	0.06	22	3	1	-	-	-	-	-	171 *
	c	0.06	22	3	*1*	*0.05*	-	-	-	-	7695.5
	c+	*0.06*	*22*	*3*	*1*	-	*1*	*5*	*0.04*	*20*	2190
	D	0.04	32	6	1	-	-	-	-	-	215*
	d	0.04	32	6	*1*	*0.05*	-	-	-	-	7220
	d+	*0.04*	*32*	*6*	*1*	-	*2*	*10*	*0.06*	*10*	4250.5
	D0.5	*0.04*	*32*	*6*	*0.5*	-	-	-	-	-	227.5*
	d0.5	*0.04*	*32*	*6*	*0.5*	*0.05*	-	-	-	-	8334

Management of Scope 1 parameters reduces uptake time to 4,206 ± 43. Extraction rate and extraction duration worked together, as the peatland had a set depth, and extraction depth per year influenced extraction duration and vice versa. Reducing the extraction rate and duration variables resulted in it taking 4,189 ± 43 years for cumulative carbon emissions to meet net zero, with other base scenario variables retained. Similarly, restoration delay reduced the recovery time to 4224 ± 6.5 years (figure 28).

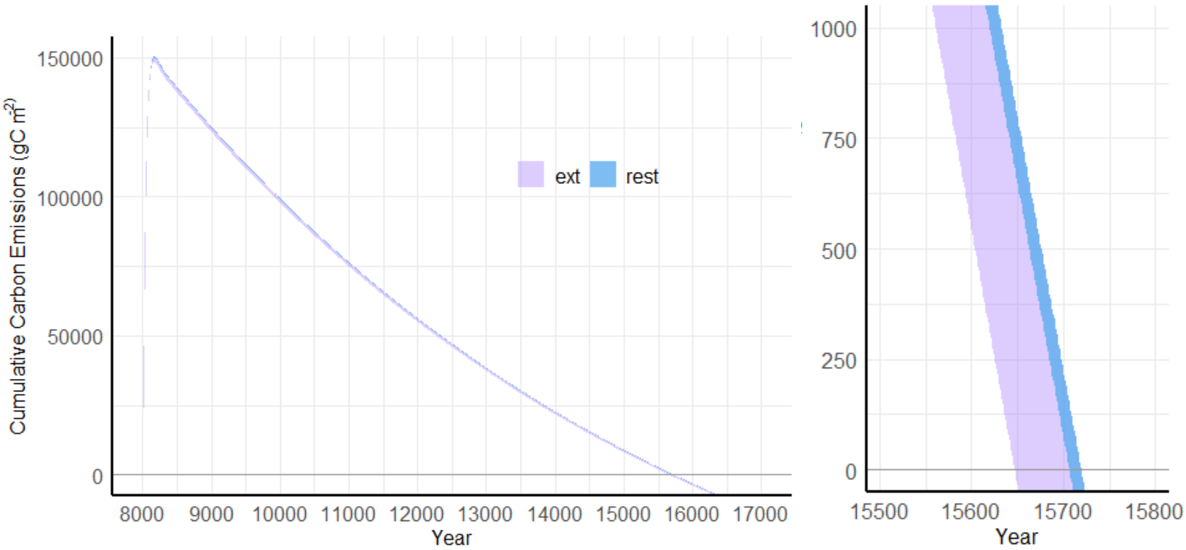

Figure 28: The cumulative carbon emissions, with variation of Scope 1 parameters. Cumulative emissions from extraction to carbon neutral point (left) and a maximised image of when the scenarios meet the carbon neutral point (right). Scenario d is the baseline used. Ext *(light purple) notes variation in extraction duration,* rest *(blue) shows variation in restoration delay.*

Scope 3 variables had a larger impact on cumulative emissions. Varying the parameters for the fate of peat would reduce cumulative carbon emissions recovery time to 3,592 ± 466 years (figure 29). For the specific parameters, varying the use of peat duration would reduce cumulative emissions recovery time to 4,096 ± 112 years, while reducing the after-use of peat variable reduces recovery time to 3378 ± 651 years. Similarly, reducing the variable for the decomposition rate of peat mixed with mineral soils reduced the recovery time to 3,826 ± 442 years. The increase in carbon stabilised proportion reduced cumulative emissions by 3,619 ± 453 years.

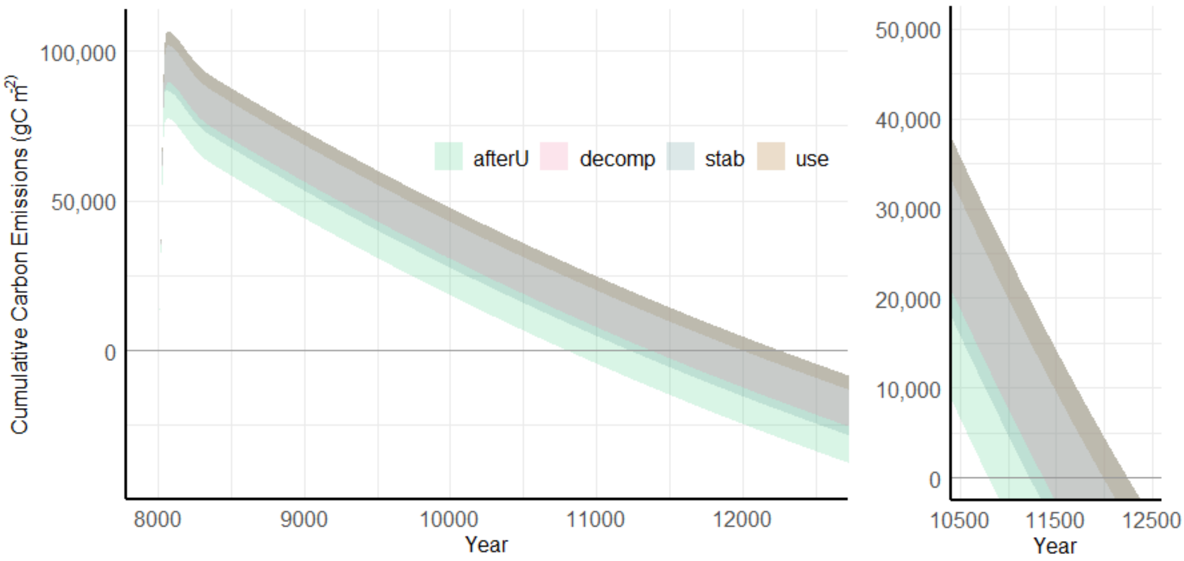

Figure 29: The cumulative carbon emissions, for Scope 3 parameter variations (fate of peat). Cumulative emissions from extraction to CNP shown (top) and a maximised image. Scenario d+ is the baseline used. AfterU, decomp, stab *and* use *represent the parameter variations of after use duration, decomposition rate for peat mixed in mineral soils, stabilisation proportion of peat carbon and use of peat duration, respectively.*

Relative to scenario d+, parameter variation can, therefore, reduce the time it takes cumulative carbon emissions to meet a carbon neutral point from 4,250 years to 3740 ± 479 years, as dependent on parameter varied (figure 30).

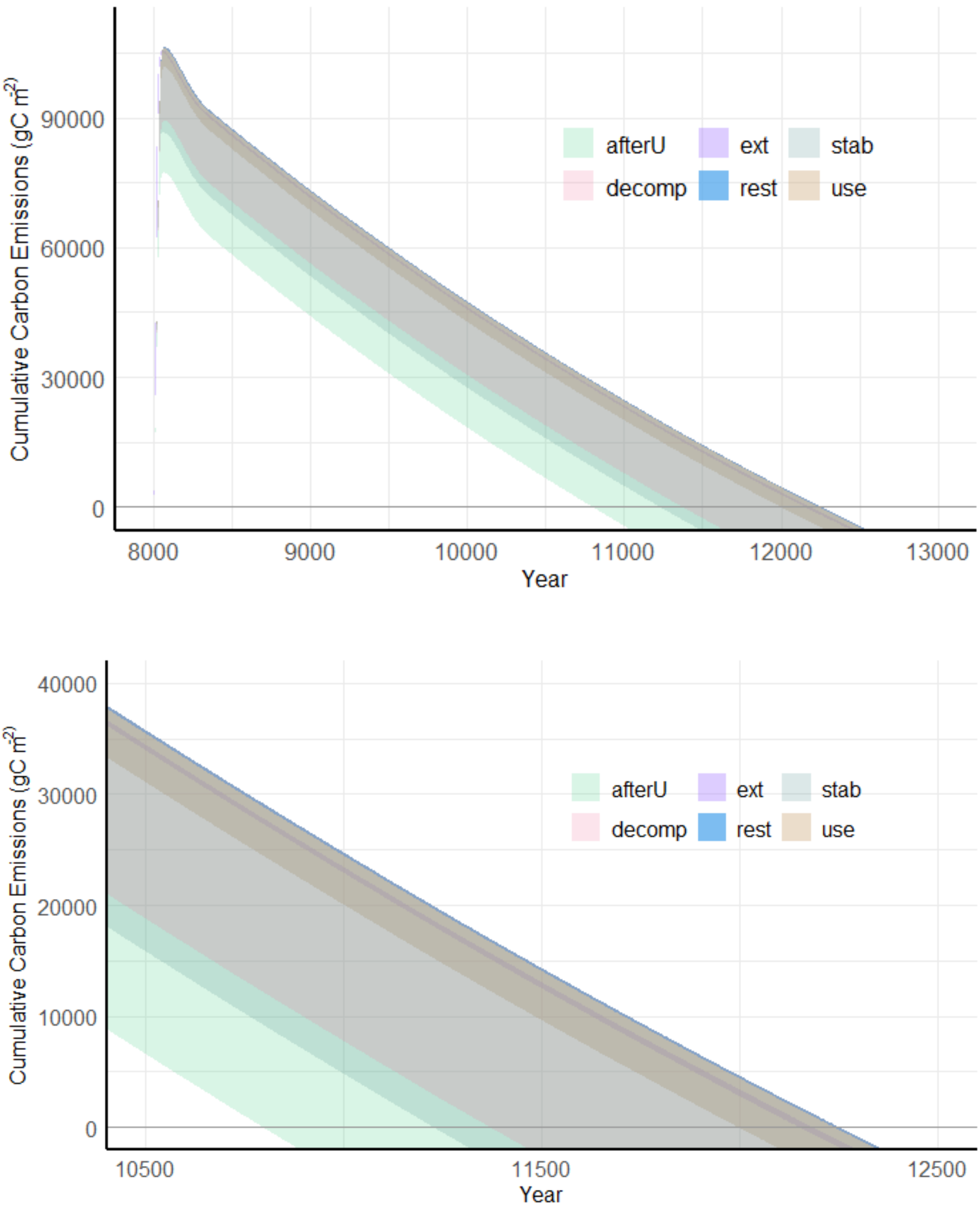

Figure 30: The cumulative carbon emissions, for parameter all variations from extraction at 8000 years to their respective carbon neutral points.

4.5: Carbon losses and gains during extraction, restoration, and use and after-use of peat

4.5.1: Biospheric carbon store and cumulative carbon emissions

Before extraction, the biospheric peat store had reached a mass of ~ 392,000 g m^{-2} (~ 392 kg m^{-2}) by 8,000 years (figure 31), equating to ~ 196 g C m^{-2}. The extraction disturbance reduced the biospheric store mass in the simulated peatland (Scope 1) to ~ 76,000 g m^{-2} (~ 38,000 g C m^{-2}).

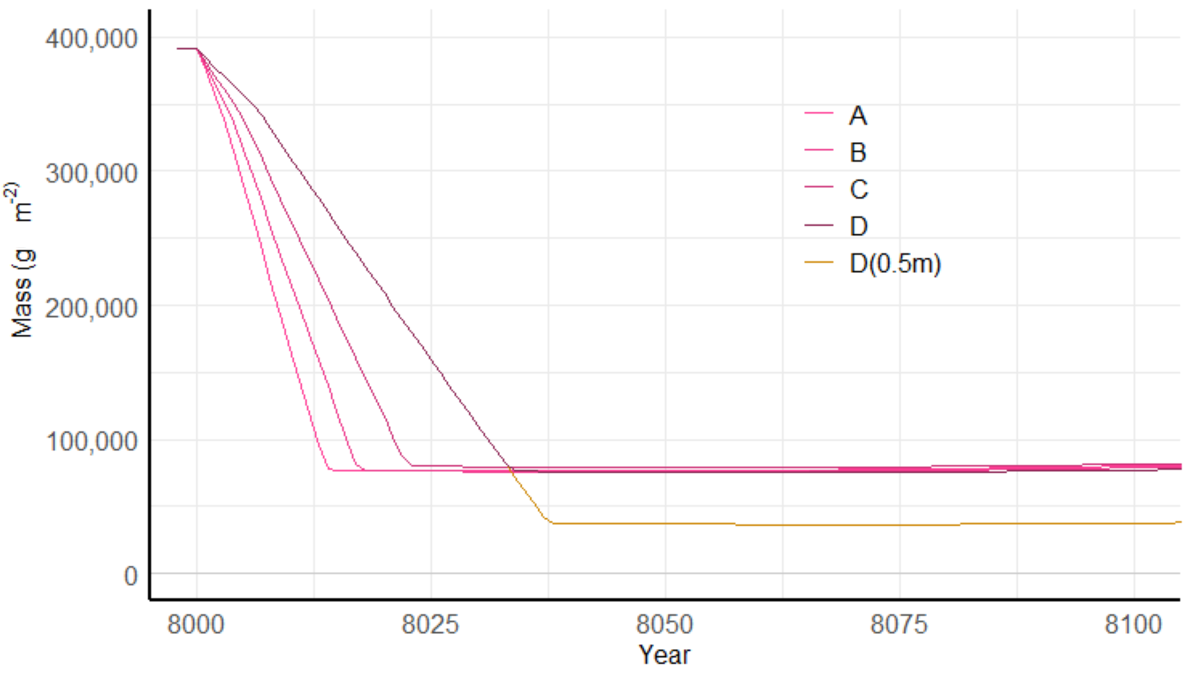

Figure 31: The biospheric carbon store mass over time, extraction occurs at 8000 years.

While the biospheric store follows the perspective of the amount of carbon stored in the peatland, the emissions are what result from the changes in storage. I ran the model simulation until cumulative carbon emissions returned to zero, i.e. they met a carbon neutral point (CNP). For scenarios a, b, c, and d, I assume extracted peat decomposes at 5% per year (Sharma, 2024) until no peat remains; it takes 7,692.5 ± 21.98 years for these scenarios to reach the CNP, at 7667, 7687.5, 7695.5, and 7720 years respectively (figure 16, table 1). When the management of the fate of peat, is included in the scenarios, the CNP is reduced after 2,028 ± 1636 years. For the respective individual scenarios *a+, b+, c+,* and *d+* the CNP is met after 499, 1,174, 2,190, and 4250.5 years (figure 33, table 3). Scope 1-only scenarios will never meet a carbon-neutral point as downstream emissions are not considered. However, restoration will offset the field emissions for scenarios A, B, C, and D within 124, 145 171, and 215 years respectively (figure 32).

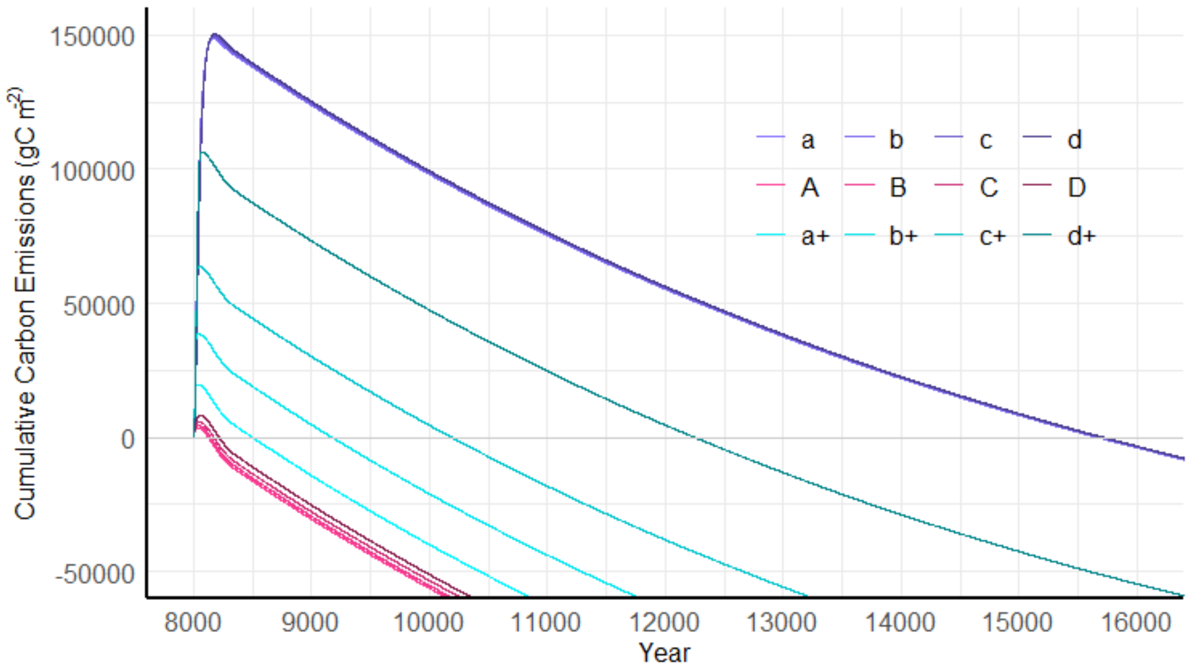

Figure 32: The cumulative carbon emissions over time for all scenarios, from extraction at 8000 years to their respective carbon neutral points.

4.5.2: Annual carbon emissions

Annual carbon emissions are the emissions each year, therefore, with restoration, we can reach annual net-zero emissions within 200 years of peat extraction ending and restoration beginning. Figures 33 and 34 only consider the carbon emissions experienced by the peatland that is extracted and restored, whereas Figure 35 also considers the carbon emissions due to the use or lack thereof of extracted peat.

During extraction, the simulated extraction peatland had high initial annual emissions. As more peat mass was removed, our simulated 'field' emissions reduced relative to the mass available. While the model reports in g C m^{-2} y^{-1}, we converted to an average per day emission to compare with values in the literature by dividing by 365. The simulated mean carbon emissions were 0.838 ± 0.122 g C m^{-2} d^{-1} for the first 15 years of extraction, which is greater than the measured 0.4 ± 0.3 g C m^{-2} d^{-1} for the same period (Clark *et al.*, 2023) (Figure 33). Similarly, for the last ten years of emissions from simulated extraction, and for measured sites open for 30-35 years, the means were 0.387 ± 0.049

and 0.2 ± 0.1 g C m^{-2} d^{-1}(Clark *et al.,* 2023), respectively. The simulated daily carbon emissions during extraction are within the Clark *et al.* flux standard deviations. The simulated mean for the entire extraction period is 0.598 ± 0.259 g C m^{-2} d^{-1}.

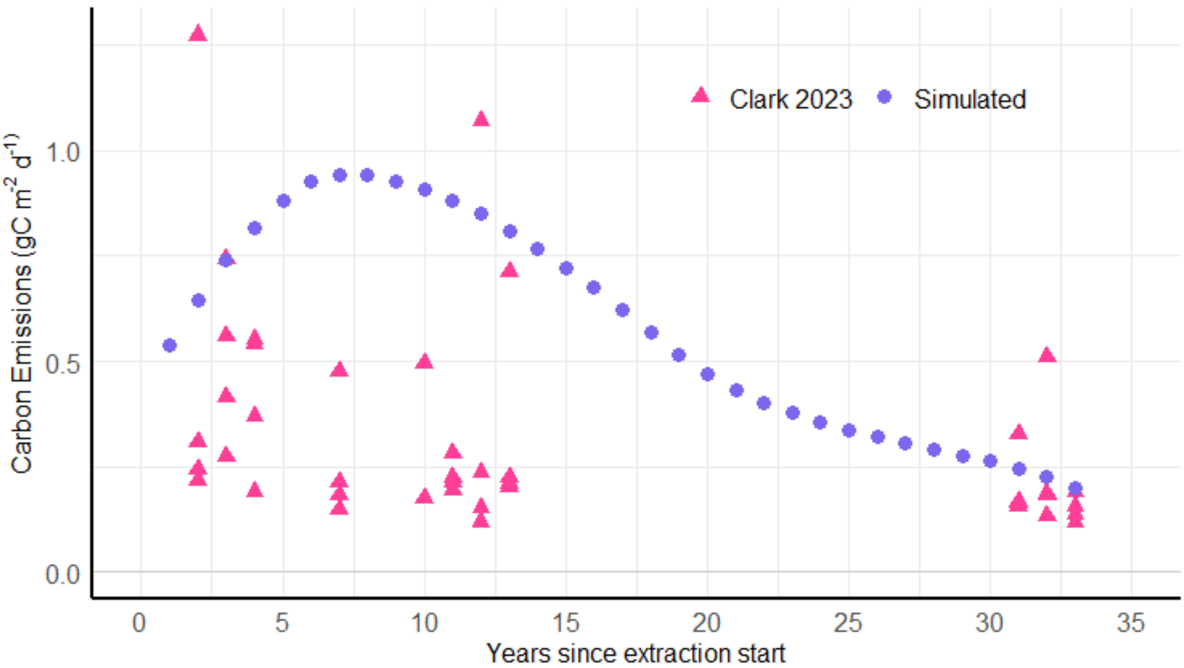

Figure 33: The cumulative carbon emissions over time for scope all scenarios for 50 years after extraction begins. Both simulated and Clark et al. (2023) measured values are shown.

After extraction was complete (i.e. the 1 m of catotelm peat stipulation was met), the peatland would experience a time lag before restoration. During the restoration delay, peatland decomposition would continue and NPP would remain at 0. Simulated restoration stops water store ditch drainage (surface and subsurface drainage continues) and reintroduces vegetation. The modelled peatland annual emissions transition from net emission to net uptake takes approximately 20 years from restoration start year (Figure 34). Restored peatlands in eastern Quebec have been measured to transition from net carbon emissions to net carbon uptake in the second decade (Nugent *et al.,* 2019). Initially, simulated mean annual carbon emissions were lower than measured values for 5-year-old and younger restored sites at 45.5 ± 9.4 g C m^{-2} y^{-1} and 219.9 ± 215.1 g C m^{-2} y^{-1} (Nugent *et al.,* 2019), respectively. Sites that had experienced restoration 15 years prior, measured a mean uptake of 34.6 ± 111.9 g C m^{-2} y^{-1} over the three-year research period (Nugent *et al.,* 2019) compared to simulated mean annual carbon emissions were 29.6 ± 4.9 g C m^{-2} y^{-1}. The simulated mean annual carbon emissions for a restoration peatland are within the standard deviation of Nugent *et al.* measured values. Finally, the simulated peatland had a mean annual carbon uptake of 6.30 ± 0.74 g C m^{-2} y^{-1} between 30 and 40 years after restoration had begun, and sites that experienced restoration between 30 and 40 years ago also had an uptake, at a mean carbon uptake of 16.7 ± 40.1 g C m^{-1} y^{-1} (Nugent *et al.*, 2019; figure 34), there are no comparative field studies of extracted peatlands 40 years after restoration.

