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Development of a forested peatland carbon dynamics module for the Carbon Budget Model of the Canadian Forest Sector

Kara Webster
Clement Akumu
Jagtar Bhatti
Kelly Bona
Dimitre Dimitrov
Arlene Hilger
Werner Kurz
Cindy Shaw
Clarissa Theriault
Daniel Thompson
Stephanie Wilson

Natural Resources Canada
Canadian Forest Service

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K.L. Webster et al.

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1. Executive Summary

The aim of this three-year project, funded by NRCan, is to develop a simplified module of peatland carbon dynamics that will integrate with the national Carbon Budget Model of the Canadian Forest Sector (CBM-CFS). The module, the Canadian Model for Peatlands (CaMP), will improve our understanding of carbon dynamics to inform national carbon stock estimation and reporting of peatland carbon emissions and removals. The module will be based on knowledge of key carbon cycling processes of different peatland types (i.e., fen, bog, swamp), and will simulate carbon dynamics through empirical and process-based modelling approaches. The module will be designed to be consistent with the future (CBM-CFS4) structure of the CBM-CFS model. Development of the module is proceeding in parallel to syntheses of spatial layers and peatland databases to delineate key peatland types in Canada, their properties and key parameter values.

The development of the CaMP recognizes the unique processes that influence carbon cycling in peatlands, resulting in carbon emissions to, and removals from, the atmosphere. These include the presence of deep organic (peat) soil layers, the influence of a fluctuating water table on oxygen conditions, and new biomass pools that are not currently modelled in upland forest systems (i.e., mosses, sedges and shrubs). In addition to the emission and removal of carbon dioxide, methane emissions produced from anaerobic decomposition in the organic soil and methane removals from oxidation will be simulated in the CaMP.

The project will be implemented in two phases. In phase 1, spatial databases will be compiled to provide the “best available” spatial input layers for the model. For module calibration and evaluation, field databases will be compiled. The conceptual approach underlying the algorithms for the module will be described in a module design document. These algorithms will then be programmed and tested in selected landscapes. The initial runs of the module will use a static water table (i.e., average depth of aerobic layer for each peatland type and ecozone) and no disturbances. In a related activity, baseline national estimates of peatland atmospheric carbon emissions and removals will be produced using literature values of carbon dioxide sequestration and methane emission rates, combined with the Peatlands of Canada database of peatland types.

In phase 2, the CaMP development will continue with the plan to address: a) inclusion of a dynamic water table using relationships between water table depth and meteorological and terrain factors; b) response of carbon dynamics to soil moisture and temperature conditions and, c) disturbances (e.g., fires, insect, permafrost thaw, hydroelectric dam reservoirs, harvesting, etc.). Inclusion of disturbance data will require additional data gathering and syntheses on disturbance activities and parameterization of disturbance matrices that describe the impacts on each of the carbon pools for each disturbance type.

This work will contribute to an understanding of the natural range of variation in peatland ecosystems and of the vulnerability of carbon stocks in the boreal zone to natural and anthropogenic disturbances and climate change. Integrating knowledge of key peatland functional types, their carbon dynamics and their distribution on the landscape will allow for improved estimates of greenhouse gas emissions and removals from peatlands to be made at a national scale. The expected outcomes of this work will be:

1. A better understanding of carbon dynamics within forests on organic soils and boreal peatlands, including permafrost peatlands, and their distribution across the country.

2. National estimates of emissions and removals of carbon dioxide, methane, and (in the case of fire) N_2O, that incorporate the distribution of different types of forested peatlands and their greenhouse gas budgets given regional climate.
3. Improved knowledge of the impacts of disturbance caused by human activities and climate change on forested peatland carbon budgets.
4. Identification of key data and knowledge gaps contributing to uncertainty in estimation of peatland carbon budgets.