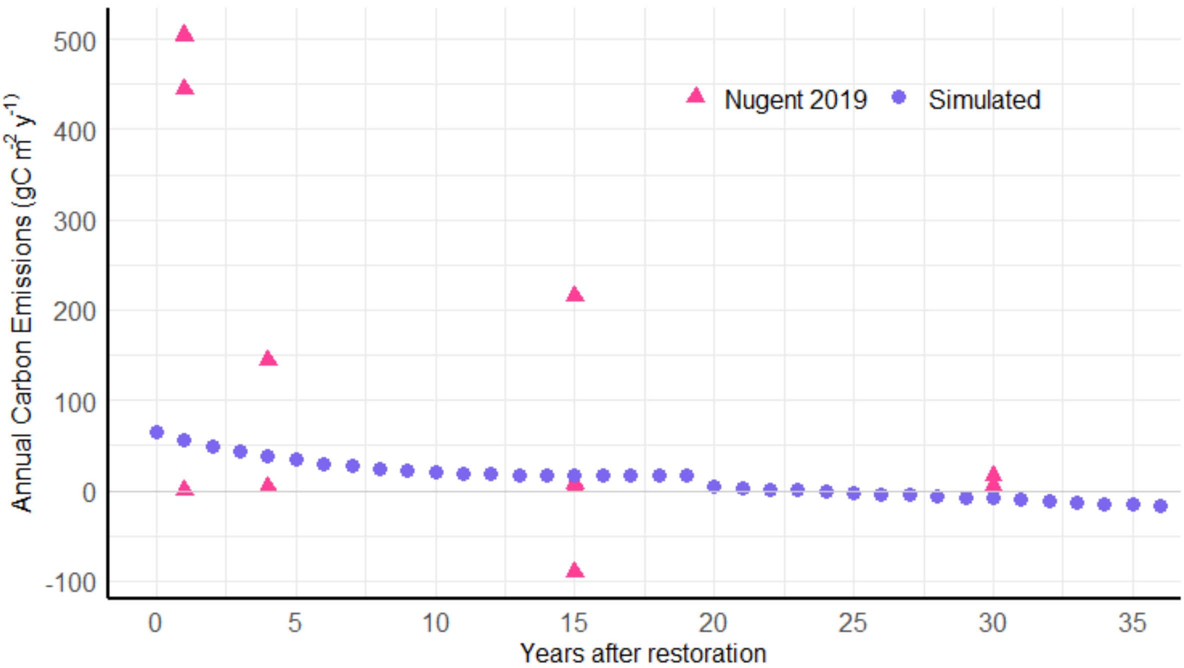

Figure 34: The annual carbon emissions over time for scenario D field emissions post- restoration. Both simulated and Nugent et al 2019 measured values are shown.

For the scenarios, initially, the fate of peat increases net annual emissions (figure 35) as limed peat for use has a higher decomposition rate than peat in the peatland (Sharma, 2024), and peat mixed with mineral soils has a different decomposition rate again. The stabilisation proportion assumption then reduces net annual emissions as some extracted peat carbon would then become unavailable for decomposition. Simultaneously, effective restoration in all scenarios allows the simulated peatland to uptake carbon from the atmosphere. The delay between extraction and restoration also impacts net annual emissions. I refer to the point at which biospheric net annual carbon emissions go from positive (emission) to negative (uptake) as net zero.

As the most intense extraction scenario, A, has the greatest net annual emissions but meets a net-zero point within 53 years after extraction begins. Scenario D, as the longest extraction duration and restoration delay does not meet a net-zero point until 74 years after extraction begins. Scenarios B and C respectively will take 60 and 66 years for net annual carbon emissions to be zero.

The inclusion of downstream emissions increases scenario *a*'s net annual carbon emissions to meet a net-zero point at 184 years after extraction begins. Scenario *d* also experiences an increase in net annual carbon emissions lengthening the time taken to reach net zero to 196 years. Scenarios *b* and *c* net annual carbon emissions meet zero after 187 and 190 years respectively (figure 35).

The inclusion of the fate of peat management reduces the time for scenario *a+*'s net annual carbon emissions to be zero by 3.5 times, from 184 years to 53 years. Scenario *d* experiences a decrease in time for net annual carbon emissions to be zero by 2.2 times, reducing recovery time from 196 years to 89 years. Scenarios *b* and *c* respectively experience reductions by 3.1 and 2.8 times, corresponding to net annual carbon emissions reaching zero after 60 and 69 years (figure 35).

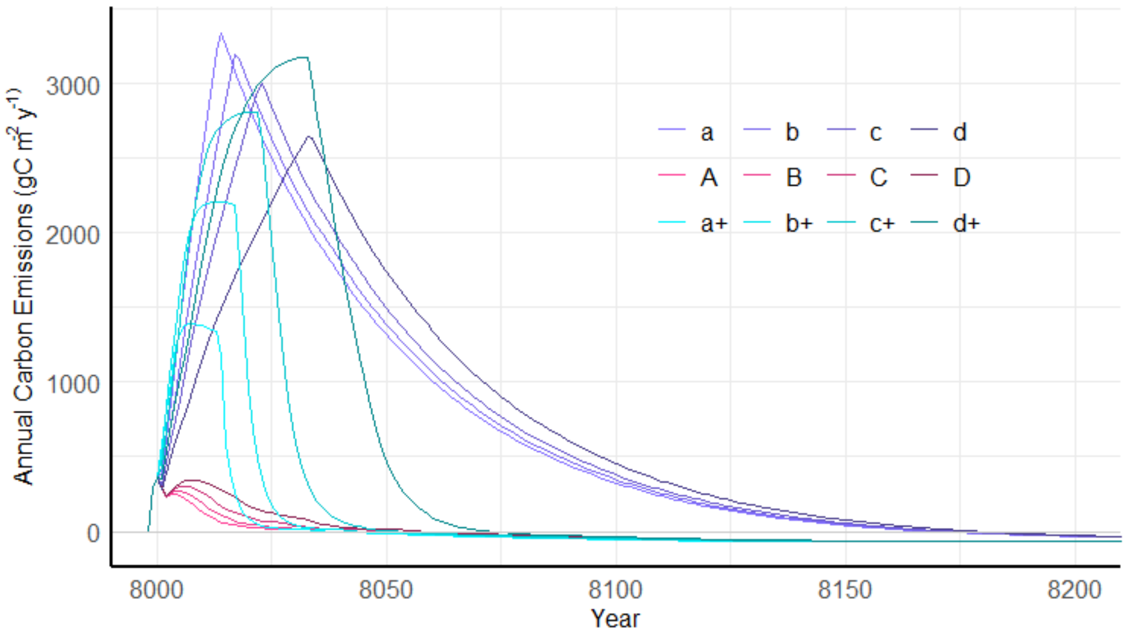

Figure 35: The annual carbon emissions over time for all scenarios, from extraction at 8000 years to their respective net-zero points.

Chapter 5: Discussion

In this thesis, I developed a model to simulate the change in carbon stores and emissions from a peatland that was disturbed and restored for horticultural peat extraction in eastern Canada. My objects were: to assess both annual and cumulative carbon emissions pre-, during and post-extraction; use these values to determine the offset of irreducible emissions that are required to meet Canada's 2050 net-zero emissions targets; and compare results that consider Scope 1 only (field emissions), and two Scope 1 and 3 inclusive (field emissions and downstream emissions with decomposition, and field emissions and downstream emissions with fate of peat management variables) emissions scenarios.

My simulations show that when disturbed through drainage and extraction, peatlands become net carbon sources to the atmosphere. This is not a new finding – numerous empirical and other modelling studies have shown it. However, I show that the emissions during extraction can be reduced by different management practices (table 4, column iv). I calculated emissions reduction through both cumulative carbon emissions and the time taken to reach when uptake from restoration offsets extracted peat emissions. Extracting faster reduced the length of time a peat field is open and with immediate restoration, these practices reduce cumulative carbon emissions. My simulations highlight that successful restoration can compensate for the emissions from the peat fields during extraction, and cumulative carbon emissions are offset by restoration within approximately ~ 165 years (the mean of scenarios A, B, C and D). Rapid restoration combined with intensive, short-duration peat extraction produces the least direct emissions. Delaying restoration can increase emissions by ~ 40 % (table 4, column ii).

Emissions generated by the use and fate of extracted peat after its horticulture lifetime are, by far, the largest sources of carbon to the atmosphere. Peat use management, therefore, has the greatest potential for reducing the time taken for net cumulative carbon emissions to be zero, i.e. reach a carbon neutral point (CNP). A lack of knowledge on the fate of peat after it is used makes estimates of the total emissions uncertain. Variations within scenarios indicate that emissions could be 50 times greater than the direct emissions during extraction, taking over 7600 to 7800 years after the peat was extracted to recover emitted peat carbon from the atmosphere.

My simulated peat management scenarios demonstrate that if strategies for post-peat use could be developed to stabilise a portion of the extracted peat mass, preventing it from decomposing, there would be significant reductions in cumulative biospheric carbon emissions. We know little about the post-use fate of peat, and further research is needed. A successfully restored peatland will eventually recover the emitted peat carbon, but only after centuries to millennia (table 4, column ix). While emitted peat carbon is recoverable, the time for recovery is very long and is on an order of magnitude greater than the time frame considered for climate policy. Thus, peat carbon is biophysically recoverable, but irrecoverable on a policy timeline (Harris *et al.,* 2021). While using peat in horticulture will always result in net carbon emissions, it is unlikely that there are economically viable ways to offset the emissions in this industry on the short term. My analysis could be used as a method to examine alternative growing media to peat, but any growing media used for soilless agriculture will produce emissions, and a complete life-cycle analysis of cumulative carbon emissions is required for useful and fair comparisons.

Table 4: Summary table of all scenarios and their carbon emissions over scenario-specific units of time. t^{-1} corresponds to the duration of each phase. Scenario description details respective time units. Unless stated as a duration of time in years, all values are the cumulative carbon emissions from the set time phase described in the column header.

		Column no.	i	ii	iii	iv	v	vi	vii	viii	ix
			Scope 1 carbon emissions (g C m^{-2} t^{-1})					**Scope 3 carbon emissions (g C m^{-2} t^{-1})**			
	Scenario	Description	Extraction phase	Restoration delay phase	Restoration start until net annual emissions are negative	Total emissions from the peat field	Time to restoration offset peat field emissions (years)	Extracted peat	Extracted peat with Scope 3 management	Scope 1 and Scope 3 total emissions (g C m^{-2} t^{-1})	Time to carbon neutral point (years)
	Scope 1 only scenarios										
	A	1.0 m of residual peat, extraction time 13.75 years, immediate restoration,	2959	/	539	3498	126	/	/	/	/
	B	1.0 m of residual peat, extraction time 17.25 years, restoration delay 3 years,	3797	164	442	4403	146	/	/	/	/
	C	1.0 m of residual peat, extraction time 22.5 years, restoration delay 3 215years,	5048	200	578	5827	172	/	/	/	/
Baseline 1	*D*	*1.0 m of residual peat, extraction time 33.5 years, restoration delay 6 years,*	*7643*	*287*	*289*	*8218*	*216*	*/*	*/*	*/*	*/*
Baseline 1a	D0.5	0.5 m of residual peat, extraction time 37.25 years, restoration delay 6 years,	7834	197	397	8429	229	/	/	/	/
	Scope 3 inclusive scenarios										
	a	1.0 m of residual peat, extraction time 13.75 years, immediate restoration, extracted peat k = 0.05 y^{-1}	2959	/	539	3498	272	145206	/	148706	7667
	b	1.0 m of residual peat, extraction time 17.25 years, restoration delay 3 years, extracted peat k = 0.05 y^{-1}	3797	164	442	4403	294	144959	/	149362	7687.5

	c	1.0 m of residual peat, extraction time 22.5 years, restoration delay 3 years, extracted peat k = 0.05 y^{-1}	5048	200	578	5827	335	143813	/	149640	7695.5
Baseline 2	*d*	*1.0 m of residual peat, extraction time 33.5 years, restoration delay 6 years, extracted peat k = 0.05 y^{-1}*	*7643*	*287*	*289*	*8218*	*410*	*142277*	*/*	*150495*	*7720*
Baseline 2a	d0.5	0.5 m of residual peat, extraction time 37.25 years, restoration delay 6 years, extracted peat k = 0.05 y^{-1}	7834	197	397	8429	416	161034	/	169463	8334
	a+	1.0 m of residual peat, extraction time 13.75 years, immediate restoration, extracted peat k = 0.05 y^{-1} .0.25 years use and 1 year after use durations. Peat-mineral-soil-mixture k = 0.02 y-1. 0.4 stabilisation proportion.	2959	/	539	3498	124	/	16256	19754	499
	b+	1.0 m of residual peat, extraction time 17.25 years, restoration delay 3 years, extracted peat k = 0.05 y^{-1} 0.5 years use and 2 years after use durations. Peat-mineral-soil-mixture k = 0.04 y-1. 0.3 stabilisation proportion.	3797	164	442	4403	145	/	34143	38546	1174
	c+	1.0 m of residual peat, extraction time 22.5 years, restoration delay 3 years, extracted peat k = 0.05 y^{-1} .1 year use and 5 years after use durations. Peat-mineral-soil-mixture k = 0.04 y-1. 0.2 stabilisation proportion.	5048	200	578	5827	171	/	57840	63666	2190
Baseline 3	*d+*	*1.0 m of residual peat, extraction time 33.5 years, restoration delay 6 years, extracted peat k = 0.05 y^{-1} 2 years use and 10 years after use durations. Peat-mineral-soil-*	*7643*	*287*	*289*	*8218*	*215*	*/*	*98122*	*106340*	*4250.5*

mixture k = 0.06 y-1. 0.1 stabilisation proportion.			

5.1: Sensitivity analysis

Management strategies were linked to model parameters, and sensitivity analysis showed simulated cumulative carbon emissions responses to Scope 1 and 3 variables. In my scenarios A, B, C and D, for the average year a peat field is open, it would take an additional ~ 7 years to recover the emitted peat carbon if the peatland was successfully restored (table 4). This is why I highlight a more intensive extraction rate, that has the peat field open for a shorter duration, as a method of reducing cumulative carbon emissions.

For each year there is a delay between extraction ending, and the start of restoration (for up to 6 years), the restoration offset time increased by up to a decade. This is similar to Nugent *et al.* (2018) carbon emissions figures. They suggested that for every year a peatland is not restored after extraction has ended, radiative forcing increases by up to seven times (Nugent *et al.,* 2019). My simulation does not include methane and therefore does not produce radiative forcing futures. I considered the carbon uptake of the restored peatland phase in my simulation, and it is within the standard deviation of Nugent *et al.,* (2019) restored peatland fluxes. My model covers a longer period and restoration is assumed to be effective, there are no comparative studies that consider peatland carbon recovery post-restoration for longer than 500 years (e.g. Nugent *et al.,* 2019).

The introduction of Scope 3 downstream emissions substantially increased cumulative carbon emissions. As peat carbon does not disappear from the closed carbon cycle after extraction, scenarios that include downstream emissions are more appropriate for biospheric carbon evaluation studies – i.e. what the atmosphere 'sees'. For this reason, I apply the term carbon neutral point (CNP) only to scenarios that include Scope 3 emissions. Scope 1 emissions can be offset by carbon uptake due to peatland restoration, but as the fate of peat is not considered, the peatland system will not be carbon neutral until its mass is also taken up either by the peatland itself or some other ecosystem.

I developed three baseline scenarios (table 4) that are similar to current and presumed horticultural peat extraction practices. Baseline 1 only considered field emissions and management, baseline 2 built on baseline 1 and assumed that the extracted peat decomposed until none remained, and baseline 3 considered management of the fate of peat, downstream (Scope 3) emissions. These baselines correspond to scenarios D, d and d+ respectively (table 1). Using a decomposition rate of the extracted peat indicated that it would take ~7700 years for the biosphere to recover extracted peat carbon. Differences in management of Scope 3 variables then reduced the carbon emissions. By including the fate of peat, its use, and after-use and assuming peat was mixed with mineral soils after-use, the time taken to meet a CNP was reduced from ~7700 (baseline 2) to ~4250 years (baseline 3) in scenarios d and d+.

Stabilising a proportion of peat carbon reduced the time taken to meet a CNP by up to 1024 years in my baseline 3 scenario. Thus, for every 10% of peat carbon that is stabilised in the biosphere, the CNP is reached ~ 470 years sooner. Similarly, peat mixed with mineral soils would have a different decomposition rate than that of the growing media peat. For every 0.01 decrease in decomposition rate (between 0.06 and 0.02) the CNP can be met ~ 210 years sooner with corresponding lower emissions. I emphasise that I am considering management practice scenarios and that these are the two variables where there is a dearth of information, and further empirical research would be useful in future analysis. One suggestion would be sandbox-style experiments where peat growing media is mixed with different mineral soils, and carbon emissions monitored.

5.2: Limitations and uncertainties

5.2.1: Decomposition rates for use, after-use and peat-mineral-soil-mixture.

My model was sensitive to parameter variations. Recent research does show that the decomposition rate of peat that has been limed for use is ~ 5 % per year (Sharma, 2024). I have used the 5 % per year decomposition rate, but further studies should verify whether this decomposition rate could change depending on the local climate or product (Sharma, 2024). This 5 % per year decomposition rate could also change over time or be different if acidity is neutralised with a method other than peat liming (Sharma, 2024). There is little information about the decomposition rate of organic matter in mineral soils or the proportion of peat carbon stabilisation. I use a 2 % to 6 % per year range for my decomposition rate of organic matter mixed with mineral soils, which is similar to the Sharma (2024) value and includes the Bona (2014) ~ 2 % per year *Sphagnum*-moss decay rate used in MOSS-C, a sub-module of the Canadian Budget Model of the Canadian Forest Sector. There is no comparative information regarding peat carbon stabilisation proportion, so my assumption that 10 % to 40 % of peat carbon per year being stabilised is speculated. Again, further research would reduce the uncertainty in stabilisation proportion. Still, peat decay as a rate suggests that some peat carbon will always remain in the biosphere (Sharma, 2024).

5.2.2: Transfer from simulation to in-practice.

Scenario *a+* (most intensive extraction rate, immediate restoration and highest stabilisation proportion) is the shortest to reach CNP after extraction (table 1). Extraction rate via extraction duration and extraction depth per year variable had the greatest impact on Scope 1-only scenarios. My model uses fairly basic hydrology, and I cannot test the feasibility of this extraction rate in practice. This scenario may be more appropriate as a demonstration of the best-case-scenario rather than practical management strategies, but a more complex model that can account for peat quality and soil physics on a daily-to-sub-daily time-step, such as CoupModel (He *et al.,* 2023) would be needed to assess whether either scenarios A, *a* or *a+* are realistic.

A residual peat layer of 1 m is left in the field in my simulations. In practice in Canada, peat extraction may continue until 0.5 m thickness of peat remains in the field. The maximum extent of ion diffusion through the peat column is ~1 m of peat (Fraser *et al.,* 2001), suggesting that restoration on top of peat less than 1 m thick may not be as successful. I adapted baseline scenarios 1 and 2 to run using a 0.5 m residual peat thickness and assumed the effective restoration. I called these scenarios baseline 1a and 2a. There was no difference in the ratios of variable sensitivity to management, but an additional 39000 g of peat mass of extracted and took 12.5 years longer for restoration to offset field emissions, and 416 more years if I assumed the extracted peat decomposed at a rate of 0.05 (table 4).

5.3: Scenarios on an ecological time scale

5.3.1: Base scenario compared to common peat extraction practice

Peatlands in eastern Canada are extracted for a mean of 30 years, and peatlands should be restored within three years as part of the licencing certification. The average

thickness of residual peat post-extraction is uncertain, and a thicker residual peat layer suggests a greater chance of bog restoration success (Graf *et al.,* 2008). I assume restoration success and use a 1 m residual peat thickness. The only consequence of using a 1 m residual peat layer as opposed to 0.5 m was increased emissions due to a longer extraction duration and peat mass removed. After extraction, peat restoration usually waits for favourable conditions, or the peatland may be reopened for a year, so a six-year restoration delay is not unheard of (Boudreau, May 2022, *pers.* comm).
Extracted peat is expected to be used for at least three months and Sharma (June 2022, *pers. comm*) suggested that peat could have multiple use phases for different produce but is likely 'used' before 2 years. Peat is known to be stored after use in piles for months to years (Jackson, 2019).
For the baseline scenarios 1, 2 and 3 (D, *d* and *d*+), I assume the peat extraction duration of 33.50 years and an extraction depth per year of 0.04 m y^{-1}, and the peatland is restored on 1 m of residual peat. While three years is the common restoration delay, I wanted to consider the greatest lag time between extraction ending and restoration beginning, which is why the restoration delay in the base scenario is 6 years. Similarly, two years was chosen as the use duration of extracted peat for this scenario to consider what the greatest emissions from the use of peat could be. After-use does not have a measured duration, as used peat is often piled and neglected for a period. I assume that the maximum period of time after-use that peat is stored is 10 years, at which time I introduce mixing with mineral soils. Various biogeochemical processes can impact the decomposition of peat soils. Fertilisation treatments of peatlands suggest that different proportions of phosphorus, nitrogen and other macronutrients impact the peat carbon emissions (Juutinen *et al.,* 2018; Luan *et al.,* 2019), and the concept that exponential decrease of carbon mass due to a decay rate leaving a proportion of peat behind (Sharma, 2024) imply that mixing used peat with mineral soils could also stabilise a proportion of the peat carbon store. Again, the decomposition rate of organic matter when mixed with mineral soils is under-researched, and nothing is known about the potential stabilisation proportion of peat carbon as a result. I proposed that a maximum of 6 % of the peat-mineral-soil mixture would decompose per year, and a minimum of 10 % of peat carbon would be stabilised per year in scenario *d*+ (baseline 3).

My subsequent scenarios were developed assuming that they would cause a reduction in cumulative carbon emissions compared to the scenario prior. This is why my scenarios increase in extraction intensity and decrease in restoration delay for scenarios D, C, B and A. Similarly, scenario *a+* has the shortest use time and after-use time of peat, the lowest decomposition rate of peat mixed in mineral soils, and the greatest stabilisation proportion of peat carbon, compared to scenarios *b+, c+,* and *d+*.

5.3.2: Scope 1 only management scenarios

If I only consider biospheric carbon emissions related to the extraction field, cumulative carbon emissions will not be offset by restoration until 165 ± 40 years. The four Scope 1-only scenarios (A, B, C and D) demonstrate the impact of management strategies for peat extraction rate and the delay time between extraction ending and restoration beginning. They identify that an intensive extraction rate, which I modelled as the shortest extraction duration time and greatest extraction depth per year in scenario A, reduces cumulative carbon emissions the most.

5.3.3: Scope 1 management, with downstream (Scope 3) decomposing extracted peat scenarios

If I consider biospheric carbon emissions related to the extraction field and assume that extracted peat slowly decomposes until none remains, cumulative carbon emissions will not reach a post-extraction carbon neutral point (CNP) until ~ 7700 years. The four scenarios (*a, b, c* and *d*) demonstrate the impact of including the fate of peat and downstream emissions, but not monitoring Scope 3 management. They identify that the inclusion of the fate of peat increases cumulative carbon emissions by up to 50 times.