2. Introduction and background

2.1 Introduction

Within the boreal ecosystem, forested and peatland areas are interspersed on the landscape. Peatlands occupy wetter areas and are characterized by a decline in tree canopy cover and increases in organic layer depth (> 40 cm). The forest-peatland continuum transitions from vegetation communities characterized by forests on mineral soils with deep organic layers (0-40 cm depth) to peatlands (peat >40 cm depth) that are forested (>25% cover), treed (<25% cover) and on to more open shrub, moss or sedge dominated peatlands. These ecosystems are an important component of Canada's boreal zone, occupying a large area (1050 x 10^3 km^2; Kurz et al. 2013; Figure 1) and providing many important ecosystem services (e.g., water storage, wildlife habitat and carbon sequestration). Organic soils in the boreal zone alone contain 137 Pg of organic carbon (C) (Kurz et al. 2013), representing approximately 67% of all peatland organic C stored in Canada (Tarnocai 2006; Figure 2). Approximate 30% of the carbon in peatland organic soils within the boreal zone is contained within permafrost peatlands (Kurz et al. 2013; Figure 3).

The importance of boreal peatlands in the carbon balance of Canada and the globe has been recognized for decades but we still have very poor understanding of the distribution of peatlands on the landscape and their net greenhouse gas balance at a national level. Using a very simplistic approach to estimate the greenhouse gas balance of peatlands in Canada, Kurz et al. (1992) estimated a peatland area of 93.5 Mha with a net carbon accumulation of 26.2 Mt C yr^{-1} and a methane release of 0.5 Mt C yr^{-1} (or 12.5 Mt CO_2e yr^{-1}). Kurz et al. (1992) did not attempt to quantify the impacts of disturbances, in particular fire, on the greenhouse gas balance of peatlands. These estimates are in line with other estimates for net C accumulation between 25 and 37 Mt C yr^{-1} (Roulet 2000), but a bit lower than estimates of methane release of 2 to 5 Mt C yr^{-1} (Moore and Roulet 1995; Roulet 2000).

Of particular concern is the uncertainty in the future C balance due to susceptibility of peatlands, particularly permafrost peatlands, to global warming (Figure 4) and effects of increased fire frequency and intensity, pressure from management activities such as harvesting of trees or peat, and exploration and extraction of natural resources, including oil, gas, and minerals.

This knowledge gap in national peatland carbon budgeting must be addressed to satisfy growing international pressure for better carbon estimation and reporting of organic soils on managed lands (e.g., Intergovernmental Panel on Climate Change [IPCC] 2013a Supplement to the 2006 Guidelines for National Greenhouse Gas Inventories: Wetlands [Wetlands Supplement]). Globally, peatlands contain twice the amount of C than the atmosphere. In the IPCC 5th Assessment Report (2013b), the SRES (Special Report on Emission Scenarios) model predictions contain no feedback between peatlands and permafrost responses and climate change for projections to the end of the century. Independent analyses indicate that we may be losing 1 Gt of carbon per year from peatlands in the next century.

Mitigation efforts to meet greenhouse gas reduction and stabilization targets depend on feedback of peatlands and the IPCC is not currently able to include this feedback in their projections.

Nationally, several recent documents have highlighted information gaps regarding C dynamics within permafrost and peatlands (e.g., Bernier et al. 2012, Kurz et al. 2013, Webster et al. 2015). Even at a provincial level, permafrost and peatlands are increasingly being recognized for the role they play in the global climate system. Most provinces have some policy or strategy related to wetland conservation. Several notable recent initiatives are those in Ontario, Manitoba and Alberta. In October 2010, Ontario passed Bill 191: The Far North Act, with a planning objective of: "The maintenance of biological diversity, ecological processes and ecological functions, including the storage and sequestration of carbon in the Far North". Further recognition of the importance of peatland carbon led to its inclusion in Ontario's 2011 State of the Forest Report, where for the first time, a peatland carbon pool indicator (Indicator 4.1.2) of sustainability was reported for Ontario. Manitoba, as part of its 2012 Green Plan, released a new Peatlands Stewardship Strategy that ensures a balanced approach between the protection and wise use of peatlands and the establishment of 'no-go zones' for commercial peat development in provincial parks and wildlife management areas and other sensitive, designated peatlands (http://www.gov.mb.ca/conservation/peatlandsstewardshipstrategy/protect.html). The Alberta Government released its new Alberta Wetland Policy in 2013, with the goal of the policy to conserve, restore, protect, and manage Alberta's wetlands to sustain the benefits they provide to the environment, society, and the economy (http://www.wetlandsalberta.ca/policy).