5.3.4: Scenarios with both Scope 1 and Scope 3 management

The inclusion of management of Scope 3 emissions means that the CNP is met after ~ 2000 ± 1600 years. The four Scope 3 inclusive management scenarios (*a+, b+, c+* and *d+*) highlight the impact of the fate of extracted peat management on the biospheric carbon store. Scenario *d+* reduces the CNP time to 4250 years relative to scenario *d's* 7720 years (table 4)*;* a ~45 % decrease. Scenario *a+* reduces the CNP time to ~500 years relative to scenario *a* (~7670 years*);* a ~ 94 % decrease. These scenarios highlight the need for more research into the fate of peat and indicate that there are potentially better management strategies and carbon accounting mechanisms than scenarios *a* and *d* present alone. Scenarios *b*+ and *c*+ have the same decomposition rate for the peat-mineral-soil-mixture, and the same restoration delay, but show different CNP times. They show ~ 85 % and ~ 72 % decreases relative to their respective scenarios b and c, reducing the CNP time to ~ 1170 for scenario *b*+ and ~ 2200 for scenario *c*+.

Regardless of the scenario, in all cases, the biosphere recovers peat carbon lost during the extraction process, and in the fate of peat, on an ecological timescale.

5.4: Scenarios on a policy time scale

5.4.1: My scenarios in the context of 2050 targets

The human lifespan is not on the same ecological timescale as peatlands. Anthropogenic-induced climate change has led to a series of political net-zero carbon emissions targets, in an attempt to mitigate global warming to 1.5 ˚C relative to pre-industrial times by 2050 (UNFCCC, 2015). The 2050 geo-political emissions target is one-quarter of a century away from the writing of this thesis (2024). Through the lens of policy, the 'deadlines' set for emissions targets are soon. Peat carbon is, therefore, irrecoverable on a policy time scale.

My scenarios also present a method of mitigating cumulative carbon emissions, meaning the amount of irreducible carbon is lower, and 2050 carbon offsets per scenario can be calculated if we can attribute a start year. In 2016 the licencing requirement that stipules restoration beginning within three years of extraction ending came into effect. I assume that 2016 is then equivalent to my extraction start year and 2050 is 34 years later (figure 36).

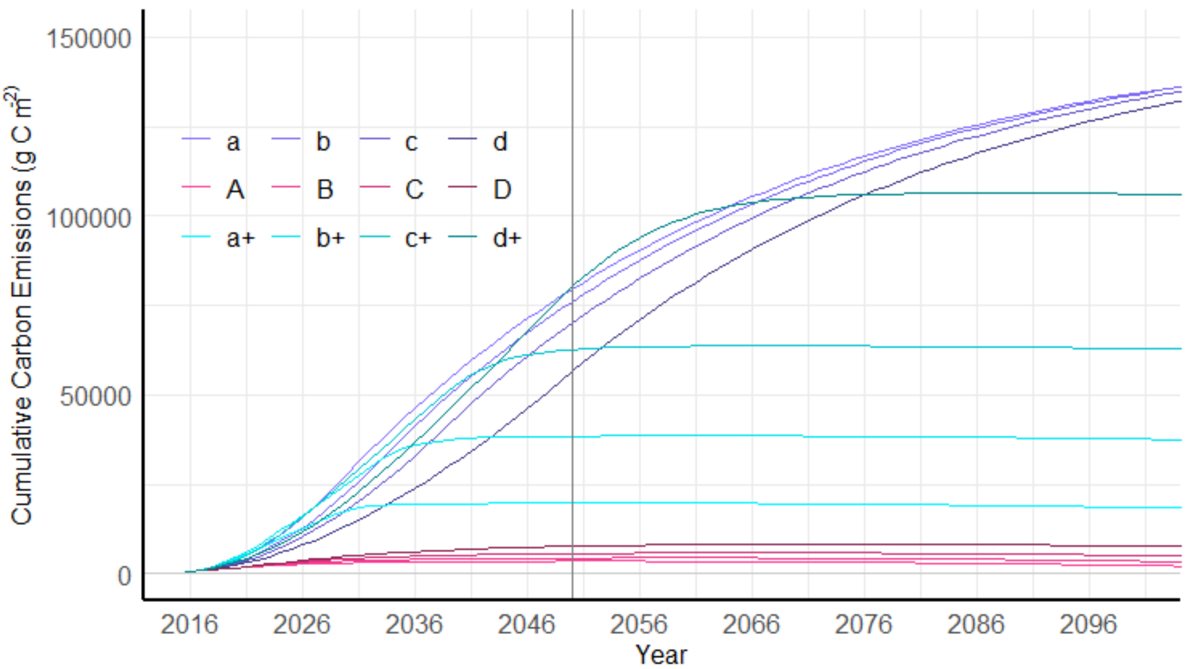

Figure 36: The cumulative Carbon emissions for all scenarios, assuming peat extraction began in 2016. A grey line marks the 2050 intercept on the x-axis for offset analysis.

Table 5: Offset required to meet net zero in a theoretical 2050 for each scenario.

Scenario	Mass to Offset in 2050 (g C m^{-2})
A	3,496
a	*79,539*
a+	*19,752*
B	4,330
b	*76,088*
b+	*38,438*
C	5,629
c	*70,142*
c+	*62,678*
D	7,708
d	*56,653*
d+	*80,210*

Once a scenario is followed, the trajectory cannot be changed in my simulation, so the irreducible cumulative emissions are set in each scenario. The offset required in each scenario can be calculated as the difference between the cumulative carbon emissions in the 2050 year, and an artificial CNP (0 g C m^{-2}), which I will call the off-set carbon-neutral point net-zero.

Scope 1-only scenarios only consider field emissions, so they present lower cumulative carbon emissions to offset than the Scope 3 inclusive scenarios. If scenario A management strategy were used instead of scenario D management strategy, the offset required would increase by 1.5 times (table 5), this is because scenario D would be continuously extracting peat carbon in 2050 so not as much mass had been removed, relative to scenario A which would have completed extraction by 2050.

Scope 3 inclusive scenarios present greater cumulative carbon emissions than Scope 1 only scenarios due to the inclusion of the fate of peat. Scenarios a, b, c and d produce greater cumulative carbon emissions than all other scenarios, and therefore the irreducible emissions for each scenario are also greater. The scenario *a* management strategy is a 75 % offset reduction compared to the scenario *d* management strategy (table 5).

5.4.2: Tree-planting as an offset-mechanism

Offsets have a monetary value as they are usually met through carbon sequestration mechanisms or artificial carbon capture technology (Broekhoff *et al.,* 2019). Consequently, I can speculate a cost that corresponds to each scenario's 2050 offset by tree-planting. To do this, I use Drever *et al.,* (2021) and CCA (2021) data (table 6).

Table 6: Costs of tree-planting phases from Drever et al., 2021 and CCA (2021)

Item	Cost Range ($ ha^{-1})	Notes
Site preparation	~ 700	An upfront cost
Tending	~ 600	An upfront cost
Seeding	~ 900 to ~ 2,000	Range from evergreen needle leaf to deciduous broadleaf.
Planting	~ 730 to ~ 1,200	For evergreen needle leaf with increasing slope
Planting	~ 865 to ~ 1,000	For mixed forests, the range is dependent on the mix.
Planting	~ 1,000	Broadleaf forests throughout

In Canada, there is a 2 billion trees by 2031 target (NRCan, 2021), via national tree planting. Canadian forests have a mean above-ground biomass (AGB) of 73 t C ha^{-1} (Santoro *et al.,* 2021). The uptake of AGB declines by 0.035, 0.021, 0.032 and 0.069 t C ha^{-1} y^{-1} for deciduous broadleaf, early-successional coniferous, mixed stand and latesuccessional coniferous forests respectively (Chen and Luo, 2015). For the sake of speculation, I assume the tree planting of a mixed forest. As mixed forest AGB change is 0.032 t C ha^{-1} y^{-1} over approximately 150 years of model study (Chen and Luo, 2015), I assume that the AGB of a 'mature' 150-year-old mixed forest would be 250 t C ha^{-1}. If I reason that the planting cost and seeding costs of the mixed forest were on the lower Drever *et al.,* (2021) range at \$900 ha^{-1} and \$1,400 ha^{-1} respectively, it will cost \$2,300 ha^{-1}, plus an upfront \$1,300 ha^{-1} to tree-plant for offsets. For offset speculation purposes, I will use 250 t C ha^{-1} as the above-ground biomass of a mature forest in Canada, in which case it will cost ~ 14.4 CAD to offset one metric tonne of carbon.

To offset scenario *D*'s 7,708 g C m^{-2} (77.08 t C ha^{-1}) in 2050, it would cost a minimum of ~ 1,110 CAD per hectare. On the other end of the spectrum, to offset scenario A's 3,496 g C m^{-2} (34.96 t C ha^{-1}), it would cost a minimum of ~ 500 CAD per hectare. The management practices chosen for Scope 1 management can therefore reduce potential offset costs by ~ 55 %. But extracted peat does not simply disappear, it continues to decompose downstream, and further offsets will be required.

To offset scenario d's 56,653 g C m^{-2} (566.53 t C ha^{-1}) in 2050, it would cost ~ 8,200 CAD per hectare. On the other end of the spectrum, to offset scenario a's 79,539 g C m^{-2} (795.39 t C ha^{-1}), it would cost a minimum of ~ 11,500 CAD per hectare. A lack of management practices in Scope 3 downstream emissions management can therefore increase potential offset costs by ~ 40 %.

Scope 3 inclusive scenarios reduce the offsets and therefore reduce offset costs. To offset scenario *d+*'s 80,210 g C m^{-2} (802.10 t C ha^{-1}) in 2050, it would cost a minimum of ~ 11,600 CAD per hectare. On the other end of the spectrum, to offset scenario *a+*'s 19,752 g C m^{-2} (197.52 t C ha^{-1}), it would cost a minimum of ~ 2,800 CAD per hectare. The management practices chosen for Scope 3 management can therefore reduce potential offset costs by ~ 75 %.

As management trajectory is set, comparing different scenarios within a scope does not highlight the extent of the impact on management practices and carbon accounting. If I contrast scenario d with scenario *d+*, the only difference in required offset is the management of the fate of peat. Managing the fate of peat in cumulative carbon emissions increases the offset cost by ~ 42 %, from ~ 8,200 \$ ha^{-1} in scenario d to ~ 11,600 \$ ha^{-1} in scenario *d+*. On the other hand, for scenarios a and *a+*, including the fate of peat reduces the offset cost from ~ 11,500 \$ ha^{-1} to ~ 2,800 \$ ha^{-1} respectively, a reduction of ~ 75 %.

The Canadian peat industry has extracted 350km^2 of Canada's peatlands for horticulture (Harris *et al.,* 2021). If their extraction and restoration practices followed scenario d, offsets via tree planting of a mixed stand forest could cost up to 285,500,000 CAD to meet 2050 net-zero emissions targets.

5.5: Double or more the recovered carbon

Peatlands with effective restoration will eventually take up the equivalent carbon from the atmosphere after millennia (i.e. reach the carbon neutral point). If peatland cumulative carbon emissions are also offset, it implies that there is a double counting of biospheric carbon. This could mean the industries offsetting peatland extraction carbon emissions, are offset carbon that would naturally be uptaken. Poplars, pines, spruce and cedar are popular choices for tree replanting as native Canadian species (Tree Canada, 2024). These trees reach maturity at approximately 200, 100, 250 and 100 years after planting respectively (NRCan, 2024), and some pine and cedar trees have been found at over 1000 years old where they have survived disturbance.
If the mean maturity age of these years is around ~150 years, after which time the dead trees re-emit up taken carbon back to the atmosphere via decomposition. The question is then raised whether industry would be responsible for continuously planting trees on 150-year cycles, planting fewer trees each time, until the peatland carbon neutral point is reached naturally after millennia. Assuming that cumulative carbon emissions would have to be offset every 150 years (as each tree-planted forest stand met maturity or died), planting and re-planting would increase the costs of offsetting extracted carbon by 2 times for Scope 1 only scenarios, ~ 145 times for the Scope 3 with no management scenarios and ~ 10 to ~ 65 times for Scope 3 with management scenarios.

These hypotheses do not account for the risk of natural disturbances, such as wildfire, that could threaten to reduce the lifetime of a planted forest for offsets and would consequently need replanting if post-fire forest regeneration was unsuccessful. The increase in forest density and stands of a singular maturity, puts tree-planted forests at risk of wildfire (Doctorow, 2023; Moyles, 2023).

Therefore, I would raise the question of whether offsets are a realistic tool for evaluation and consideration when the subject is peatlands, or whether it would be more economical (as well as better for the biospheric carbon store and climate change) not to extract the peatlands at all.

Peatland extraction, with net zero emissions, is neither financially nor environmentally sustainable in relation to current industry revenue and profit margins. Even with management strategies, the mitigation of cumulative carbon emissions is not great enough for irreducible emissions to equal zero, or for the system to be considered sustainable. The potential lifecycle of ecological sequestration mechanisms (i.e. tree planting) is as much as 28 to 50 times shorter than the biospheric carbon recovery time of the disturbed peatland system (relative to scenarios *d*+ and *d*). Mechanical sequestration techniques, such as carbon capture, are not financially viable for the peat industry.

5.6: Alternatives to peat

Peat alternatives include coir (coconut shell fibres), wood fibres, perlite, rock wool (spun basaltic rock), bark and sand (Vinci and Rapa, 2019; Toboso-Chavero *et al.,* 2021; Paoli *et al.,* 2022). Both coir pith and rockwool have greater impacts on the environment through the total of human health, resources, climate change and ecosystem quality indicators than peat when mechanical and transport emissions are also taken into account (Paoli *et al.,* 2022). Perlite is occasionally mixed with peat, or used alone, and exhibits environmental impacts 44 to 99.9 % greater than those of coir and peat (Toboso-Chavero *et al.,* 2021). Other alternatives bark and sand are thought to be the most sustainable through a combination of life-cycle assessments and carbon footprint total impact analysis, and that peat is the most expensive substrate per 1,000 cm^3(Vinci and Rapa, 2019).

None of the substrate alternatives to peat are carbon neutral on policy time scales, but coir and bark have the potential to be carbon neutral on ecological timescales shorter than that of peat, management-dependent. Growing media with peat content less than 40% will produce a poorer yield (Cleary *et al.,* 2005), as it diminishes peat's nutrient fixing, soil buffering and ore water retention capacity abilities.

A similar study to mine could be conducted for each peat alternative, to assess the biospheric cumulative carbon emissions from development/ extraction through to fate (in addition to any mechanical emissions) as well as the natural biospheric recovery time.

Chapter 6: Concluding Remarks

The use of peat for horticulture results in significant carbon emissions. Emissions can be reduced through peat extraction management and effective restoration. Still, the peat scientific community does not know enough about the fate of extracted peat to recognise the extent to which it could reduce cumulative carbon emissions. My simulations show that understanding emissions from the fate of peat will have an impact on the understanding of cumulative carbon emissions. But no practical scenario could reduce cumulative carbon emissions enough for emissions to be zero, and peat extraction to be sustainable on human policy timescales. Peat extraction for horticulture is sustainable within short geological timescales, and the damage done to peatlands during disturbance needs millennia to naturally meet a carbon-neutral point, even after effective restoration.

My thesis makes an important contribution to the peat scientific community. Not only do my simulations inform science by presenting cumulative carbon emissions of a disturbed peatland, but they also demonstrate the time taken for cumulative carbon emissions to reach a carbon-neutral point. Furthermore, the combination of management variables I present can advise the horticultural peat extraction industry on which practices have the greatest impact on cumulative carbon emissions, such as impact of extraction duration on annual cumulative carbon emissions. I then highlight the need for further research on the downstream emissions of extracted peat (i.e. the fate of peat) to better understand the relocation of peat carbon within the biosphere. Finally, my findings situate anthropogenic peatland disturbance in the context of national and international emissions targets and note key considerations for the horticultural peat extraction industry for offsetting emissions by subsequent target years.

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Appendix I

Codes for the environmental systems model both including and excluding the fate of peat. Codes are also available as text files and can be converted for use in R as described by Babak and Alexey (2012).

Table of Contents

Babak, N., & V., Alexey. (2012). StellaR: A software to translate Stella models into R open-source environment. Environmental Modelling and Software. 38. 117-118. 10.1016/j.envsoft.2012.05.012.

Simulation including downstream emissions via decomposition.

```
Nat_Ext_Z_v22.stmx
{ The model has 108 (108) variables (array expansion in parens).
  In root model and 0 additional modules with 0 sectors.
  Stocks: 11 (11) Flows: 23 (23) Converters: 74 (74)
  Constants: 30 (30) Equations: 67 (67) Graphicals: 9 (9)
  There are also 15 expanded macro variables.  }

Top-Level Model:
acrotelm(t) = acrotelm(t - dt) + (acrotelm_transfer +
restored_acrotelm_transfer - catotelm_transfer -
extraction_disturbance_acro) * dt {NON-NEGATIVE}
    INIT acrotelm = 0
    UNITS: grams per square meter
    DOCUMENT: Stock for build up of acrotelm layer. Both initial and
restored acrotelm conveyors feed into acrotelm stock. The acrotelm
stock is experiences an extraction outflow during the extraction
period. Peat carbon is emptied into the catotelm stock each dt. The
acrotelm stock also has an outflow function of decompostion and the
total acrotelm carbon store.
catotelm(t) = catotelm(t - dt) + (catotelm_transfer -
extraction_disturbance_cato - catotelm_C_out) * dt {NON-NEGATIVE}
    INIT catotelm = 0
    UNITS: grams per square meter
    DOCUMENT: Catotelm stock of peat carbon. Inflow comes from the
acrotelm. Outflow function of decompostion and the total catotelm
carbon store. The catotelm stock also experiences extraction during
extraction start and end years.
cummluative_extracted_emissiosn(t) = cummluative_extracted_emissiosn(t
- dt) + (decomp_extracted_peat) * dt
    INIT cummluative_extracted_emissiosn = 0
    UNITS: grams per square meter
extracted_peat(t) = extracted_peat(t - dt) +
(extraction_disturbance_acro + extraction_disturbance_cato -
decomp_extracted_peat) * dt {NON-NEGATIVE}
    INIT extracted_peat = 0
    UNITS: grams per square meter
inital_acrotelm(t) = inital_acrotelm(t - dt) +
(litter_to_acrotelm_transfer - acrotelm_transfer - acro_conveyor_C_out)
* dt {CONVEYOR}
    INIT inital_acrotelm = 1
        TRANSIT TIME =
IF(TIME<Start_Year)THEN(acrotelm_tranfer_time)ELSE(IF(TIME>=Start_Year)
AND(TIME<=End_Year)THEN(1)ELSE(IF(TIME>Restoration_EndYear)THEN(acrotel
m_tranfer_time)ELSE(acrotelm_tranfer_time)))
```

```
        FIFO
    DISCRETE
    ACCEPT MULTIPLE BATCHES
    UNITS: grams per square meter
    DOCUMENT: Conveyor for build up of acrotelm layer, before
extraction. Peat carbon will transfer through the initial acrotelm over
a transit time before being emptied into a stock acrotelm. The acrotelm
conveyor also experiences a leak function related to acrotelm
decomposition.
InitialLitter(t) = InitialLitter(t - dt) + (C_in_est - litter_transfer
- Litter_conveyor_C_out) * dt {CONVEYOR}
    INIT InitialLitter = 0
        TRANSIT TIME = 1
    CONTINUOUS
    ACCEPT MULTIPLE BATCHES
    UNITS: grams per square meter
    DOCUMENT: Conveyor for build up of litter layer, before extraction.
The litter conveyor also experiences a leak function related to litter
decomposition.
litter(t) = litter(t - dt) + (litter_transfer -
litter_to_acrotelm_transfer - litter_removal) * dt {NON-NEGATIVE}
    INIT litter = 0
    UNITS: grams per square meter
    DOCUMENT: Stock for litter layer, before extraction. Litter can be
removed from this stock prior to extraction. The litter stock also has
an outflow function of decomposition and the total litter carbon store.
removed_litter(t) = removed_litter(t - dt) + (litter_removal -
removed_litter_c_out) * dt {NON-NEGATIVE}
    INIT removed_litter = 0
    UNITS: grams per square meter
    DOCUMENT: Stock for litter removed from the extractable litter
layer. Litter in this stock is reserved and a proportion can be reused
during restoration.  L
restaration_Litter(t) = restaration_Litter(t - dt) + (C_in_Rest -
restored_litter_to_acrotelm_transfer - restored_litter_conveyor_c_out)
* dt {CONVEYOR}
    INIT restaration_Litter = 0
        TRANSIT TIME = 1
    CONTINUOUS
    ACCEPT MULTIPLE BATCHES
    UNITS: grams per square meter
    DOCUMENT: Conveyor for build up of litter layer, after restoration.
The litter conveyor also experiences a leak function related to litter
decomposition.
restoration_acro(t) = restoration_acro(t - dt) +
(restored_litter_to_acrotelm_transfer - restored_acrotelm_transfer -
restored_acro_conveyor_C_out) * dt {CONVEYOR}
    INIT restoration_acro = 0
        TRANSIT TIME =
IF(TIME<restoration_start_year)THEN(acrotelm_tranfer_time)ELSE(IF(TIME>
=restoration_start_year)AND(TIME<=Restoration_EndYear)THEN(restoration_
duration)ELSE(IF(TIME>Restoration_EndYear)THEN(acrotelm_tranfer_time)EL
SE(acrotelm_tranfer_time)))
        FIFO
    CONTINUOUS
    ACCEPT MULTIPLE BATCHES
    UNITS: grams per square meter
```

```
    DOCUMENT: Conveyor for build up of acrotelm layer, after
restoration. Peat carbon will transfer through the restoration acrotelm
over a transit time before being emptied into the acrotelm stock. The
acrotelm conveyor also experiences a leak function related to acrotelm
decomposition.
Water_Store(t) = Water_Store(t - dt) + (water_inflow - Outflow_ET -
Outflow_ground - Drainage) * dt {NON-NEGATIVE}
    INIT Water_Store = 0
    UNITS: Centimeters
    DOCUMENT: Store of water as stock, measured as a height in
centimeters.
acro_conveyor_C_out = LEAKAGE OUTFLOW
    LEAKAGE FRACTION = actual_acro_decomp
    LINEAR LEAKAGE
    LEAK ZONE = 0% to 100%
    UNITS: grams per meter square per year
    DOCUMENT: Leak outflow from acrotelm conveyor. Leak fraction is the
actual acrotelm decomposition rate.
acrotelm_transfer = CONVEYOR OUTFLOW
    UNITS: grams per meter square per year
    DOCUMENT: Main outflow from initial acrotelm layer conveyor to
acrotelm stock.
C_in_est =
IF(TIME<=Drainage_Start_Year)THEN(biomass_to_C*NPP_Actual)ELSE(IF(TIME>
=Drainage_Start_Year)AND(TIME<=End_Year)THEN(0)ELSE(IF(TIME>End_Year)TH
EN(0)ELSE(biomass_to_C*NPP_Actual))) {UNIFLOW}
    UNITS: grams per meter square per year
    DOCUMENT: Flow demonstrating the carbon entering the peat carbon
store.  Expressed as a function of net primary productivity and the
conversion proportion of carbon in accumulated biomass. C in flow is
limited to 0 after drainage start year.
C_in_Rest = NPP_Actual_Restoration*biomass_to_C {UNIFLOW}
    UNITS: grams per meter square per year
catotelm_C_out = catotelm*actual_cato_decomp {UNIFLOW}
    OUTFLOW PRIORITY: 2
    UNITS: grams per meter square per year
    DOCUMENT:  The catotelm stock also has an outflow function of
actual catotelm decomposition rate and the total catotelm carbon store.
catotelm_transfer =
IF(TIME<=Drainage_Start_Year)THEN(acrotelm)ELSE(IF(TIME>Drainage_Start_
Year)AND(TIME<Restoration_EndYear)THEN(0)ELSE(IF(TIME>=Restoration_EndY
ear)THEN(acrotelm)ELSE(acrotelm))) {UNIFLOW}
    OUTFLOW PRIORITY: 1
    UNITS: grams per meter square per year
    DOCUMENT: Main outflow from acrotelm stock to catotelm stock.
decomp_extracted_peat = extracted_peat_decomposotion*extracted_peat
{UNIFLOW}
    UNITS: grams per meter square per year
Drainage =
IF(TIME<Drainage_Start_Year)THEN(0)ELSE(IF(TIME>=Drainage_Start_Year)AN
D(peat_height>=min_peat_height_remaining)AND(TIME<=restoration_start_ye
ar)THEN(Water_Store*drainage_rate_extraction)ELSE(0)) {UNIFLOW}
    OUTFLOW PRIORITY: 3
    UNITS: Centimeters/years
    DOCUMENT: Drainage from water store to begin two years before
extraction, and continue until restoration. Function of drainage rate
during extraction.
```

```
extraction_disturbance_acro =
IF(TIME<Start_Year)AND(TIME>End_Year)THEN(0)ELSE(IF(acro_height<0.001)T
HEN(0)ELSE(IF(TIME>=Start_Year)AND(acro_height>0.001)AND(TIME<End_Year)
THEN(extr_racte_calc_acro)ELSE(0))) {UNIFLOW}
    OUTFLOW PRIORITY: 2
    UNITS: grams per meter square per year
    DOCUMENT: Extraction disturbance from acrotelm. Disturbance is a
function of the calculated extraction rate. Will begin when time =
start year and end when acrotelm is empty. Disturbance will only occur
in the extraction duration.
extraction_disturbance_cato =
IF(TIME<Start_Year)AND(TIME>End_Year)THEN(0)ELSE(IF(peat_height<min_pea
t_height_remaining)THEN(0)ELSE(IF(TIME>=Start_Year)AND(acro_height<0.00
1)AND(TIME<End_Year)THEN(extraction_rate_calc)ELSE(0))) {UNIFLOW}
    OUTFLOW PRIORITY: 1
    UNITS: grams per meter square per year
    DOCUMENT: Extraction disturbance from catotelm. Disturbance is a
function of the calculated extraction rate. Will begin only when time =
start year and acrotelm height is close to zero. The disturbance
outflow will continue until peat height is equal to the prescribed
minimum peat height remaining. Disturbance will only occur in the
extraction duration.
Litter_conveyor_C_out = LEAKAGE OUTFLOW
    LEAKAGE FRACTION = actual_litter_decomp
    LINEAR LEAKAGE
    LEAK ZONE = 0% to 100%
    UNITS: grams per meter square per year
    DOCUMENT: Leak outflow from litter conveyor. Leak fraction is the
litter decomposition rate.
litter_removal =
IF(TIME<Drainage_Start_Year)AND(TIME>End_Year)THEN(0)ELSE(IF(TIME>=Drai
nage_Start_Year)AND(TIME<=End_Year)THEN(litter)ELSE(0)) {UNIFLOW}
    OUTFLOW PRIORITY: 2
    UNITS: grams per meter square per year
    DOCUMENT: Litter removal from litter layer prior to extraction.
litter_to_acrotelm_transfer = litter {UNIFLOW}
    OUTFLOW PRIORITY: 1
    UNITS: grams per meter square per year
    DOCUMENT: Main outflow from litter stock to acrotelm conveyor.
litter_transfer = CONVEYOR OUTFLOW
    UNITS: grams per meter square per year
    DOCUMENT: Main outflow from initial litter layer conveyor to litter
stock.
Outflow_ET = actual_ET {UNIFLOW}
    OUTFLOW PRIORITY: 1
    UNITS: Centimeters/years
    DOCUMENT: flow of water out of the store from ET, function of
actual ET from Water Store.
Outflow_ground =
IF(TIME>=restoration_start_year)AND(TIME<=Restoration_EndYear)THEN(0)EL
SE((q)) {UNIFLOW}
    OUTFLOW PRIORITY: 2
    UNITS: Centimeters/years
    DOCUMENT: Flow of water out of the store through ground, as a
function of discharge (q). Zero during restoration to reflect ditch
blocking post-extraction.
```

removed_litter_c_out = removed_litter*Litter_decomp {UNIFLOW}
    UNITS: grams per meter square per year
    DOCUMENT: Outflow from removed litter is a function of litter decomposition rate and the total removed litter carbon store.
restored_acro_conveyor_C_out = LEAKAGE OUTFLOW
    LEAKAGE FRACTION = actual_acro_decomp
    LINEAR LEAKAGE
    LEAK ZONE = 0% to 100%
    UNITS: grams per meter square per year
    DOCUMENT: Leak outflow from acrotelm conveyor. Leak fraction is the actual acrotelm decomposition rate.
restored_acrotelm_transfer = CONVEYOR OUTFLOW
    UNITS: grams per meter square per year
    DOCUMENT: Main outflow from restored acrotelm layer conveyor to acrotelm stock.
restored_litter_conveyor_c_out = LEAKAGE OUTFLOW
    LEAKAGE FRACTION = actual_litter_decomp
    LINEAR LEAKAGE
    LEAK ZONE = 0% to 100%
    UNITS: grams per meter square per year
    DOCUMENT: Leak outflow from litter conveyor. Leak fraction is the litter decomposition rate.
restored_litter_to_acrotelm_transfer = CONVEYOR OUTFLOW
    UNITS: grams per meter square per year
    DOCUMENT: Main outflow from restored litter layer conveyor to restored acrotelm conveyor.
reuse_litter =
IF(TIME<=End_Year)THEN(0)ELSE(IF(TIME>End_Year)THEN(ususable_litter_litter)ELSE(0)) {UNIFLOW}
    DOCUMENT: Inflow from proportion of removed litter store that is eligible for reuse. Aims to reflect moss transfer/ ecological restoration.
water_inflow = Prandom/mm_to_cm {UNIFLOW}
    UNITS: Centimeters/years
    DOCUMENT: flow of water into the store, function of random precipitation and a mm to cm conversion.
acro_acc = (litter_transfer+restored_litter_to_acrotelm_transfer)-(acro_conveyor_C_out+acrotelm_transfer+extraction_disturbance_acro+restored_acro_conveyor_C_out+restored_acrotelm_transfer)
    UNITS: grams C per m2 per year
    DOCUMENT: Acrotelm carbon accumulation rate. Function of in and outflows of carbon relating to the acrotelm stores.
acro_decomp = 0.8
    DOCUMENT: acrotelm decomposition set between 0.8 and 0.9 based on Clymo 1990.
acro_desnity = 80
    UNITS: kilograms per cubic meter
    DOCUMENT: density of the acrotelm. Based on literature.
acro_height = (acro_mass)/(acro_desnity*kg_to_g)
    UNITS: Meters
    DOCUMENT: height of acrotelm, function of acrotelm mass, acrotelm density and a conversion of kg to g.
acro_mass = (restoration_acro+inital_acrotelm+acrotelm)*2
    UNITS: Grams
    DOCUMENT: Sum of the masses of acrotelm conveyors and acrotelm stock. Assumed to be double the carbon store mass, based on Clymo's assumptions and Nigel's information (pers. comm) for biomass to carbon.
acro_z_relationship = GRAPH(Zsmooth)

```
Points: (-60.00, 1.1000), (-53.3333333333, 1.0750), (-46.6666666667,
1.0500), (-40.00, 1.0250), (-33.3333333333, 1.0000), (-26.6666666667,
0.9750), (-20.00, 0.9500), (-13.3333333333, 0.9250), (-6.66666666667,
0.9000), (0.00, 0.8750), (6.66666666667, 0.8500), (13.3333333333,
0.8250), (20.00, 0.8000)
    DOCUMENT: relationship between water table and acrotelm
decomposition by 10% above/below acro_decomp, based on literature.
acrotelm_tranfer_time = 150
actual_acro_decomp =
IF(TIME<Start_Year)THEN(acro_z_relationship*acro_decomp)ELSE(IF(TIME>=S
tart_Year)AND(TIME<=End_Year)THEN(0.01)ELSE(IF(TIME>End_Year)THEN(acro_
decomp*acro_z_relationship)ELSE(acro_decomp*acro_z_relationship)))
    DOCUMENT: Actual acrotelm decomposition rate, function of acrotelm
z relationship and acrotelm decomposition. Also related to extraction
period.
actual_cato_decomp = IF(TIME<Drainage_Start_Year)THEN(cato_decomp)
ELSE(IF(TIME>=Drainage_Start_Year)AND(TIME<=Restoration_EndYear)THEN(sm
ooth_massZ_relationship)
ELSE(IF(TIME>Restoration_EndYear)AND(TIME<=restoration_start_year+3*acr
otelm_tranfer_time/2)THEN(smooth_massZ_relationship)
ELSE(IF(TIME>restoration_start_year+3*acrotelm_tranfer_time/2)AND(TIME<
=restoration_start_year+2*acrotelm_tranfer_time)THEN((smooth_massZ_rela
tionship+cato_decomp)/2)
ELSE(IF(TIME>restoration_start_year+acrotelm_tranfer_time)THEN((smooth_
massZ_relationship+cato_decomp)/2) ELSE(cato_decomp)))))
    DOCUMENT: actual decomposition rate in catotelm. During extraction,
function of relationship between catotelm mass and z, and catotelm
decomposition. Otherwise function of catotelm decomposition and total
catotelm carbon store.


    IF(TIME<Drainage_Start_Year)THEN(cato_decomp)

ELSE(IF(TIME>=Drainage_Start_Year)AND(TIME<=restoration_start_year+acro
telm_tranfer_time)THEN(smooth_massZ_relationship)ELSE(IF(TIME>restorati
on_start_year+acrotelm_tranfer_time)AND(TIME<=restoration_start_year+10
*acrotelm_tranfer_time)THEN(((cato_decomp)+(3*smooth_massZ_relationship
))/4)ELSE(IF(TIME>restoration_start_year+10*acrotelm_tranfer_time)AND(T
IME<=restoration_start_year+20*acrotelm_tranfer_time)THEN(((cato_decomp
)+(smooth_massZ_relationship))/2)

ELSE(IF(TIME>restoration_start_year+20*acrotelm_tranfer_time)AND(TIME<=
restoration_start_year+40*acrotelm_tranfer_time)THEN(((3*cato_decomp)+(
smooth_massZ_relationship))/4)
    ELSE(cato_decomp)))))

    IF(TIME<Drainage_Start_Year)THEN(cato_decomp)

ELSE(IF(TIME>=Drainage_Start_Year)AND(TIME<=restoration_start_year+acro
telm_tranfer_time)THEN(smooth_massZ_relationship)ELSE(IF(TIME>restorati
on_start_year+acrotelm_tranfer_time)AND(TIME<=restoration_start_year+50
*acrotelm_tranfer_time)THEN(((cato_decomp)+(3*smooth_massZ_relationship
))/4)ELSE(cato_decomp)))))

    IF(TIME<Drainage_Start_Year)THEN(cato_decomp)

ELSE(IF(TIME>=Drainage_Start_Year)AND(TIME<=restoration_start_year+acro
telm_tranfer_time)THEN(smooth_massZ_relationship)ELSE(IF(TIME>restorati
```

```
on_start_year+acrotelm_tranfer_time)THEN(cato_decomp)ELSE(cato_decomp))
)


    IF(TIME<Drainage_Start_Year)THEN(cato_decomp)

ELSE(IF(TIME>=Drainage_Start_Year)AND(TIME<=Restoration_EndYear)THEN(sm
ooth_massZ_relationship)

ELSE(IF(TIME>Restoration_EndYear)AND(TIME<=restoration_start_year+3*acr
otelm_tranfer_time/2)THEN(smooth_massZ_relationship)

ELSE(IF(TIME>restoration_start_year+3*acrotelm_tranfer_time/2)AND(TIME<
=restoration_start_year+2*acrotelm_tranfer_time)THEN((smooth_massZ_rela
tionship+cato_decomp)/2)

ELSE(IF(TIME>restoration_start_year+acrotelm_tranfer_time)THEN((smooth_
massZ_relationship+cato_decomp)/2)
    ELSE(cato_decomp)))))
actual_ET = IF(z>=-70)THEN(ETrandom*PET)ELSE(IF(z<-70)THEN(0)ELSE(0))
    UNITS: Centimeters
    DOCUMENT: actual evapotranspiration based on relationship between
depth of the water table, baseline ET and potential ET
actual_litter_decomp =
IF(TIME>STARTTIME+1)AND(TIME<STARTTIME+establishment_delay)THEN(Litter_
decomp/litter_est_relationship)ELSE(IF(TIME>=STARTTIME+establishment_de
lay)THEN(Litter_decomp)ELSE(Litter_decomp))
biomass_to_C = .5
    DOCUMENT: Proportion of biomass produced that contains carbon.
From numbers given by Nigel.
C_in_flows = C_in_est+C_in_Rest
    DOCUMENT: Sum of all C in flows
C_Out_Flows =
restored_litter_conveyor_c_out+Litter_conveyor_C_out+catotelm_C_out+res
tored_acro_conveyor_C_out+acro_conveyor_C_out+removed_litter_c_out+deco
mp_extracted_peat
    DOCUMENT: Sum of all C outflows


restored_litter_conveyor_c_out+Litter_conveyor_C_out+catotelm_C_out+acr
o_conveyor_C_out+restored_acro_conveyor_C_out+Flow_1
cato_acc = (restored_acrotelm_transfer+acrotelm_transfer)-
(catotelm_C_out+extraction_disturbance_cato)
    UNITS: grams C per m2 per year
    DOCUMENT: Catotelm carbon accumulation rate. Function of in and
outflows of carbon relating to the catotelm stores.
cato_decomp = 0.00025
    DOCUMENT: Rate of decomposition that occurs in the peat column
below the water table.  Based on a combination of Hilbert et al 2000,
and frolking et al 2001, which place this value between 0.0001 and
0.0003, but more commonly as a rate of 0.00025 per year.
cato_density = 80
    UNITS: kilograms per cubic meter
    DOCUMENT: desnity of the catotelm, based on literature.
cato_height = (cato_mass)/(cato_density*kg_to_g)
    UNITS: Meters
    DOCUMENT: Height of the catotelm, calculated as a function of peat
mass, peat density, and the conversion from kg to g.
```

```
cato_mass = catotelm*2
    UNITS: Grams
    DOCUMENT: The accumulated mass of catotelm peat, from the peat
carbon store.  Assumed to be double the carbon store mass, based on
Clymo's assumptions and Nigel's information (pers. comm) for biomass to
carbon.
count_from_restoraiton = year-restoration_start_year
    DOCUMENT: difference between current year and restoration start
year.
cumulative_emissions =
(acro_conveyor_C_out+catotelm_C_out+Litter_conveyor_C_out+restored_litt
er_conveyor_c_out+restored_acro_conveyor_C_out)-(C_in_est+C_in_Rest)
drainage_rate_extraction = .5
    DOCUMENT: Drainage rate during extraction. Value informed by
sensitivity analysis to empty water store to a depth that Industry aims
for prior to extraction.
Drainage_Start_Year = Start_Year-2
    UNITS: Years
    DOCUMENT: Set to begin two years before the extraction start year.
End_Year = extraction_duration+Start_Year
    UNITS: Years
    DOCUMENT: Year extraction ends, function of extraction start year
and extraction duration.
establishment_delay = 200
ET0 = 25
    UNITS: Centimeters
    DOCUMENT: baseline Evapotranspiration. good starting value: 20-35
(25 best)
ETrandom = RANDOM((ET0*0.9), (ET0*1.1), ET0)
    DOCUMENT: randomisation of evapotranspiration by 10%.
extr_racte_calc_acro =
extraction_depth_per_year*(kg_to_g*extraction_acro_desnity)
    UNITS: grammes per meter square per year
extracted_peat_decomposotion = 0.025
extraction_acro_desnity = 80
extraction_catotelm_density = 120
    UNITS: kilograms per cubic meter
    DOCUMENT: Density of catotelm during extraction
extraction_depth_per_year = 0.04
    UNITS: meters per year
    DOCUMENT: depth of extraction per year
extraction_duration = 33.5
    DOCUMENT: time for which extraction can occur. Based on this
simulation, a 0.06 extraction rate will run for 15 years, 0.04 for 22
years and a 0.02 for 42 years before minimum peat height is reached.
extraction_rate_calc =
extraction_depth_per_year*(kg_to_g*extraction_catotelm_density)
    UNITS: grams per meter square per year
    DOCUMENT: Extraction rate per year calculated as a function of
extraction depth per year, peat density during extraction and kg to g
conversion. Ranges between 2.4k g yr-1 and 7.2k g yr-1, most influenced
by extraction depth per year.


grad = 0.001
    UNITS: Dimensionless
    DOCUMENT: gradient of H/L assuming growth of 1m H = 1000m W to
eveuntally 5m H = 5000m W --> H/L = 0.001 dim.
```

```
kg_to_g = 1000
    DOCUMENT: conversion of kilograms to grams for calculations.
Litter_decomp = .3
    DOCUMENT: Decomposition rate of the litter layer, set at 0.3 based
on literature.
litter_est_relationship = GRAPH(year)
Points: (0.0, 0.1000), (20.0, 0.4576), (40.0, 0.6740), (60.0, 0.8050),
(80.0, 0.8843), (100.0, 0.9324), (120.0, 0.9614), (140.0, 0.9790),
(160.0, 0.9897), (180.0, 0.9961), (200.0, 1.0000)
mass_z_relationship_extraction = IF(TIME>=200)THEN((((-2.4*z)-
0.94)/0.6)/cato_mass)ELSE(0)
    DOCUMENT: Catotelm decompostion factor based on catotelm mass and
z, based on He et al 2023.
mean_smooth_peat_c = MEAN(smooth_peat_c_acc, 10)
min_peat_height_remaining = 0.98
    UNITS: Meters
    DOCUMENT: minimum peat height that must be preserved in the
catotelm after extraction. 1m should be preserved to avoid mineral
layer-peat contamination according to literature. PremierTech 17ft ~5m
peatland, expect more than 1-2m remaining.
mm_to_cm = 10
    UNITS: Dimensionless
    DOCUMENT: conversion from mm to cm
net_flows = C_Out_Flows-C_in_flows
NPP = 600
    DOCUMENT: Net primary productivity of the system, refers to the
energy stored as biomass by vegetation as it grows.  Numbers from
Clymo, Frolking et al 2001, Frolking et al 2010 and Basiliko et al
2006.  Range between 400 and 600.
NPP_Actual =
IF(TIME<STARTTIME+establishment_delay)THEN(NPP*NPP_z_relationship*NPP_v
eg_est_relationship)ELSE(IF(TIME>=STARTTIME+establishment_delay)AND(TIM
E<Start_Year)THEN(NPP*NPP_z_relationship)ELSE(NPP*NPP_z_relationship))
    DOCUMENT: Actual net primary productivity. Before drainage and
after restoration is complete, function of  NPP and the relationship
between water table depth and NPP. During restoration also a function
of ration restoration time. Restricted by time, with actual NPP equal
to zero during extraction and before restoration.



IF(TIME<Start_Year)THEN(NPP*NPP_z_relationship)ELSE(IF(TIME>=Start_Year
)AND(TIME<restoration_start_year)THEN(0)ELSE(IF(TIME>=restoration_start
_year)AND(TIME<Restoration_EndYear)THEN(2*ratio_restoration_time*NPP*NP
P_z_relationship)ELSE(IF(TIME>=Restoration_EndYear)AND(TIME<Restoration
_EndYear+50)THEN(NPP*NPP_z_relationship/2)ELSE(IF(TIME>=Restoration_End
Year+50)THEN(NPP*NPP_z_relationship)ELSE(NPP*NPP_z_relationship)))))
NPP_Actual_Restoration =
IF(TIME<restoration_start_year)THEN(0)ELSE(IF(TIME>=restoration_start_y
ear)AND(TIME<Restoration_EndYear)THEN("re-
establishment_of_vegetation_relationship_NPP"*NPP_Restoration*NPP_z_rel
ationship)ELSE(IF(TIME>=Restoration_EndYear)AND(TIME<Restoration_EndYea
r+establishment_delay)THEN(NPP_veg_REST_relatioship*NPP_Restoration*NPP
_z_relationship)ELSE(IF(TIME>=Restoration_EndYear+establishment_delay)T
HEN(NPP*NPP_z_relationship)ELSE(NPP*NPP_z_relationship))))
NPP_Restoration = GRAPH(establishment_delay)
```

```
Points: (1.0, 0.0), (20.9, 7.579), (40.8, 26.05), (60.7, 69.92), (80.6,
160.6), (100.5, 300.0), (120.4, 439.4), (140.3, 530.1), (160.2, 574.0),
(180.1, 592.4), (200.0, 600.0)
    DOCUMENT:
IF(TIME<STARTTIME+establishment_delay)THEN(NPP*NPP_z_relationship*ratio
)ELSE(IF(TIME<Start_Year)THEN(NPP*NPP_z_relationship)ELSE(IF(TIME>=Star
t_Year)AND(TIME<restoration_start_year)THEN(0)ELSE(IF(TIME>=restoration
_start_year)AND(TIME<Restoration_EndYear)THEN(NPP*NPP_z_relationship*ra
tio_restoration_time)ELSE(IF(TIME>=Restoration_EndYear)AND(TIME<Restora
tion_EndYear+establishment_delay)THEN(NPP*NPP_z_relationship*ratio2)ELS
E(IF(TIME>=Restoration_EndYear+establishment_delay)THEN(NPP*NPP_z_relat
ionship)ELSE(NPP*NPP_z_relationship))))))
NPP_veg_est_relationship = GRAPH(year)
Points: (0.0, 0.000), (20.0, 0.1505), (40.0, 0.2868), (60.0, 0.410),
(80.0, 0.5215), (100.0, 0.6225), (120.0, 0.7138), (140.0, 0.7964),
(160.0, 0.8711), (180.0, 0.9388), (200.0, 1.000)
NPP_veg_REST_relatioship = GRAPH(count_from_restoraiton)
Points: (0.0, 0.000), (20.0, 0.1505), (40.0, 0.2868), (60.0, 0.410),
(80.0, 0.5215), (100.0, 0.6225), (120.0, 0.7138), (140.0, 0.7964),
(160.0, 0.8711), (180.0, 0.9388), (200.0, 1.000)
NPP_z_relationship = GRAPH(Zsmooth)
Points: (-60.00, 0.000), (-59.2424242424, 0.040404040404), (-
58.4848484848, 0.0799835085549), (-57.7272727273, 0.118738404453), (-
56.9696969697, 0.156668728097), (-56.2121212121, 0.193774479489), (-
55.4545454545, 0.230055658627), (-54.696969697, 0.265512265512), (-
53.9393939394, 0.300144300144), (-53.1818181818, 0.333951762523), (-
52.4242424242, 0.366934652649), (-51.6666666667, 0.399092970522), (-
50.9090909091, 0.430426716141), (-50.1515151515, 0.460935889507), (-
49.3939393939, 0.49062049062), (-48.6363636364, 0.519480519481), (-
47.8787878788, 0.547515976087), (-47.1212121212, 0.574726860441), (-
46.3636363636, 0.601113172542), (-45.6060606061, 0.626674912389), (-
44.8484848485, 0.651412079983), (-44.0909090909, 0.675324675325), (-
43.3333333333, 0.698412698413), (-42.5757575758, 0.720676149248), (-
41.8181818182, 0.742115027829), (-41.0606060606, 0.762729334158), (-
40.303030303, 0.782519068233), (-39.5454545455, 0.801484230056), (-
38.7878787879, 0.819624819625), (-38.0303030303, 0.836940836941), (-
37.2727272727, 0.853432282004), (-36.5151515152, 0.869099154813), (-
35.7575757576, 0.88394145537), (-35.00, 0.897959183673), (-
34.2424242424, 0.911152339724), (-33.4848484848, 0.923520923521), (-
32.7272727273, 0.935064935065), (-31.9696969697, 0.945784374356), (-
31.2121212121, 0.955679241394), (-30.4545454545, 0.964749536178), (-
29.696969697, 0.97299525871), (-28.9393939394, 0.980416408988), (-
28.1818181818, 0.987012987013), (-27.4242424242, 0.992784992785), (-
26.6666666667, 0.997732426304), (-25.9090909091, 1.00185528757), (-
25.1515151515, 1.00515357658), (-24.3939393939, 1.00762729334), (-
23.6363636364, 1.00927643785), (-22.8787878788, 1.0101010101), (-
22.1212121212, 1.0101010101), (-21.3636363636, 1.00927643785), (-
20.6060606061, 1.00762729334), (-19.8484848485, 1.00515357658), (-
19.0909090909, 1.00185528757), (-18.3333333333, 0.997732426304), (-
17.5757575758, 0.992784992785), (-16.8181818182, 0.987012987013), (-
16.0606060606, 0.980416408988), (-15.303030303, 0.97299525871), (-
14.5454545455, 0.964749536178), (-13.7878787879, 0.955679241394), (-
13.0303030303, 0.945784374356), (-12.2727272727, 0.935064935065), (-
11.5151515152, 0.923520923521), (-10.7575757576, 0.911152339724), (-
10.00, 0.897959183673), (-9.24242424242, 0.88394145537), (-
8.48484848485, 0.869099154813), (-7.72727272727, 0.853432282004), (-
6.9696969697, 0.836940836941), (-6.21212121212, 0.819624819625), (-
5.45454545455, 0.801484230056), (-4.69696969697, 0.782519068233), (-
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3.93939393939, 0.762729334158), (-3.18181818182, 0.742115027829), (-2.42424242424, 0.720676149248), (-1.66666666667, 0.698412698413), (-0.909090909091, 0.675324675325), (-0.151515151515, 0.651412079984), (0.606060606061, 0.626674912389), (1.36363636364, 0.601113172542), (2.12121212121, 0.574726860441), (2.87878787879, 0.547515976087), (3.63636363636, 0.519480519481), (4.39393939394, 0.490620490621), (5.15151515152, 0.460935889507), (5.90909090909, 0.430426716141), (6.66666666667, 0.399092970522), (7.42424242424, 0.366934652649), (8.18181818182, 0.333951762523), (8.93939393939, 0.300144300144), (9.69696969697, 0.265512265512), (10.4545454545, 0.230055658627), (11.2121212121, 0.193774479489), (11.9696969697, 0.156668728097), (12.7272727273, 0.118738404453), (13.4848484848, 0.079983508555), (14.2424242424, 0.0404040404041), (15.00, 1.41046896385e-13)

UNITS: Dimensionless

DOCUMENT: Relationship between NPP and WTD. Graphic function using the equation G = k(Z0-Zmin)(Zmax-Z0), where Z0 water table depth below the peat surface cm, Z0* equilibrium water table depth below peat surface cm, Zmax maximum water table depth where G becomes zero cm, and Zmin minimum water table depth where G becomes zero

P = 900

UNITS: Millimeters

DOCUMENT: annual precipitation set at 900mm/yr. good starting value: 850-950. Based on annual precipitation in quebec, specifically Riviere du Loup.

peat_C_acc = cato_acc+acro_acc

UNITS: grams C per m2 per year

DOCUMENT: peat carbon accumulation, as sum of both carbon accumulations.

peat_height = acro_height+cato_height

UNITS: Meters

DOCUMENT: Height of the simulated peatland, sum of acrotelm and catotelm heights.

peat_height_cm = peat_height*100

DOCUMENT: peat height in centimeters

PET = GRAPH(z)

Points: (-70.00, 1.400), (-65.3333333333, 1.700), (-60.6666666667, 2.200), (-56.00, 2.500), (-51.3333333333, 2.550), (-46.6666666667, 2.500), (-42.00, 2.400), (-37.3333333333, 2.350), (-32.6666666667, 2.550), (-28.00, 2.763), (-23.3333333333, 3.100), (-18.6666666667, 3.500), (-14.00, 3.9562), (-9.33333333333, 4.605), (-4.66666666667, 5.079), (0.00, 5.974)

DOCUMENT: potential evapotranspiration/ based on LaFleur et al 2005. adjusted to project PET above -25cm and below 10cm

Porosity = 0.9

UNITS: Dimensionless

DOCUMENT: porosity. Calculated as 0.887..... using equation by (REMEBER WHO), rounded to 0.9.

Prandom = RANDOM((P*0.9), (P*1.1), P)

DOCUMENT: randomisation of precipitation by 10%.

q = IF(TIME=0)THEN(0)ELSE(IF(TIME>=1)THEN(grad*thickness)ELSE(0))

UNITS: Centimeters

DOCUMENT: Discharge function as gradient and thickness. q = run off

ratio_for_post_decomp = GRAPH(year)

```
Points: (8000, 1.000), (8200, 0.6027), (8400, 0.3622), (8600, 0.2166),
(8800, 0.1285), (9000, 0.07516), (9200, 0.04287), (9400, 0.02333),
(9600, 0.0115), (9800, 0.004335), (10000, 0.000)
"re-establishment_of_vegetation_relationship_NPP" =
GRAPH(count_from_restoraiton)
Points: (0.00, 0.0000), (2.00, 0.02258), (4.00, 0.04301), (6.00,
0.0615), (8.00, 0.07823), (10.00, 0.09337), (12.00, 0.1071), (14.00,
0.1195), (16.00, 0.1307), (18.00, 0.1408), (20.00, 0.1500)
    DOCUMENT: ratio between 'difference between current year and
restoration start year' and restoration duration.
restoration_delay = 6
    DOCUMENT: delay period before restoration can begin.
restoration_duration = 20
Restoration_EndYear = restoration_start_year+restoration_duration
    UNITS: Years
    DOCUMENT: end year of restoration, based on start year of
restoration and restoration duration
restoration_start_year = restoration_delay+End_Year
    DOCUMENT: Year in which restoration begins. Function of extraction
end year and a restoration delay.
reusable_litter_proporiton = 0.5
    DOCUMENT: Proportion of removed litter that is available to be
reused during restoration.
smooth_massZ_relationship = SMTH1(mass_z_relationship_extraction, 5)
smooth_peat_c_acc = SMTH1(peat_C_acc, 2)
Start_Year = 8000
    UNITS: Years
    DOCUMENT: Year in which extraction begins.  Chosen as a moment in
time where the natural peat carbon store is tending to equilibrium OR
as age of field site oldest samples Riviere du Loup.
thickness = (peat_height_cm/Porosity)-z
    UNITS: Centimeters
    DOCUMENT: thickness of peat layer below water table, calculated
using z, H and porosity. = thickness * K geometric mean * gradient of
slope.  = (H-z)*K*grad
total_mass = cato_mass+acro_mass
    DOCUMENT: total peat mass, sum of catotelm and acrotelm masses.
ususable_litter_litter = reusable_litter_proporiton*removed_litter
    DOCUMENT: actual volume of litter available to be reused, function
of reusable litter proportion and removed litter.
year = TIME
    DOCUMENT: time model has been running
z = Water_Store-(peat_height_cm*Porosity)
    UNITS: Centimeters
    DOCUMENT: water table depth. Function of peat height in
centimeters, peat porosity and the water store height.
Zsmooth = SMTH1(z, 5, 0)
    UNITS: Centimeters
    DOCUMENT: smoothZ over 5 years, inital set at -20
```

Simulation including Fate of Peat Management

```
Nat_Ext_Z_FoP.stmx
{ The model has 117 (117) variables (array expansion in parens).
  In root model and 0 additional modules with 0 sectors.
  Stocks: 13 (13) Flows: 28 (28) Converters: 76 (76)
  Constants: 34 (34) Equations: 70 (70) Graphicals: 9 (9)
  There are also 15 expanded macro variables.  }

Top-Level Model:
"'AFTER_USE'"(t) = "'AFTER_USE'"(t - dt) + (after_use_transfer -
OMMS_transfer - after_use_c_out) * dt {CONVEYOR}
    INIT "'AFTER_USE'" = 0
        TRANSIT TIME = 10
    CONTINUOUS
    ACCEPT MULTIPLE BATCHES
    UNITS: grams per square meter
    DOCUMENT: Conveyor for after use of peat. Peat carbon will transfer
through the 'after used peat conveyor', after extraction disturbance
has begun, over a transit time before being emptied into an organic
matter in mineral soil stock. The after use peat conveyor also
experiences a leak function related to decomposition rate of peat in
use.
"'USED_PEAT'"(t) = "'USED_PEAT'"(t - dt) + (extraction_disturbance_acro
+ extraction_disturbance_cato - after_use_transfer - used_peat_C_out) *
dt {CONVEYOR}
    INIT "'USED_PEAT'" = 0
        TRANSIT TIME = 2
    CONTINUOUS
    ACCEPT MULTIPLE BATCHES
    UNITS: grams per square meter
    DOCUMENT: Conveyor for use of peat. Peat carbon will transfer
through the 'used peat conveyor', after extraction disturbance has
begun, over a transit time before being emptied into an after use
converyor. The used peat conveyor also experiences a leak function
related to decomposition rate of peat in use.
acrotelm(t) = acrotelm(t - dt) + (acrotelm_transfer +
restored_acrotelm_transfer - catotelm_transfer -
extraction_disturbance_acro) * dt {NON-NEGATIVE}
    INIT acrotelm = 0
    UNITS: grams per square meter
    DOCUMENT: Stock for build up of acrotelm layer. Both initial and
restored acrotelm conveyors feed into acrotelm stock. The acrotelm
stock is experiences an extraction outflow during the extraction
period. Peat carbon is emptied into the catotelm stock each dt. The
acrotelm stock also has an outflow function of decompostion and the
total acrotelm carbon store.
catotelm(t) = catotelm(t - dt) + (catotelm_transfer -
extraction_disturbance_cato - catotelm_C_out) * dt {NON-NEGATIVE}
    INIT catotelm = 0
    UNITS: grams per square meter
    DOCUMENT: Catotelm stock of peat carbon. Inflow comes from the
acrotelm. Outflow function of decompostion and the total catotelm
carbon store. The catotelm stock also experiences extraction during
extraction start and end years.
inital_acrotelm(t) = inital_acrotelm(t - dt) +
(litter_to_acrotelm_transfer - acrotelm_transfer - acro_conveyor_C_out)
* dt {CONVEYOR}
```

```
    INIT inital_acrotelm = 1
        TRANSIT TIME =
IF(TIME<Start_Year)THEN(acrotelm_tranfer_time)ELSE(IF(TIME>=Start_Year)
AND(TIME<=End_Year)THEN(1)ELSE(IF(TIME>Restoration_EndYear)THEN(acrotel
m_tranfer_time)ELSE(acrotelm_tranfer_time)))
        FIFO
    DISCRETE
    ACCEPT MULTIPLE BATCHES
    UNITS: grams per square meter
    DOCUMENT: Conveyor for build up of acrotelm layer, before
extraction. Peat carbon will transfer through the initial acrotelm over
a transit time before being emptied into a stock acrotelm. The acrotelm
conveyor also experiences a leak function related to acrotelm
decomposition.
InitialLitter(t) = InitialLitter(t - dt) + (C_in_est - litter_transfer
- Litter_conveyor_C_out) * dt {CONVEYOR}
    INIT InitialLitter = 0
        TRANSIT TIME = 1
    CONTINUOUS
    ACCEPT MULTIPLE BATCHES
    UNITS: grams per square meter
    DOCUMENT: Conveyor for build up of litter layer, before extraction.
The litter conveyor also experiences a leak function related to litter
decomposition.
litter(t) = litter(t - dt) + (litter_transfer -
litter_to_acrotelm_transfer - litter_removal) * dt {NON-NEGATIVE}
    INIT litter = 0
    UNITS: grams per square meter
    DOCUMENT: Stock for litter layer, before extraction. Litter can be
removed from this stock prior to extraction. The litter stock also has
an outflow function of decomposition and the total litter carbon store.
OM_mineral_soil(t) = OM_mineral_soil(t - dt) + (OMMS_transfer -
stabiisation_c_transfer - OMMS_C_out) * dt {NON-NEGATIVE}
    INIT OM_mineral_soil = 0
    UNITS: grams per square meter
    DOCUMENT: Stock on organic matter carbon of peat mixed with mineral
soil. Inflow comes from the after use conveyor. Outflows to stabilised
carbon and as function of decompostion of peat carbon mixed in mineral
soils and the total OMMS carbon store.
removed_litter(t) = removed_litter(t - dt) + (litter_removal -
removed_litter_c_out) * dt {NON-NEGATIVE}
    INIT removed_litter = 0
    UNITS: grams per square meter
    DOCUMENT: Stock for litter removed from the extractable litter
layer. Litter in this stock is reserved and a proportion can be reused
during restoration.  L
restaration_Litter(t) = restaration_Litter(t - dt) + (C_in_Rest -
restored_litter_to_acrotelm_transfer - restored_litter_conveyor_c_out)
* dt {CONVEYOR}
    INIT restaration_Litter = 0
        TRANSIT TIME = 1
    CONTINUOUS
    ACCEPT MULTIPLE BATCHES
    UNITS: grams per square meter
    DOCUMENT: Conveyor for build up of litter layer, after restoration.
The litter conveyor also experiences a leak function related to litter
decomposition.
```

```
restoration_acro(t) = restoration_acro(t - dt) +
(restored_litter_to_acrotelm_transfer - restored_acrotelm_transfer -
restored_acro_conveyor_C_out) * dt {CONVEYOR}
    INIT restoration_acro = 0
        TRANSIT TIME =
IF(TIME<restoration_start_year)THEN(acrotelm_tranfer_time)ELSE(IF(TIME>
=restoration_start_year)AND(TIME<=Restoration_EndYear)THEN(restoration_
duration)ELSE(IF(TIME>Restoration_EndYear)THEN(acrotelm_tranfer_time)EL
SE(acrotelm_tranfer_time)))
        FIFO
    CONTINUOUS
    ACCEPT MULTIPLE BATCHES
    UNITS: grams per square meter
    DOCUMENT: Conveyor for build up of acrotelm layer, after
restoration. Peat carbon will transfer through the restoration acrotelm
over a transit time before being emptied into the acrotelm stock. The
acrotelm conveyor also experiences a leak function related to acrotelm
decomposition.
Stab_C(t) = Stab_C(t - dt) + (stabiisation_c_transfer) * dt {NON-
NEGATIVE}
    INIT Stab_C = 0
    UNITS: grams per square meter
    DOCUMENT: Peat carbon that has been stabilised and is therefore no
longer available for decomposition.
Water_Store(t) = Water_Store(t - dt) + (water_inflow - Outflow_ET -
Outflow_surface_and_subsurface - Drainage) * dt {NON-NEGATIVE}
    INIT Water_Store = 0
    UNITS: Centimeters
    DOCUMENT: Store of water as stock, measured as a height in
centimeters.
acro_conveyor_C_out = LEAKAGE OUTFLOW
    LEAKAGE FRACTION = actual_acro_decomp
    LINEAR LEAKAGE
    LEAK ZONE = 0% to 100%
    UNITS: grams per meter square per year
    DOCUMENT: Leak outflow from acrotelm conveyor. Leak fraction is the
actual acrotelm decomposition rate.
acrotelm_transfer = CONVEYOR OUTFLOW
    UNITS: grams per meter square per year
    DOCUMENT: Main outflow from initial acrotelm layer conveyor to
acrotelm stock.
after_use_c_out = LEAKAGE OUTFLOW
    LEAKAGE FRACTION = decomp_use
    EXPONENTIAL LEAKAGE
    LEAK ZONE = 0% to 100%
    UNITS: grams per meter square per year
    DOCUMENT: C out leak fraction from peat after use, function of peat
decomposition when in use.
after_use_transfer = CONVEYOR OUTFLOW
    UNITS: grams per meter square per year
    DOCUMENT: transfer of peat C from used to after use
C_in_est =
IF(TIME<=Drainage_Start_Year)THEN(biomass_to_C*NPP_Actual)ELSE(IF(TIME>
=Drainage_Start_Year)AND(TIME<=End_Year)THEN(0)ELSE(IF(TIME>End_Year)TH
EN(0)ELSE(biomass_to_C*NPP_Actual))) {UNIFLOW}
    UNITS: grams per meter square per year
    DOCUMENT: Flow demonstrating the carbon entering the peat carbon
store.  Expressed as a function of net primary productivity and the
```

```
conversion proportion of carbon in accumulated biomass. C in flow is
limited to 0 after drainage start year.
C_in_Rest = NPP_Actual_Restoration*biomass_to_C {UNIFLOW}
    UNITS: grams per meter square per year
catotelm_C_out = catotelm*actual_cato_decomp {UNIFLOW}
    OUTFLOW PRIORITY: 2
    UNITS: grams per meter square per year
    DOCUMENT:  The catotelm stock also has an outflow function of
actual catotelm decomposition rate and the total catotelm carbon store.
catotelm_transfer =
IF(TIME<=Drainage_Start_Year)THEN(acrotelm)ELSE(IF(TIME>Drainage_Start_
Year)AND(TIME<Restoration_EndYear)THEN(0)ELSE(IF(TIME>=Restoration_EndY
ear)THEN(acrotelm)ELSE(acrotelm))) {UNIFLOW}
    OUTFLOW PRIORITY: 1
    UNITS: grams per meter square per year
    DOCUMENT: Main outflow from acrotelm stock to catotelm stock.
Drainage =
IF(TIME<Drainage_Start_Year)THEN(0)ELSE(IF(TIME>=Drainage_Start_Year)AN
D(peat_height>=min_peat_height_remaining)AND(TIME<=restoration_start_ye
ar)THEN(Water_Store*drainage_rate_extraction)ELSE(0)) {UNIFLOW}
    OUTFLOW PRIORITY: 3
    UNITS: Centimeters/years
    DOCUMENT: Drainage from water store to begin two years before
extraction, and continue until restoration. Function of drainage rate
during extraction.
extraction_disturbance_acro =
IF(TIME<Start_Year)AND(TIME>End_Year)THEN(0)ELSE(IF(acro_height<0.001)T
HEN(0)ELSE(IF(TIME>=Start_Year)AND(acro_height>0.001)AND(TIME<End_Year)
THEN(extr_racte_calc_acro)ELSE(0))) {UNIFLOW}
    INFLOW PRIORITY: 1
    OUTFLOW PRIORITY: 2
    UNITS: grams per meter square per year
    DOCUMENT: Extraction disturbance from acrotelm. Disturbance is a
function of the calculated extraction rate. Will begin when time =
start year and end when acrotelm is empty. Disturbance will only occur
in the extraction duration.
extraction_disturbance_cato =
IF(TIME<Start_Year)AND(TIME>End_Year)THEN(0)ELSE(IF(peat_height<min_pea
t_height_remaining)THEN(0)ELSE(IF(TIME>=Start_Year)AND(acro_height<0.00
1)AND(TIME<End_Year)THEN(extraction_rate_calc)ELSE(0))) {UNIFLOW}
    INFLOW PRIORITY: 2
    OUTFLOW PRIORITY: 1
    UNITS: grams per meter square per year
    DOCUMENT: Extraction disturbance from catotelm. Disturbance is a
function of the calculated extraction rate. Will begin only when time =
start year and acrotelm height is close to zero. The disturbance
outflow will continue until peat height is equal to the prescribed
minimum peat height remaining. Disturbance will only occur in the
extraction duration.
Litter_conveyor_C_out = LEAKAGE OUTFLOW
    LEAKAGE FRACTION = actual_litter_decomp
    LINEAR LEAKAGE
    LEAK ZONE = 0% to 100%
    UNITS: grams per meter square per year
    DOCUMENT: Leak outflow from litter conveyor. Leak fraction is the
litter decomposition rate.
```

```
litter_removal =
IF(TIME<Drainage_Start_Year)AND(TIME>End_Year)THEN(0)ELSE(IF(TIME>=Drai
nage_Start_Year)AND(TIME<=End_Year)THEN(litter)ELSE(0)) {UNIFLOW}
    OUTFLOW PRIORITY: 2
    UNITS: grams per meter square per year
    DOCUMENT: Litter removal from litter layer prior to extraction.
litter_to_acrotelm_transfer = litter {UNIFLOW}
    OUTFLOW PRIORITY: 1
    UNITS: grams per meter square per year
    DOCUMENT: Main outflow from litter stock to acrotelm conveyor.
litter_transfer = CONVEYOR OUTFLOW
    UNITS: grams per meter square per year
    DOCUMENT: Main outflow from initial litter layer conveyor to litter
stock.
OMMS_C_out = OM_mineral_soil*OMMS_decomp_rate {UNIFLOW}
    OUTFLOW PRIORITY: 2
    UNITS: grams per meter square per year
    DOCUMENT: Flow demonstrating the carbon leaving organic matieral
peat C in mineral soil.  Expressed as a function of OM mineral soil
decomp rate and the peat carbon store.
OMMS_transfer = CONVEYOR OUTFLOW
    UNITS: grams per meter square per year
    DOCUMENT: transfer of peat C from after use to organic matter in
mineral soil
Outflow_ET = actual_ET {UNIFLOW}
    OUTFLOW PRIORITY: 1
    UNITS: Centimeters/years
    DOCUMENT: flow of water out of the store from ET, function of
actual ET from Water Store.
Outflow_surface_and_subsurface =
IF(TIME>=restoration_start_year)AND(TIME<=Restoration_EndYear)THEN(0)EL
SE((q)) {UNIFLOW}
    OUTFLOW PRIORITY: 2
    UNITS: Centimeters/years
    DOCUMENT: Flow of water out of the store through ground, as a
function of discharge (q). Zero during restoration to reflect ditch
blocking post-extraction.


removed_litter_c_out = removed_litter*Litter_decomp {UNIFLOW}
    UNITS: grams per meter square per year
    DOCUMENT: Outflow from removed litter is a function of litter
decomposition rate and the total removed litter carbon store.
restored_acro_conveyor_C_out = LEAKAGE OUTFLOW
    LEAKAGE FRACTION = actual_acro_decomp
    LINEAR LEAKAGE
    LEAK ZONE = 0% to 100%
    UNITS: grams per meter square per year
    DOCUMENT: Leak outflow from acrotelm conveyor. Leak fraction is the
actual acrotelm decomposition rate.
restored_acrotelm_transfer = CONVEYOR OUTFLOW
    UNITS: grams per meter square per year
    DOCUMENT: Main outflow from restored acrotelm layer conveyor to
acrotelm stock.
restored_litter_conveyor_c_out = LEAKAGE OUTFLOW
    LEAKAGE FRACTION = actual_litter_decomp
    LINEAR LEAKAGE
    LEAK ZONE = 0% to 100%
```

```
    UNITS: grams per meter square per year
    DOCUMENT: Leak outflow from litter conveyor. Leak fraction is the
litter decomposition rate.
restored_litter_to_acrotelm_transfer = CONVEYOR OUTFLOW
    UNITS: grams per meter square per year
    DOCUMENT: Main outflow from restored litter layer conveyor to
restored acrotelm conveyor.
reuse_litter =
IF(TIME<=End_Year)THEN(0)ELSE(IF(TIME>End_Year)THEN(ususable_litter_lit
ter)ELSE(0)) {UNIFLOW}
    DOCUMENT: Inflow from proportion of removed litter store that is
eligible for reuse. Aims to reflect moss transfer/ ecological
restoration.
stabiisation_c_transfer = OM_mineral_soil*stabilised_proportion
{UNIFLOW}
    OUTFLOW PRIORITY: 1
    UNITS: grams per meter square per year
    DOCUMENT: transfer flow from peat carbon onganic matter mixed with
mineral soil, to stabilised peat carbon, as a function of a
stabilisation proportion and total OMMS carbon.
used_peat_C_out = LEAKAGE OUTFLOW
    LEAKAGE FRACTION = decomp_use
    EXPONENTIAL LEAKAGE
    LEAK ZONE = 0% to 100%
    UNITS: grams per meter square per year
    DOCUMENT: C out leak fraction from used peat, function of peat
decomposition when in use.
water_inflow = Prandom/mm_to_cm {UNIFLOW}
    UNITS: Centimeters/years
    DOCUMENT: flow of water into the store, function of random
precipitation and a mm to cm conversion.
acro_acc = (litter_transfer+restored_litter_to_acrotelm_transfer)-
(acro_conveyor_C_out+acrotelm_transfer+extraction_disturbance_acro+rest
ored_acro_conveyor_C_out+restored_acrotelm_transfer)
    UNITS: grams C per m2 per year
    DOCUMENT: Acrotelm carbon accumulation rate. Function of in and
outflows of carbon relating to the acrotelm stores.
acro_decomp = 0.8
    DOCUMENT: acrotelm decomposition set between 0.8 and 0.9 based on
Clymo 1990.
acro_desnity = 80
    UNITS: kilograms per cubic meter
    DOCUMENT: density of the acrotelm. Based on literature.
acro_height = (acro_mass)/(acro_desnity*kg_to_g)
    UNITS: Meters
    DOCUMENT: height of acrotelm, function of acrotelm mass, acrotelm
density and a conversion of kg to g.
acro_mass = (restoration_acro+inital_acrotelm+acrotelm)*2
    UNITS: Grams
    DOCUMENT: Sum of the masses of acrotelm conveyors and acrotelm
stock. Assumed to be double the carbon store mass, based on Clymo's
assumptions and Nigel's information (pers. comm) for biomass to carbon.
acro_z_relationship = GRAPH(Zsmooth)
Points: (-60.00, 1.1000), (-53.3333333333, 1.0750), (-46.6666666667,
1.0500), (-40.00, 1.0250), (-33.3333333333, 1.0000), (-26.6666666667,
0.9750), (-20.00, 0.9500), (-13.3333333333, 0.9250), (-6.66666666667,
0.9000), (0.00, 0.8750), (6.66666666667, 0.8500), (13.3333333333,
0.8250), (20.00, 0.8000)
```

```
    DOCUMENT: relationship between water table and acrotelm
decomposition by 10% above/below acro_decomp, based on literature.
acrotelm_tranfer_time = 150
actual_acro_decomp =
IF(TIME<Start_Year)THEN(acro_z_relationship*acro_decomp)ELSE(IF(TIME>=S
tart_Year)AND(TIME<=End_Year)THEN(0.01)ELSE(IF(TIME>End_Year)THEN(acro_
decomp*acro_z_relationship)ELSE(acro_decomp*acro_z_relationship)))
    DOCUMENT: Actual acrotelm decomposition rate, function of acrotelm
z relationship and acrotelm decomposition. Also related to extraction
period.
actual_cato_decomp = IF(TIME<Drainage_Start_Year)THEN(cato_decomp)
ELSE(IF(TIME>=Drainage_Start_Year)AND(TIME<=Restoration_EndYear)THEN(sm
ooth_massZ_relationship)
ELSE(IF(TIME>Restoration_EndYear)AND(TIME<=restoration_start_year+3*acr
otelm_tranfer_time/2)THEN(smooth_massZ_relationship)
ELSE(IF(TIME>restoration_start_year+3*acrotelm_tranfer_time/2)AND(TIME<
=restoration_start_year+2*acrotelm_tranfer_time)THEN((smooth_massZ_rela
tionship+cato_decomp)/2)
ELSE(IF(TIME>restoration_start_year+acrotelm_tranfer_time)THEN((smooth_
massZ_relationship+cato_decomp)/2) ELSE(cato_decomp)))))
    DOCUMENT: actual decomposition rate in catotelm. During extraction,
function of relationship between catotelm mass and z, and catotelm
decomposition. Otherwise function of catotelm decomposition and total
catotelm carbon store.


    IF(TIME<Drainage_Start_Year)THEN(cato_decomp)

ELSE(IF(TIME>=Drainage_Start_Year)AND(TIME<=restoration_start_year+acro
telm_tranfer_time)THEN(smooth_massZ_relationship)ELSE(IF(TIME>restorati
on_start_year+acrotelm_tranfer_time)AND(TIME<=restoration_start_year+10
*acrotelm_tranfer_time)THEN(((cato_decomp)+(3*smooth_massZ_relationship
))/4)ELSE(IF(TIME>restoration_start_year+10*acrotelm_tranfer_time)AND(T
IME<=restoration_start_year+20*acrotelm_tranfer_time)THEN(((cato_decomp
)+(smooth_massZ_relationship))/2)

ELSE(IF(TIME>restoration_start_year+20*acrotelm_tranfer_time)AND(TIME<=
restoration_start_year+40*acrotelm_tranfer_time)THEN(((3*cato_decomp)+(
smooth_massZ_relationship))/4)
    ELSE(cato_decomp)))))

    IF(TIME<Drainage_Start_Year)THEN(cato_decomp)

ELSE(IF(TIME>=Drainage_Start_Year)AND(TIME<=restoration_start_year+acro
telm_tranfer_time)THEN(smooth_massZ_relationship)ELSE(IF(TIME>restorati
on_start_year+acrotelm_tranfer_time)AND(TIME<=restoration_start_year+50
*acrotelm_tranfer_time)THEN(((cato_decomp)+(3*smooth_massZ_relationship
))/4)ELSE(cato_decomp)))))

    IF(TIME<Drainage_Start_Year)THEN(cato_decomp)

ELSE(IF(TIME>=Drainage_Start_Year)AND(TIME<=restoration_start_year+acro
telm_tranfer_time)THEN(smooth_massZ_relationship)ELSE(IF(TIME>restorati
on_start_year+acrotelm_tranfer_time)THEN(cato_decomp)ELSE(cato_decomp))
)


    IF(TIME<Drainage_Start_Year)THEN(cato_decomp)
```

```
ELSE(IF(TIME>=Drainage_Start_Year)AND(TIME<=Restoration_EndYear)THEN(sm
ooth_massZ_relationship)

ELSE(IF(TIME>Restoration_EndYear)AND(TIME<=restoration_start_year+3*acr
otelm_tranfer_time/2)THEN(smooth_massZ_relationship)

ELSE(IF(TIME>restoration_start_year+3*acrotelm_tranfer_time/2)AND(TIME<
=restoration_start_year+2*acrotelm_tranfer_time)THEN((smooth_massZ_rela
tionship+cato_decomp)/2)

ELSE(IF(TIME>restoration_start_year+acrotelm_tranfer_time)THEN((smooth_
massZ_relationship+cato_decomp)/2)
    ELSE(cato_decomp)))))
actual_ET = IF(z>=-70)THEN(ETrandom*PET)ELSE(IF(z<-70)THEN(0)ELSE(0))
    UNITS: Centimeters
    DOCUMENT: actual evapotranspiration based on relationship between
depth of the water table, baseline ET and potential ET
actual_litter_decomp =
IF(TIME>STARTTIME+1)AND(TIME<STARTTIME+establishment_delay)THEN(Litter_
decomp/litter_est_relationship)ELSE(IF(TIME>=STARTTIME+establishment_de
lay)THEN(Litter_decomp)ELSE(Litter_decomp))
annual_emissions =
(acro_conveyor_C_out+catotelm_C_out+Litter_conveyor_C_out+restored_litt
er_conveyor_c_out+restored_acro_conveyor_C_out)-(C_in_est+C_in_Rest)
biomass_to_C = .5
    DOCUMENT: Proportion of biomass produced that contains carbon.
From numbers given by Nigel.
C_in_flows = C_in_est+C_in_Rest
    DOCUMENT: Sum of all C in flows
C_Out_Flows =
restored_litter_conveyor_c_out+Litter_conveyor_C_out+catotelm_C_out+res
tored_acro_conveyor_C_out+acro_conveyor_C_out+removed_litter_c_out+used
_peat_C_out+OMMS_C_out+after_use_c_out
    DOCUMENT: Sum of all C outflows


restored_litter_conveyor_c_out+Litter_conveyor_C_out+catotelm_C_out+acr
o_conveyor_C_out+restored_acro_conveyor_C_out+Flow_1
cato_acc = (restored_acrotelm_transfer+acrotelm_transfer)-
(catotelm_C_out+extraction_disturbance_cato)
    UNITS: grams C per m2 per year
    DOCUMENT: Catotelm carbon accumulation rate. Function of in and
outflows of carbon relating to the catotelm stores.
cato_decomp = 0.00025
    DOCUMENT: Rate of decomposition that occurs in the peat column
below the water table.  Based on a combination of Hilbert et al 2000,
and frolking et al 2001, which place this value between 0.0001 and
0.0003, but more commonly as a rate of 0.00025 per year.
cato_density = 80
    UNITS: kilograms per cubic meter
    DOCUMENT: desnity of the catotelm, based on literature.
cato_height = (cato_mass)/(cato_density*kg_to_g)
    UNITS: Meters
    DOCUMENT: Height of the catotelm, calculated as a function of peat
mass, peat density, and the conversion from kg to g.
cato_mass = catotelm*2
    UNITS: Grams
```

DOCUMENT: The accumulated mass of catotelm peat, from the peat carbon store. Assumed to be double the carbon store mass, based on Clymo's assumptions and Nigel's information (pers. comm) for biomass to carbon.
count_from_restoraiton = year-restoration_start_year
DOCUMENT: difference between current year and restoration start year.
decomp_use = 0.05
UNITS: Dimensionless
DOCUMENT: decomposition rate of peat in/ after use. Value educated guess, not well studied in literature.
drainage_rate_extraction = .5
DOCUMENT: Drainage rate during extraction. Value informed by sensitivity analysis to empty water store to a depth that Industry aims for prior to extraction.
Drainage_Start_Year = Start_Year-2
UNITS: Years
DOCUMENT: Set to begin two years before the extraction start year.
End_Year = extraction_duration+Start_Year
UNITS: Years
DOCUMENT: Year extraction ends, function of extraction start year and extraction duration.
establishment_delay = 200
ET0 = 25
UNITS: Centimeters
DOCUMENT: baseline Evapotranspiration. good starting value: 20-35 (25 best)
ETrandom = RANDOM((ET0*0.9), (ET0*1.1), ET0)
DOCUMENT: randomisation of evapotranspiration by 10%.
extr_racte_calc_acro = extraction_depth_per_year*(kg_to_g*extraction_acro_desnity)
UNITS: grammes per meter square per year
extraction_acro_desnity = 80
extraction_catotelm_density = 120
UNITS: kilograms per cubic meter
DOCUMENT: Density of catotelm during extraction
extraction_depth_per_year = 0.04
UNITS: meters per year
DOCUMENT: depth of extraction per year
extraction_duration = 33.5
DOCUMENT: time for which extraction can occur. Based on this simulation, a 0.06 extraction rate will run for 15 years, 0.04 for 22 years and a 0.02 for 42 years before minimum peat height is reached.
extraction_rate_calc = extraction_depth_per_year*(kg_to_g*extraction_catotelm_density)
UNITS: grams per meter square per year
DOCUMENT: Extraction rate per year calculated as a function of extraction depth per year, peat density during extraction and kg to g conversion. Ranges between 2.4k g yr-1 and 7.2k g yr-1, most influenced by extraction depth per year.

grad = 0.001
UNITS: Dimensionless
DOCUMENT: gradient of H/L assuming growth of 1m H = 1000m W to eveuntally 5m H = 5000m W --> H/L = 0.001 dim.
kg_to_g = 1000
DOCUMENT: conversion of kilograms to grams for calculations.

```
Litter_decomp = .3
    DOCUMENT: Decomposition rate of the litter layer, set at 0.3 based
on literature.
litter_est_relationship = GRAPH(year)
Points: (0.0, 0.1000), (20.0, 0.4576), (40.0, 0.6740), (60.0, 0.8050),
(80.0, 0.8843), (100.0, 0.9324), (120.0, 0.9614), (140.0, 0.9790),
(160.0, 0.9897), (180.0, 0.9961), (200.0, 1.0000)
mass_z_relationship_extraction = IF(TIME>=200)THEN((((-2.4*z)-
0.94)/0.6)/cato_mass)ELSE(0)
    DOCUMENT: Catotelm decompostion factor based on catotelm mass and
z, based on He et al 2023.
mean_smooth_peat_c = MEAN(smooth_peat_c_acc, 10)
min_peat_height_remaining = 1
    UNITS: Meters
    DOCUMENT: minimum peat height that must be preserved in the
catotelm after extraction. 1m should be preserved to avoid mineral
layer-peat contamination according to literature. PremierTech 17ft ~5m
peatland, expect more than 1-2m remaining.
mm_to_cm = 10
    UNITS: Dimensionless
    DOCUMENT: conversion from mm to cm
net_flows = C_Out_Flows-C_in_flows
NPP = 600
    DOCUMENT: Net primary productivity of the system, refers to the
energy stored as biomass by vegetation as it grows.  Numbers from
Clymo, Frolking et al 2001, Frolking et al 2010 and Basiliko et al
2006.  Range between 400 and 600.
NPP_Actual =
IF(TIME<STARTTIME+establishment_delay)THEN(NPP*NPP_z_relationship*NPP_v
eg_est_relationship)ELSE(IF(TIME>=STARTTIME+establishment_delay)AND(TIM
E<Start_Year)THEN(NPP*NPP_z_relationship)ELSE(NPP*NPP_z_relationship))
    DOCUMENT: Actual net primary productivity. Before drainage and
after restoration is complete, function of  NPP and the relationship
between water table depth and NPP. During restoration also a function
of ration restoration time. Restricted by time, with actual NPP equal
to zero during extraction and before restoration.



IF(TIME<Start_Year)THEN(NPP*NPP_z_relationship)ELSE(IF(TIME>=Start_Year
)AND(TIME<restoration_start_year)THEN(0)ELSE(IF(TIME>=restoration_start
_year)AND(TIME<Restoration_EndYear)THEN(2*ratio_restoration_time*NPP*NP
P_z_relationship)ELSE(IF(TIME>=Restoration_EndYear)AND(TIME<Restoration
_EndYear+50)THEN(NPP*NPP_z_relationship/2)ELSE(IF(TIME>=Restoration_End
Year+50)THEN(NPP*NPP_z_relationship)ELSE(NPP*NPP_z_relationship)))))
NPP_Actual_Restoration =
IF(TIME<restoration_start_year)THEN(0)ELSE(IF(TIME>=restoration_start_y
ear)AND(TIME<Restoration_EndYear)THEN("re-
establishment_of_vegetation_relationship_NPP"*NPP_Restoration*NPP_z_rel
ationship)ELSE(IF(TIME>=Restoration_EndYear)AND(TIME<Restoration_EndYea
r+establishment_delay)THEN(NPP_veg_REST_relatioship*NPP_Restoration*NPP
_z_relationship)ELSE(IF(TIME>=Restoration_EndYear+establishment_delay)T
HEN(NPP*NPP_z_relationship)ELSE(NPP*NPP_z_relationship))))
NPP_Restoration = GRAPH(establishment_delay)
Points: (1.0, 0.0), (20.9, 7.579), (40.8, 26.05), (60.7, 69.92), (80.6,
160.6), (100.5, 300.0), (120.4, 439.4), (140.3, 530.1), (160.2, 574.0),
(180.1, 592.4), (200.0, 600.0)
```

```
    DOCUMENT:
IF(TIME<STARTTIME+establishment_delay)THEN(NPP*NPP_z_relationship*ratio
)ELSE(IF(TIME<Start_Year)THEN(NPP*NPP_z_relationship)ELSE(IF(TIME>=Star
t_Year)AND(TIME<restoration_start_year)THEN(0)ELSE(IF(TIME>=restoration
_start_year)AND(TIME<Restoration_EndYear)THEN(NPP*NPP_z_relationship*ra
tio_restoration_time)ELSE(IF(TIME>=Restoration_EndYear)AND(TIME<Restora
tion_EndYear+establishment_delay)THEN(NPP*NPP_z_relationship*ratio2)ELS
E(IF(TIME>=Restoration_EndYear+establishment_delay)THEN(NPP*NPP_z_relat
ionship)ELSE(NPP*NPP_z_relationship))))))
NPP_veg_est_relationship = GRAPH(year)
Points: (0.0, 0.000), (20.0, 0.1505), (40.0, 0.2868), (60.0, 0.410),
(80.0, 0.5215), (100.0, 0.6225), (120.0, 0.7138), (140.0, 0.7964),
(160.0, 0.8711), (180.0, 0.9388), (200.0, 1.000)
NPP_veg_REST_relatioship = GRAPH(count_from_restoraiton)
Points: (0.0, 0.000), (20.0, 0.1505), (40.0, 0.2868), (60.0, 0.410),
(80.0, 0.5215), (100.0, 0.6225), (120.0, 0.7138), (140.0, 0.7964),
(160.0, 0.8711), (180.0, 0.9388), (200.0, 1.000)
NPP_z_relationship = GRAPH(Zsmooth)
Points: (-60.00, 0.000), (-59.2424242424, 0.040404040404), (-
58.4848484848, 0.0799835085549), (-57.7272727273, 0.118738404453), (-
56.9696969697, 0.156668728097), (-56.2121212121, 0.193774479489), (-
55.4545454545, 0.230055658627), (-54.696969697, 0.265512265512), (-
53.9393939394, 0.300144300144), (-53.1818181818, 0.333951762523), (-
52.4242424242, 0.366934652649), (-51.6666666667, 0.399092970522), (-
50.9090909091, 0.430426716141), (-50.1515151515, 0.460935889507), (-
49.3939393939, 0.49062049062), (-48.6363636364, 0.519480519481), (-
47.8787878788, 0.547515976087), (-47.1212121212, 0.574726860441), (-
46.3636363636, 0.601113172542), (-45.6060606061, 0.626674912389), (-
44.8484848485, 0.651412079983), (-44.0909090909, 0.675324675325), (-
43.3333333333, 0.698412698413), (-42.5757575758, 0.720676149248), (-
41.8181818182, 0.742115027829), (-41.0606060606, 0.762729334158), (-
40.303030303, 0.782519068233), (-39.5454545455, 0.801484230056), (-
38.7878787879, 0.819624819625), (-38.0303030303, 0.836940836941), (-
37.2727272727, 0.853432282004), (-36.5151515152, 0.869099154813), (-
35.7575757576, 0.88394145537), (-35.00, 0.897959183673), (-
34.2424242424, 0.911152339724), (-33.4848484848, 0.923520923521), (-
32.7272727273, 0.935064935065), (-31.9696969697, 0.945784374356), (-
31.2121212121, 0.955679241394), (-30.4545454545, 0.964749536178), (-
29.696969697, 0.97299525871), (-28.9393939394, 0.980416408988), (-
28.1818181818, 0.987012987013), (-27.4242424242, 0.992784992785), (-
26.6666666667, 0.997732426304), (-25.9090909091, 1.00185528757), (-
25.1515151515, 1.00515357658), (-24.3939393939, 1.00762729334), (-
23.6363636364, 1.00927643785), (-22.8787878788, 1.0101010101), (-
22.1212121212, 1.0101010101), (-21.3636363636, 1.00927643785), (-
20.6060606061, 1.00762729334), (-19.8484848485, 1.00515357658), (-
19.0909090909, 1.00185528757), (-18.3333333333, 0.997732426304), (-
17.5757575758, 0.992784992785), (-16.8181818182, 0.987012987013), (-
16.0606060606, 0.980416408988), (-15.303030303, 0.97299525871), (-
14.5454545455, 0.964749536178), (-13.7878787879, 0.955679241394), (-
13.0303030303, 0.945784374356), (-12.2727272727, 0.935064935065), (-
11.5151515152, 0.923520923521), (-10.7575757576, 0.911152339724), (-
10.00, 0.897959183673), (-9.24242424242, 0.88394145537), (-
8.48484848485, 0.869099154813), (-7.72727272727, 0.853432282004), (-
6.9696969697, 0.836940836941), (-6.21212121212, 0.819624819625), (-
5.45454545455, 0.801484230056), (-4.69696969697, 0.782519068233), (-
3.93939393939, 0.762729334158), (-3.18181818182, 0.742115027829), (-
2.42424242424, 0.720676149248), (-1.66666666667, 0.698412698413), (-
0.909090909091, 0.675324675325), (-0.151515151515, 0.651412079984),
```

(0.606060606061, 0.626674912389), (1.36363636364, 0.601113172542), (2.12121212121, 0.574726860441), (2.87878787879, 0.547515976087), (3.63636363636, 0.519480519481), (4.39393939394, 0.490620490621), (5.15151515152, 0.460935889507), (5.90909090909, 0.430426716141), (6.66666666667, 0.399092970522), (7.42424242424, 0.366934652649), (8.18181818182, 0.333951762523), (8.93939393939, 0.300144300144), (9.69696969697, 0.265512265512), (10.4545454545, 0.230055658627), (11.2121212121, 0.193774479489), (11.9696969697, 0.156668728097), (12.7272727273, 0.118738404453), (13.4848484848, 0.079983508555), (14.2424242424, 0.0404040404041), (15.00, 1.41046896385e-13)
    UNITS: Dimensionless
    DOCUMENT: Relationship between NPP and WTD. Graphic function using the equation G = k(Z0-Zmin)(Zmax-Z0), where Z0 water table depth below the peat surface cm, Z0* equilibrium water table depth below peat surface cm, Zmax maximum water table depth where G becomes zero cm, and Zmin minimum water table depth where G becomes zero

OMMS_decomp_rate = 0.06
    DOCUMENT: Rate of Organic matter in mineral soil decomposition. estimated around 0.02-0.06 based on Bidhya/ Steffy. Not well studient in literature,
P = 900
    UNITS: Millimeters
    DOCUMENT: annual precipitation set at 900mm/yr. good starting value: 850-950. Based on annual precipitation in quebec, specifically Riviere du Loup.
peat_C_acc = cato_acc+acro_acc
    UNITS: grams C per m2 per year
    DOCUMENT: peat carbon accumulation, as sum of both carbon accumulations.
peat_height = acro_height+cato_height
    UNITS: Meters
    DOCUMENT: Height of the simulated peatland, sum of acrotelm and catotelm heights.
peat_height_cm = peat_height*100
    DOCUMENT: peat height in centimeters
PET = GRAPH(z)
Points: (-70.00, 1.400), (-65.3333333333, 1.700), (-60.6666666667, 2.200), (-56.00, 2.500), (-51.3333333333, 2.550), (-46.6666666667, 2.500), (-42.00, 2.400), (-37.3333333333, 2.350), (-32.6666666667, 2.550), (-28.00, 2.763), (-23.3333333333, 3.100), (-18.6666666667, 3.500), (-14.00, 3.9562), (-9.33333333333, 4.605), (-4.66666666667, 5.079), (0.00, 5.974)
    DOCUMENT: potential evapotranspiration/ based on LaFleur et al 2005. adjusted to project PET above -25cm and below 10cm
Porosity = 0.9
    UNITS: Dimensionless
    DOCUMENT: porosity. Calculated as 0.887..... using equation by (REMEBER WHO), rounded to 0.9.
Prandom = RANDOM((P*0.9), (P*1.1), P)
    DOCUMENT: randomisation of precipitation by 10%.
q = IF(TIME=0)THEN(0)ELSE(IF(TIME>=1)THEN(grad*thickness)ELSE(0))
    UNITS: Centimeters
    DOCUMENT: Discharge function as gradient and thickness. q = run off
ratio_for_post_decomp = GRAPH(year)

```
Points: (8000, 1.000), (8200, 0.6027), (8400, 0.3622), (8600, 0.2166),
(8800, 0.1285), (9000, 0.07516), (9200, 0.04287), (9400, 0.02333),
(9600, 0.0115), (9800, 0.004335), (10000, 0.000)
"re-establishment_of_vegetation_relationship_NPP" =
GRAPH(count_from_restoraiton)
Points: (0.00, 0.0000), (2.00, 0.02258), (4.00, 0.04301), (6.00,
0.0615), (8.00, 0.07823), (10.00, 0.09337), (12.00, 0.1071), (14.00,
0.1195), (16.00, 0.1307), (18.00, 0.1408), (20.00, 0.1500)
    DOCUMENT: ratio between 'difference between current year and
restoration start year' and restoration duration.
restoration_delay = 0
    DOCUMENT: delay period before restoration can begin.
restoration_duration = 20
Restoration_EndYear = restoration_start_year+restoration_duration
    UNITS: Years
    DOCUMENT: end year of restoration, based on start year of
restoration and restoration duration
restoration_start_year = restoration_delay+End_Year
    DOCUMENT: Year in which restoration begins. Function of extraction
end year and a restoration delay.
reusable_litter_proporiton = 0.5
    DOCUMENT: Proportion of removed litter that is available to be
reused during restoration.
smooth_massZ_relationship = SMTH1(mass_z_relationship_extraction, 5)
smooth_peat_c_acc = SMTH1(peat_C_acc, 2)
stabilised_proportion = .1
    DOCUMENT: rate of C stabilisation from OM in mineral soil to
burial. Estimated between 10% and 50% of OM in mineral soil. Not well
studied in literature.
Start_Year = 8000
    UNITS: Years
    DOCUMENT: Year in which extraction begins.  Chosen as a moment in
time where the natural peat carbon store is tending to equilibrium OR
as age of field site oldest samples Riviere du Loup.
thickness = (peat_height_cm/Porosity)-z
    UNITS: Centimeters
    DOCUMENT: thickness of peat layer below water table, calculated
using z, H and porosity. = thickness * K geometric mean * gradient of
slope.  = (H-z)*K*grad
total_mass = cato_mass+acro_mass
    DOCUMENT: total peat mass, sum of catotelm and acrotelm masses.
ususable_litter_litter = reusable_litter_proporiton*removed_litter
    DOCUMENT: actual volume of litter available to be reused, function
of reusable litter proportion and removed litter.
year = TIME
    DOCUMENT: time model has been running
z = Water_Store-(peat_height_cm*Porosity)
    UNITS: Centimeters
    DOCUMENT: water table depth. Function of peat height in
centimeters, peat porosity and the water store height.
Zsmooth = SMTH1(z, 5, 0)
    UNITS: Centimeters
    DOCUMENT: smoothZ over 5 years, initial set at -20
```

Appendix II

Table of Contents

SUPPLEMENTARY TABLES

Stocks

Table 1: the 13 Model stocks, with their defining information.

	NAME	EQUATION	PROPERTIES	UNITS	DOCUMENTATION	ANNOTATION
TOP-LEVEL MODEL:						
M_{AU}	"'AFTER_USE'"(t)	"'AFTER_USE'"(t - dt) + (after_use_transfer - OMMS_transfer - after_use_c_out) * dt	INIT "'AFTER_USE'" = 0 TRANSIT TIME = 5 CONTINUOUS ACCEPT MULTIPLE BATCHES	grams per square meter	Conveyor for after use of peat. Peat carbon will transfer through the 'after used peat conveyor', after extraction disturbance has begun, over a transit time before being emptied into an organic matter in mineral soil stock. The after-use peat conveyor also experiences a leak function related to decomposition rate of peat in use.	CONVEYOR
M_U	"'USED_PEAT'"(t)	"'USED_PEAT'"(t - dt) + (extraction_disturbance_cato + extraction_disturbance_acro - after_use_transfer - used_peat_C_out) * dt	INIT "'USED_PEAT'" = 0 TRANSIT TIME = 1 CONTINUOUS ACCEPT MULTIPLE BATCHES	grams per square meter	Conveyor for use of peat. Peat carbon will transfer through the 'used peat conveyor', after extraction disturbance has begun, over a transit time before being emptied into an after-use conveyor. The used peat conveyor also experiences a leak function related to decomposition rate of peat in use.	CONVEYOR
M_A	acrotelm(t)	acrotelm(t - dt) + (acrotelm_transfer + restored_acrotelm_transfer - catotelm_transfer - extraction_disturbance_acro - acro_stock_c_out) * dt	INIT acrotelm = 0	grams per square meter	Stock for build-up of acrotelm layer. Both initial and restored acrotelm conveyors feed into acrotelm stock. The acrotelm stock is experiences an extraction outflow during the extraction period. Peat carbon is emptied into the catotelm stock each dt. The acrotelm stock also has an outflow function of decomposition and the total acrotelm carbon store.	NON-NEGATIVE
M_C	catotelm(t)	catotelm(t - dt) + (catotelm_transfer - extraction_disturbance_cato - catotelm_C_out) * dt	INIT catotelm = 0	grams per square meter	Catotelm stock of peat carbon. Inflow comes from the acrotelm. Outflow function of decomposition and the total catotelm carbon store. The catotelm stock also experiences extraction during extraction start and end years.	NON-NEGATIVE
M_A	inital_acrotelm(t)	inital_acrotelm(t - dt) + (litter_to_acrotelm_transfer -	INIT inital_acrotelm = 1 TRANSIT TIME = IF(TIME<Start_Year)THEN(150)E	grams per square meter	Conveyor for build up of acrotelm layer, before extraction. Peat carbon will transfer through the initial acrotelm over a transit time	CONVEYOR

		acrotelm_transfer - acro_conveyor_C_out) * dt	LSE(IF(TIME>=Start_Year)AND(TIME<=End_Year)THEN(1)ELSE(IF(TIME>Restoration_EndYear)THEN(150)ELSE(150))) FIFO DISCRETE ACCEPT MULTIPLE BATCHES		before being emptied into a stock acrotelm. The acrotelm conveyor also experiences a leak function related to acrotelm decomposition.	
M_L	InitialLitter(t)	InitialLitter(t - dt) + (C_in - litter_transfer - Litter_conveyor_C_out) * dt	INIT InitialLitter = 0 TRANSIT TIME = 1 CONTINUOUS ACCEPT MULTIPLE BATCHES	grams per square meter	Conveyor for build-up of litter layer, before extraction. The litter conveyor also experiences a leak function related to litter decomposition.	CONVEYOR
M_L	litter(t)	litter(t - dt) + (litter_transfer - litter_to_acrotelm_transfer - litter_removal - litter_stock_c_out) * dt	INIT litter = 0	grams per square meter	Stock for litter layer, before extraction. Litter can be removed from this stock prior to extraction. The litter stock also has an outflow function of decomposition and the total litter carbon store.	NON-NEGATIVE
M_{MS}	OM_mineral_soil (t)	OM_mineral_soil(t - dt) + (OMMS_transfer - stabiisation_c_transfer - OMMS_C_out) * dt	INIT OM_mineral_soil = 0	grams per square meter	Stock on organic matter carbon of peat mixed with mineral soil. Inflow comes from the after-use conveyor. Outflows to stabilised carbon and as function of decomposition of peat carbon mixed in mineral soils and the total OMMS carbon store.	NON-NEGATIVE
M_L	removed_litter(t)	removed_litter(t - dt) + (litter_removal - removed_litter_c_out) * dt	INIT removed_litter = 0	grams per square meter	Stock for litter removed from the extractable litter layer. Litter in this stock is reserved and a proportion can be reused during restoration. L	NON-NEGATIVE
M_L	restoration_Litter (t)	restoration_Litter(t - dt) + (rest_c_in + reuse_litter - restored_litter_to_acrotelm_transfer - restored_litter_conveyor_c_out) * dt	INIT restaration_Litter = 0 TRANSIT TIME = 1 CONTINUOUS ACCEPT MULTIPLE BATCHES	grams per square meter	Conveyor for build-up of litter layer, after restoration. The litter conveyor also experiences a leak function related to litter decomposition.	CONVEYOR
M_A	restoration_acro(t)	restoration_acro(t - dt) + (restored_litter_to_acrotelm_transfer - restored_acrotelm_transfer - restored_acro_conveyor_C_out) * dt	INIT restoration_acro = 0 TRANSIT TIME = 150 CONTINUOUS ACCEPT MULTIPLE BATCHES	grams per square meter	Conveyor for build-up of acrotelm layer, after restoration. Peat carbon will transfer through the restoration acrotelm over a transit time before being emptied into the acrotelm stock. The acrotelm conveyor also experiences a leak function related to acrotelm decomposition.	CONVEYOR
M_S	Stab_C(t)	Stab_C(t - dt) + (stabiisation_c_transfer) * dt	INIT Stab_C = 0	grams per square meter	Peat carbon that has been stabilised and is therefore no longer available for decomposition.	NON-NEGATIVE
W	Water_Store(t)	Water_Store(t - dt) + (water_inflow - Outflow_ET - Outflow_ground - Drainage) * dt	INIT Water_Store = 0	Centimeters	Store of water as stock, measured as a height in centimeters.	NON-NEGATIVE

Flows

Table 2: the 30 flows, with associated information

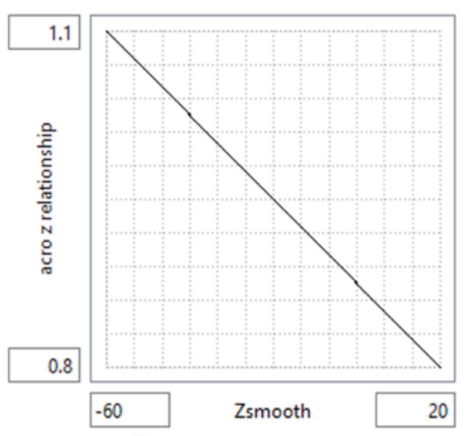
NAME	EQUATION	PROPERTIES	UNITS	DOCUMENTATION	ANNOTATION
ACRO_CONVEYOR_C_OUT	LEAKAGE OUTFLOW	LEAKAGE FRACTION = actual_acro_decomp LINEAR LEAKAGE LEAK ZONE = 0% to 100%	grams per meter square per year	Leak outflow from acrotelm conveyor. Leak fraction is the actual acrotelm decomposition rate.	
ACROTELM_TRANSFER	CONVEYOR OUTFLOW		grams per meter square per year	Main outflow from initial acrotelm layer conveyor to acrotelm stock.	
AFTER_USE_C_OUT	LEAKAGE OUTFLOW	LEAKAGE FRACTION = decomp_use EXPONENTIAL LEAKAGE LEAK ZONE = 0% to 100%	grams per meter square per year	C out leak fraction from peat after use, function of peat decomposition when in use.	
AFTER_USE_TRANSFER	CONVEYOR OUTFLOW		grams per meter square per year	transfer of peat C from used to after use	
C_IN_EST	IF(TIME<=Drainage_Start_Year)THEN(biomass_to_C*NPP_Actual)ELSE(IF(TIME>=Drainage_Start_Year)AND(TIME<=End_Year)THEN(0)ELSE(IF(TIME>End_Year)THEN(0)ELSE(biomass_to_C*NPP_Actual)))		grams per meter square per year	Flow demonstrating the carbon entering the peat carbon store as the peatland establishes. Expressed as a function of net primary productivity and the conversion proportion of carbon in accumulated biomass. C in flow is limited to 0 after drainage start year.	UNIFLOW
C_IN_REST	NPP_Actual_Restoration*biomass_to_C		grams per meter square per year	Flow demonstrating the carbon entering the peat carbon store after restoration begins. Expressed as a function of net primary productivity and the conversion proportion of carbon in accumulated biomass.	
CATOTELM_C_OUT	catotelm*actual_cato_decomp	OUTFLOW PRIORITY: 2	grams per meter square per year	The catotelm stock also has an outflow function of actual catotelm decomposition rate and the total catotelm carbon store.	UNIFLOW
CATOTELM_TRANSFER	IF(TIME<=Drainage_Start_Year)THEN(acrotelm)ELSE(IF(TIME>Drainage_Start_Year)AND(TIME<Restoration_EndYear)THEN(0)ELSE(IF(TIME>=Restoration_EndYear)THEN(acrotelm)ELSE(acrotelm)))	OUTFLOW PRIORITY: 1	grams per meter square per year	Main outflow from acrotelm stock to catotelm stock.	UNIFLOW

DRAINAGE	IF(TIME<Drainage_Start_Year)THEN(0)ELSE(IF(TIME>=Drainage_Start_Year)AND(peat_height>=min_peat_height_remaining)AND(TIME<=restoration_start_year)THEN(Water_Store*drainage_rate_extraction)ELSE(0))	OUTFLOW PRIORITY: 3	Centimeters/years	Drainage from water store to begin two years before extraction, and continue until restoration. Function of drainage rate during extraction.	UNIFLOW
EXTRACTION_DISTURBANCE_ACRO	IF(TIME<Start_Year)AND(TIME>End_Year)THEN(0)ELSE(IF(acro_height<0.001)THEN(0)ELSE(IF(TIME>=Start_Year)AND(acro_height>0.001)AND(TIME<End_Year)THEN(extraction_rate_calc)ELSE(0)))	INFLOW PRIORITY: 2 OUTFLOW PRIORITY: 2	grams per meter square per year	Extraction disturbance from acrotelm. Disturbance is a function of the calculated extraction rate. Will begin when time = start year and end when acrotelm is empty. Disturbance will only occur in the extraction duration.	UNIFLOW
EXTRACTION_DISTURBANCE_CATO	IF(TIME<Start_Year)AND(TIME>End_Year)THEN(0)ELSE(IF(peat_height<min_peat_height_remaining)THEN(0)ELSE(IF(TIME>=Start_Year)AND(acro_height<0.001)AND(TIME<End_Year)THEN(extraction_rate_calc)ELSE(0)))	INFLOW PRIORITY: 1 OUTFLOW PRIORITY: 1	grams per meter square per year	Extraction disturbance from catotelm. Disturbance is a function of the calculated extraction rate. Will begin only when time = start year and acrotelm height is close to zero. The disturbance outflow will continue until peat height is equal to the prescribed minimum peat height remaining. Disturbance will only occur in the extraction duration.	UNIFLOW
LITTER_CONVEYOR_C_OUT	LEAKAGE OUTFLOW	LEAKAGE FRACTION = Litter_decomp LINEAR LEAKAGE LEAK ZONE = 0% to 100%	grams per meter square per year	Leak outflow from litter conveyor. Leak fraction is the litter decomposition rate.	
LITTER_REMOVAL	IF(TIME<Drainage_Start_Year)AND(TIME>End_Year)THEN(0)ELSE(IF(TIME>=Drainage_Start_Year)AND(TIME<=End_Year)THEN(litter)ELSE(0))	OUTFLOW PRIORITY: 2	grams per meter square per year	Litter removal from litter layer prior to extraction.	UNIFLOW
LITTER_TO_ACROTELM_TRANSFER	litter	OUTFLOW PRIORITY: 1	grams per meter square per year	Main outflow from litter stock to acrotelm conveyor.	UNIFLOW
LITTER_TRANSFER	CONVEYOR OUTFLOW		grams per meter square per year	Main outflow from initial litter layer conveyor to litter stock.	
OMMS_C_OUT	OM_mineral_soil*OMMS_decomp_rate	OUTFLOW PRIORITY: 2	grams per meter square per year	Flow demonstrating the carbon leaving organic material peat C in mineral soil. Expressed as a function of OM mineral soil decomp rate and the peat carbon store.	UNIFLOW
OMMS_TRANSFER	CONVEYOR OUTFLOW		grams per meter square per year	transfer of peat C from after use to organic matter in mineral soil	
OUTFLOW_ET	actual_ET	OUTFLOW PRIORITY: 1	Centimeters/years	flow of water out of the store from ET, function of actual ET from Water Store.	UNIFLOW
OUTFLOW_GROUND	IF(TIME>=restoration_start_year)AND(TIME<=Restoration_EndYear)THEN(0)ELSE((q))	OUTFLOW PRIORITY: 2	Centimeters/years	Flow of water out of the store through ground, as a function of discharge (q). Zero during restoration to reflect ditch blocking post-extraction.	UNIFLOW
REMOVED_LITTER_C_OUT	removed_litter*Litter_decomp		grams per meter square per year	Outflow from removed litter is a function of litter decomposition rate and the total removed litter carbon store.	UNIFLOW

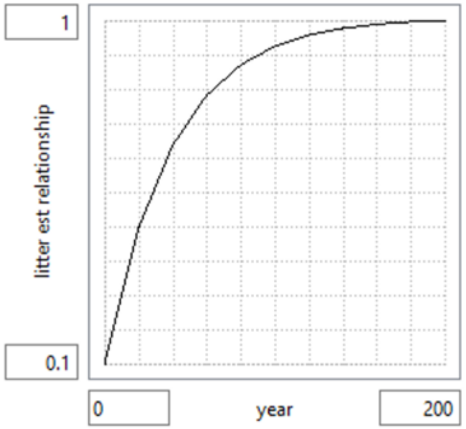
RESTORED_ACRO_CONVEYOR_C_OUT	LEAKAGE OUTFLOW	LEAKAGE FRACTION = actual_acro_decomp LINEAR LEAKAGE LEAK ZONE = 0% to 100%	grams per meter square per year	Leak outflow from acrotelm conveyor. Leak fraction is the actual acrotelm decomposition rate.	
RESTORED_ACROTELM_TRANSFER	CONVEYOR OUTFLOW		grams per meter square per year	Main outflow from restored acrotelm layer conveyor to acrotelm stock.	
RESTORED_LITTER_CONVEYOR_C_OUT	LEAKAGE OUTFLOW	LEAKAGE FRACTION = Litter_decomp LINEAR LEAKAGE LEAK ZONE = 0% to 100%	grams per meter square per year	Leak outflow from litter conveyor. Leak fraction is the litter decomposition rate.	
RESTORED_LITTER_TO_ACROTELM_TRANSFER	CONVEYOR OUTFLOW		grams per meter square per year	Main outflow from restored litter layer conveyor to restored acrotelm conveyor.	
REUSE_LITTER	IF(TIME<=End_Year)THEN(0)ELSE(IF(TIME>End_Year)THEN(ususable_litter_litter)ELSE(0))	INFLOW PRIORITY: 2	grams per meter square per year	Inflow from proportion of removed litter store that is eligible for reuse. Aims to reflect moss transfer/ ecological restoration.	UNIFLOW
STABIISATION_C_TRANSFER	OM_mineral_soil*stabilised_proportion	OUTFLOW PRIORITY: 1	grams per meter square per year	transfer flow from peat carbon organic matter mixed with mineral soil, to stabilised peat carbon, as a function of a stabilisation proportion and total OMMS carbon.	UNIFLOW
USED_PEAT_C_OUT	LEAKAGE OUTFLOW	LEAKAGE FRACTION = decomp_use EXPONENTIAL LEAKAGE LEAK ZONE = 0% to 100%	grams per meter square per year	C out leak fraction from used peat, function of peat decomposition when in use.	
WATER_INFLOW	Prandom/mm_to_cm		Centimeters/years	flow of water into the store, function of random precipitation and a mm to cm conversion.	UNIFLOW

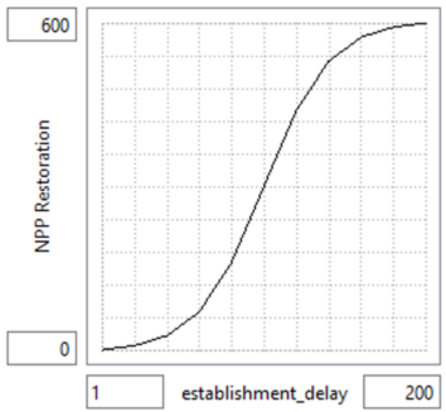
Parameters

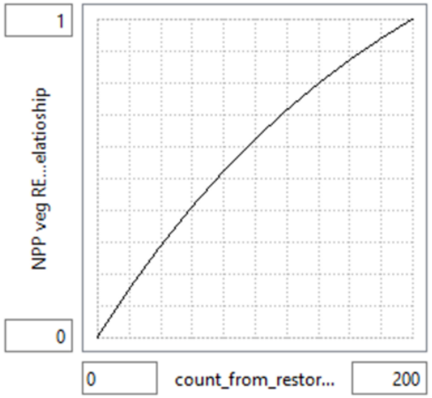
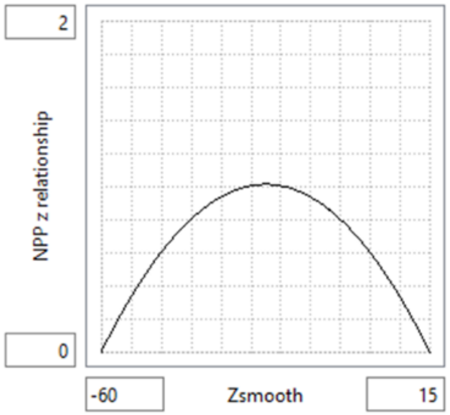
Table 3: 60 Model converters, with associated information. Where variable parameters are present, Base scenario equation values are outlined.

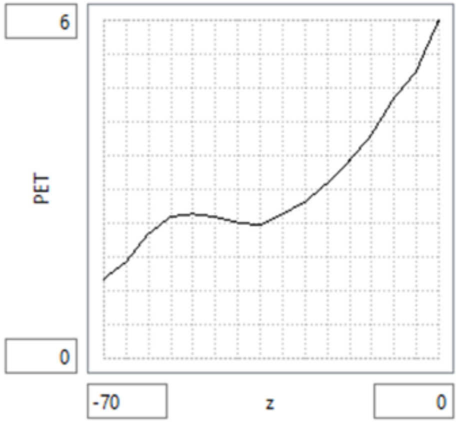
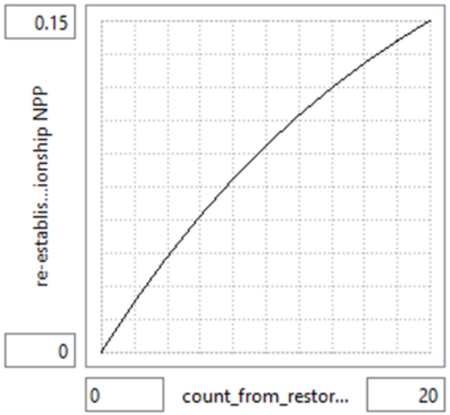
	NAME	EQUATION	UNITS	DOCUMENTATION
	acro_acc	(litter_transfer+restored_litter_to_acrotelm_transfer)-(acro_conveyor_C_out+acrotelm_transfer+extraction_disturbance_acro+restored_acro_conveyor_C_out+restored_acrotelm_transfer+acro_stock_c_out)	grams C per m2 per year	Acrotelm carbon accumulation rate. Function of in and outflows of carbon relating to the acrotelm stores.
A_2	acro_decomp	0.8	Per year	acrotelm decomposition set between 0.8 and 0.9 based on Clymo 1990.
P_A	acro_density	80	kilograms per cubic meter	density of the acrotelm. Based on literature.
H_A	acro_height	(acro_mass)/(acro_density*kg_to_g)	Meters	height of acrotelm, function of acrotelm mass, acrotelm density and a conversion of kg to g.
	acro_mass	(restoration_acro+inital_acrotelm+acrotelm)*2	Grams	Sum of the masses of acrotelm conveyors and acrotelm stock. Assumed to be double the carbon store mass, based on Clymo's assumptions and Nigel's information (pers. comm) for biomass to carbon.
	acro_z_relationship		dimensionless	relationship between water table and acrotelm decomposition by 10% above/below acro_decomp, based on literature.
	Acrotelm_transfer_time	150	Years	Time taken for biomass to transfer through the acrotelm to the catotelm
	actual_acro_decomp	IF(TIME<Start_Year)THEN(acro_z_relationship*acro_decomp)ELSE(IF(TIME>=Start_Year)AND(TIME<=End_Year)THEN(0.01)ELSE(IF(TIME>End_Year)THEN(acro_decomp*acro_z_relationship)ELSE(acro_decomp*acro_z_relationship)))	Per year	Actual acrotelm decomposition rate, function of acrotelm z relationship and acrotelm decomposition. Also related to extraction period.
	actual_cato_decomp	IF(TIME<Drainage_Start_Year)THEN(cato_decomp) ELSE(IF(TIME>=Drainage_Start_Year)AND(TIME<=Rest	Per year	actual decomposition rate in catotelm. During extraction, function of relationship between catotelm mass and z, and catotelm

		oration_EndYear)THEN(smooth_massZ_relationship) ELSE(IF(TIME>Restoration_EndYear)AND(TIME<=restoration_start_year+3*acrotelm_tranfer_time/2)THEN(smooth_massZ_relationship) ELSE(IF(TIME>restoration_start_year+3*acrotelm_tranfer_time/2)AND(TIME<=restoration_start_year+2*acrotelm_tranfer_time)THEN((smooth_massZ_relationship+cato_decomp)/2) ELSE(IF(TIME>restoration_start_year+acrotelm_tranfer_time)THEN((smooth_massZ_relationship+cato_decomp)/2) ELSE(cato_decomp)))))		decomposition. Otherwise function of catotelm decomposition and total catotelm carbon store.
ET	actual_ET	IF(z>=-70)THEN(ETrandom*PET)ELSE(IF(z<-70)THEN(0)ELSE(0))	Centimeters	actual evapotranspiration based on relationship between depth of the water table, baseline ET and potential ET
	Actual_litter_decomp	IF(TIME>STARTTIME+1)AND(TIME<STARTTIME+establishment_delay)THEN(Litter_decomp/litter_est_relationship)ELSE(IF(TIME>=STARTTIME+establishment_delay)THEN(Litter_decomp)ELSE(Litter_decomp))	Per year	Actual decomposition rate for the litter layer. Function of the relationship between litter establishment and decomp of litter. Litter establishment relates to vegetation dominance decomposition.
K	biomass_to_C	0.5	dimensionless	Proportion of biomass produced that contains carbon. From numbers given by Nigel.
	C_in_flows	C_in+rest_c_in+stabiisation_c_transfer	Grams C per m2 per year	Sum of all C in flows
	C_Out_Flows	restored_litter_conveyor_c_out+OMMS_C_out+after_use_c_out+Litter_conveyor_C_out+used_peat_C_out+catotelm_C_out+acro_conveyor_C_out+acro_stock_c_out+restored_acro_conveyor_C_out	Grams C per m2 per year	Sum of all C outflows
	cato_acc	(restored_acrotelm_transfer+acrotelm_transfer)-(catotelm_C_out+extraction_disturbance_cato)	grams C per m2 per year	Catotelm carbon accumulation rate. Function of in and outflows of carbon relating to the catotelm stores.
A_1	cato_decomp	0.00025	dimensionless	Rate of decomposition that occurs in the peat column below the water table. Based on a combination of Hilbert et al., 2000, and frolking et al., 2001, which place this value between 0.0001 and 0.0003, but more commonly as a rate of 0.00025 per year.
P_C	cato_density	80	kilograms per cubic meter	density of the catotelm, based on literature.
H_C	cato_height	(cato_mass)/(cato_density*kg_to_g)	Meters	Height of the catotelm, calculated as a function of peat mass, peat density, and the conversion from kg to g.
	cato_mass	catotelm*2	Grams	The accumulated mass of catotelm peat, from the peat carbon store. Assumed to be double the carbon store mass, based on Clymo's assumptions and Nigel's information (pers. comm) for biomass to carbon.
	count_from_restoration	year-restoration_start_year	years	difference between current year and restoration start year.
A_4	decomp_use	0.05	Dimensionless	decomposition rate of peat in/ after use. Value educated guess, not well studied in literature.
D	drainage_rate_extraction	0.5	Per year	Drainage rate during extraction. Value informed by sensitivity analysis to empty water store to a depth that Industry aims for prior to extraction.
	Drainage_Start_Year	Start_Year-2	Years	Set to begin two years before the extraction start year.

	End_Year	extraction_duration+Start_Year	Years	Year extraction ends, function of extraction start year and extraction duration.
	Establishment_delay	200	Year	the period of time it takes for a peatland to establish sphagnum as dominant vegetation type in this simulation.
ET_0	ET0	25	Centimeters	baseline Evapotranspiration. good starting value: 20-35 (25 best)
	ETrandom	RANDOM((ET0*0.9), (ET0*1.1), ET0)	dimensionless	randomisation of evapotranspiration by 10%.
P_{EX}	extraction_catotelm_density	120	kilograms per cubic meter	Density of catotelm during extraction
H_{EX}	extraction_depth_per_year	0.04	meters per year	depth of extraction per year
	extraction_duration	32	years	time for which extraction can occur. Based on this simulation, a 0.06 extraction rate will run for 15 years, 0.04 for 22 years and a 0.02 for 42 years before minimum peat height is reached.
	extraction_rate_calc	extraction_depth_per_year*(kg_to_g*extraction_catotelm_density)	grams per meter square per year	Extraction rate per year calculated as a function of extraction depth per year, peat density during extraction and kg to g conversion. Ranges between 2.4k g yr-1 and 7.2k g yr-1, most influenced by extraction depth per year.
K_W	Hydraulic gradient	0.001	Dimensionless	gradient of H/L assuming growth of 1m H = 1000m W to eventually 5m H = 5000m W --> H/L = 0.001 dim.
	kg_to_g	1000	dimensionless	conversion of kilograms to grams for calculations.
A_3	Litter_decomp	0.3	Per year	Decomposition rate of the litter layer, set at 0.3 based on literature.
	Litter_est_relationship		dimensionless	Multiplier for litter decomp as peatland establishes.
	mass_z_relationship_extraction	IF(TIME>=200)THEN((((-2.4*z)-0.94)/0.6)/cato_mass)ELSE(0)	dimensionless	Catotelm decomposition factor based on catotelm mass and z, based on He et al., 2023.
H_{MIN}	min_peat_height_remaining	1	Meters	minimum peat height that must be preserved in the catotelm after extraction. 1m should be preserved to avoid mineral layer-peat contamination according to literature. PremierTech 17ft ~5m peatland, expect more than 1-2m remaining.

	mm_to_cm	10	Dimensionless	conversion from mm to cm
	Net_Flows	C_Out_flows – C_in_Flows	G C per m2 per year	Net emissions flows as the difference between carbon outflows and carbon in flows
NPP_0	NPP	600	Grams C per m2 per year	Net primary productivity of the system, refers to the energy stored as biomass by vegetation as it grows. Numbers from Clymo, Frolking et al., 2001, Frolking et al., 2010 and Basiliko et al., 2006. Range between 400 and 600.
NPP	NPP_Actual	IF(TIME<STARTTIME+establishment_delay)THEN(NPP*NPP_z_relationship*NPP_veg_est_relationship)ELSE(IF(TIME>=STARTTIME+establishment_delay)AND(TIME<Start_Year)THEN(NPP*NPP_z_relationship)ELSE(NPP*NPP_z_relationship))	Grams c per year	Actual net primary productivity. Before drainage, function of NPP and the relationship between water table depth and NPP. During restoration also a function of ration restoration time. Restricted by time, with actual NPP equal to zero during extraction and before restoration.
	NPP Actual Restoration	IF(TIME<restoration_start_year)THEN(0)ELSE(IF(TIME>=restoration_start_year)AND(TIME<Restoration_EndYear)THEN("re-establishment_of_vegetation_relationship_NPP"*NPP_Restoration*NPP_z_relationship)ELSE(IF(TIME>=Restoration_EndYear)AND(TIME<Restoration_EndYear+establishment_delay)THEN(NPP_veg_REST_relatioship*NPP_Restoration*NPP_z_relationship)ELSE(IF(TIME>=Restoration_EndYear+establishment_delay)THEN(NPP*NPP_z_relationship)ELSE(NPP*NPP_z_relationship))))	Gram C per m2 per year	Actual net primary productivity. After extraction, function of NPP and the relationship between water table depth and NPP. During restoration also a function of ration restoration time. Restricted by time, with actual NPP equal to zero during extraction and before restoration.
	NPP Restoration		dimensionless	NPP as the peatland re-establishes after restoration. Based on the idea that vegetation cover will a) increase from sparce as part of the restoration process and b) the type of vegetation will change.

	NPP_veg_est_relationship NPP_veg_REST_relationship		dimensionless	Multiplier for NPP decomp as peatland establishes/ as it re-establishes after restoration.
NPP_Z	NPP_z_relationship		Dimensionless	Relationship between NPP and WTD. Graphic function using the equation G = k(Z0-Zmin)(Zmax-Z0), where Z0 water table depth below the peat surface cm, Z0* equilibrium water table depth below peat surface cm, Zmax maximum water table depth where G becomes zero cm, and Zmin minimum water table depth where G becomes zero
A_5	OMMS_decomp_rate	0.04	Dimensionless	Rate of Organic matter in mineral soil decomposition. estimated around 0.02-0.06 based on Bidhya/ Steffy. Not well studied in literature,
P_0	Precipitation	900	Millimeters	annual precipitation set at 900mm/yr. good starting value: 850-950. Based on annual precipitation in Quebec, specifically Riviere du Loup.
	peat_C_acc	cato_acc+acro_acc	grams C per m2 per year	peat carbon accumulation, as sum of both carbon accumulations.
H_P	peat_height	acro_height+cato_height	Meters	Height of the simulated peatland, sum of acrotelm and catotelm heights.
	peat_height_cm	peat_height*100	centimeters	peat height in centimeters

ET_Z	Potential ET with Z		dimensionless	potential evapotranspiration/ based on LaFleur et al., 2005. adjusted to project PET above -25cm and below 10cm
Φ	Porosity	0.9	Dimensionless	porosity. Calculated as 0.887, rounded to 0.9.
	Prandom	RANDOM((P*0.9), (P*1.1), P)	dimensionless	randomisation of precipitation by 10%.
Q	discharge	IF(TIME=0) THEN(0)ELSE(IF(TIME>=1)THEN(grad*thickness)ELSE(0))	Centimeters	Discharge function as gradient and thickness. q = run off
	Re-establishment_of_vegetation_relationsihp_NPP		dimensionless	Multiplier for NPP during restoration to follow Nugent 2019 pattern to 10–15-year delay before peatland starts functioning as it did before extraction.
	ratio_restoration_time	count_from_restoraiton/restoration_duration	dimensionless	ratio between 'difference between current year and restoration start year' and restoration duration.
	restoration_delay	6	years	delay period before restoration can begin.
	restoration_duration	10	Years	time for which restoration occurs
	Restoration_EndYear	restoration_start_year+restoration_duration	Years	end year of restoration, based on start year of restoration and restoration duration

	restoration_start_year	restoration_delay+End_Year	Years	Year in which restoration begins. Function of extraction end year and a restoration delay.
	reusable_litter_proporiton	0.5	Dimensionless	Proportion of removed litter that is available to be reused during restoration.
	stabilised_proportion	0.3	dimensionless	rate of C stabilisation from OM in mineral soil to burial. Estimated between 10% and 50% of OM in mineral soil. Not well studied in literature.
	Start_Year	8000	Years	Year in which extraction begins. Chosen as a moment in time where the natural peat carbon store is tending to equilibrium OR as age of field site oldest samples Riviere du Loup.
	thickness	(peat_height_cm/Porosity)-z	Centimeters	thickness of peat layer below water table, calculated using z, H and porosity. = thickness * K geometric mean * gradient of slope. = (H-z)*K*grad
Λ	total_mass	cato_mass+acro_mass	Grams C per m2	total peat mass, sum of catotelm and acrotelm masses.
	ususable_litter_litter	reusable_litter_proporiton*removed_litter	Grams C per m2	actual volume of litter available to be reused, function of reusable litter proportion and removed litter.
	year	TIME	years	time model has been running
	Water table depth	Water_Store-(peat_height_cm*Porosity)	Centimeters	water table depth. Function of peat height in centimeters, peat porosity and the water store height.
Z	Zsmooth	SMTH1(z, 5, 0)	Centimeters	smoothZ over 5 years, initial set at -20

Appendix III: Additional Fieldwork Methods and Results

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1.Methodology

1.1 FT-MIR analyses

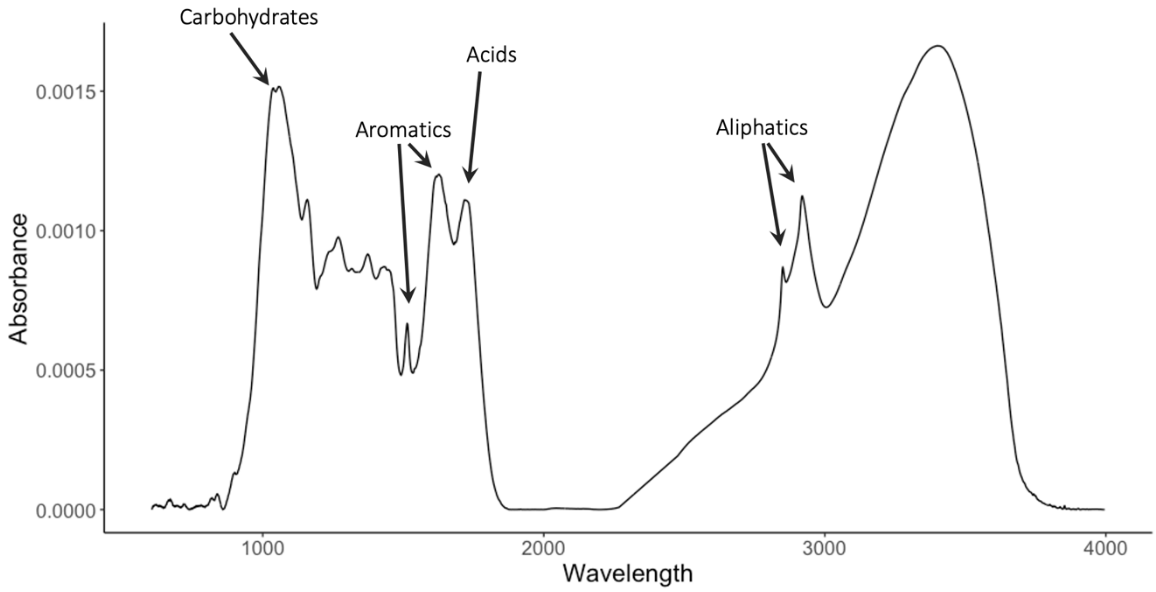
The samples sent to *WWU Münster* for Fourier transform mid-infrared (FT-MIR) spectroscopy were analysed according to FT-MIR analysis recommendations (Sharma *et al.,* 2024).

FT-MIR is a method of understanding the chemical composition of a substance based on the absorbency of different wavelengths. Each wavelength corresponds to a specific chemical signature, enabling me to identify the chemical composition of my samples.

To extract peaks from the FT-MIR data, I used the original script in Hodgkins *et al.* (2018). Long carbohydrates (polysaccharides), phenolic and aliphatic structures, aromatic and aliphatic carboxylates, carboxylic acids and aromatic esters are all identified in FT-MIR spectroscopy based on the wavelength and absorbency of their distinct chemical signatures (s.*figure 1*). A ratio of the wavelengths can then be used to assess the humification of the sample. The ratio of specific chemical signatures to that of polysaccharides (complex carbohydrates) is then used to infer humification indices (HI):

> HI_1 (1420/1090: phenolic and aliphatic structures/ polysaccharides);
> HI_2 (1510/1090: Aromatic C=C or C=0 of amides/ polysaccharides);
> HI_3 (1630/1090: aromatics and aromatic or aliphatic carboxylates/ polysaccharides); and
> HI_4 (1720/1090: carboxylic acids and aromatic esters/polysaccharides).

The greater these ratios are, the more humified a substance is said to be.

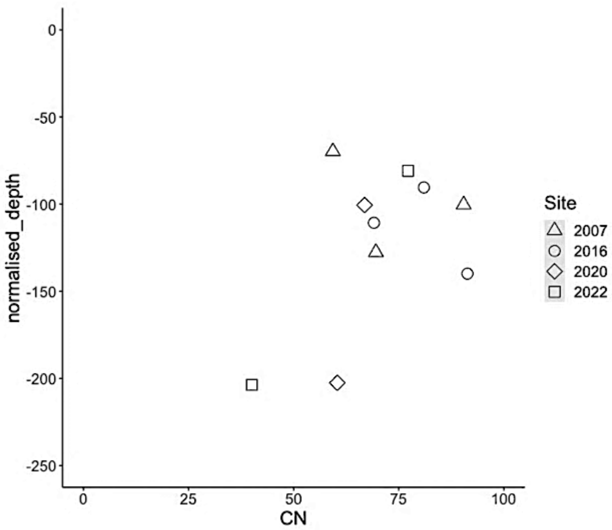


S.Figure 1: FT-MIR spectra of sample 1, with corresponding chemical identifications. Figure is based on Drollinger et al. (2020) and Teickner and Knorr (2022).

2. Results

2.1: Carbon and Nitrogen Ratio

Carbon to nitrogen (CN) ratios are often used to determine peat quality as a decrease in CN ratio suggests an increase in humification (Broder *et al.,* 2012). CN ratio typically also decreases with depth (Artz *et al*., 2008; Teickner *et al.,* 2022; Drollinger *et al.,* 2020). Our data also demonstrates a trend of CN ratio decreasing with normalised depth (s.figure 2).

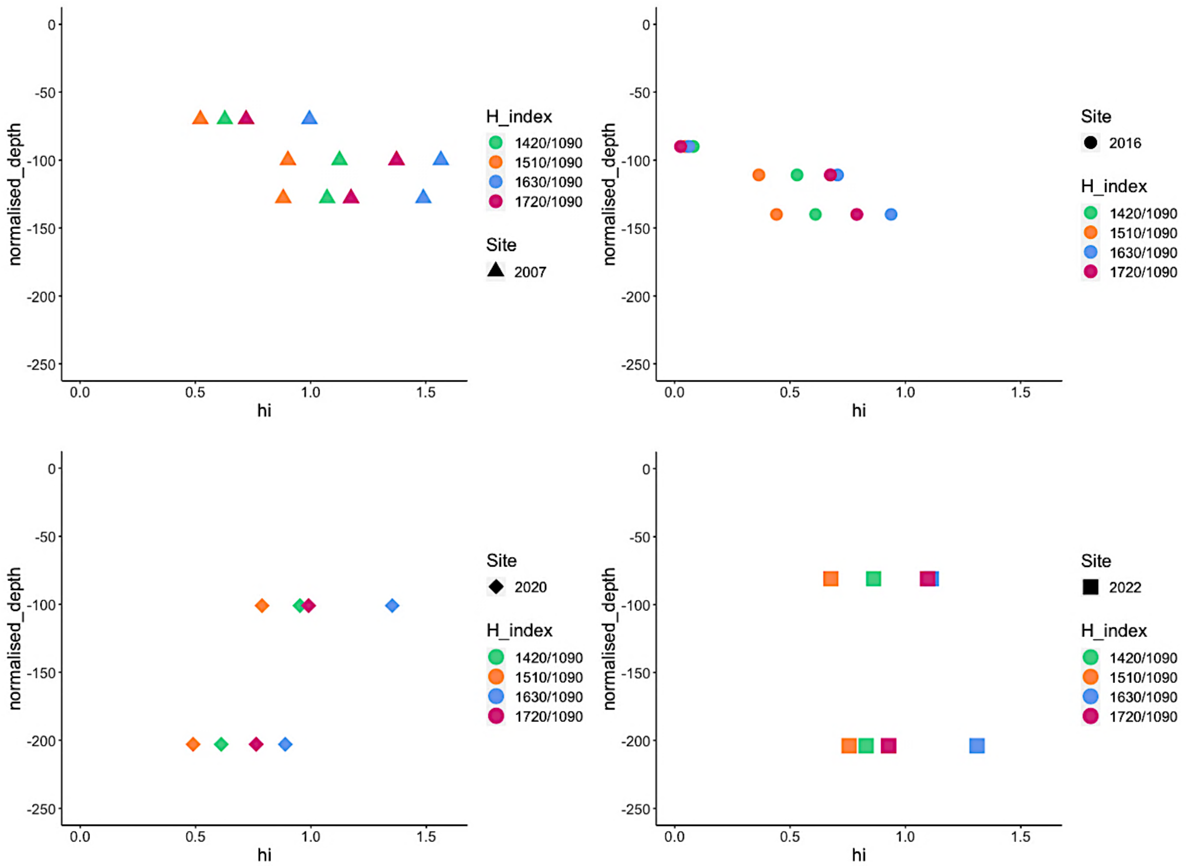


S. Figure 2: C:N ratio with normalised age-depth

2.2: FT-MIR

Humification indices analysed in FT-MIR can also be used to indicate peat quality. Humification indices are useful indicators for degradation and validation as a proxy for decomposition (Drollinger *et al.,* 2020). All our samples, excluding those at the 2020 site, show a general increase in humification with normalised depth, demonstrating increased decomposition with depth (s.figure 3). Despite samples with high mineral content being excluded, the 2020 sample at lower normalised depth may exhibit higher mineral content which could have caused the decrease in HI with depth. Alternatively, whilst the literature demonstrates a general increase in HI with depth, it is not wholly uncommon that a deeper sample may be less humified than a surface sample (Strack *pers comm.*), although the exact cause is unclear.

Humification indices are also considered more reliable than the Von Post Index humification classification, as they are not subjective and allow less space for human error. While useful on an individual platform, Von Post values are highly subjective and one author's classification may differ from another's, especially for borderline classifications. Peat type can be divided into *Sphagnum*- or *Carex*-formed classifications, often noted alongside Von Post. Instances of misclassification of peat type and Von Post have been reported in studies where the two are compared with FTIR analyses (Artz *et al.,* 2006; Granlund *et al.,* 2021). Thus, FTIR humification indices are a more reliable method of peat humification assessment, and therefore soil aggregate and nutrient stability.



S.Figure 3: Humification indices with normalised age.

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