This project will improve our understanding of carbon dynamics to inform management and national estimation and reporting of carbon in forested peatlands, including those located in areas affected by permafrost or permafrost thaw, by creating a simplified model of peatland carbon dynamics to be used as a module within the CBM-CFS. The simplified model will be based on knowledge of key sensitive processes of different peatland functional types. These types will be identified and mapped by synthesizing peatland and permafrost maps (e.g., Figure 5) into a unified geodatabase. Integrating knowledge of key peatland functional types, their C dynamics and distribution on the landscape will allow the first estimations of greenhouse gas emissions and removals to be made for peatlands in Canada at a national scale.

The outputs from this project in terms of past, present and projected future emissions and removals of C from peatlands will feed into the National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS), which provides information to Environment Canada for annual national greenhouse gas inventory reporting. NFCMARS also provides analyses in support of policy development, mitigation analyses, and negotiations.

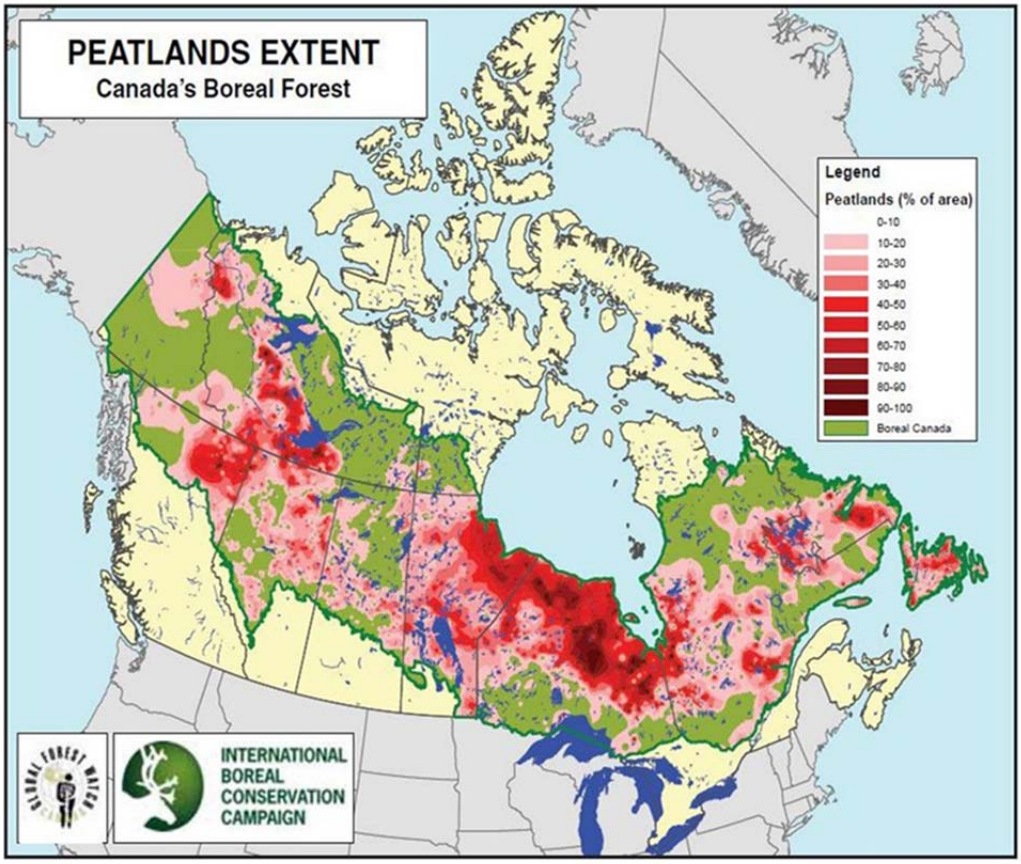

Figure 1. The extent of Canada's peatlands in the boreal (Source: International Boreal Conservation Campaign mapping of the Tarnocai et al. 2002).

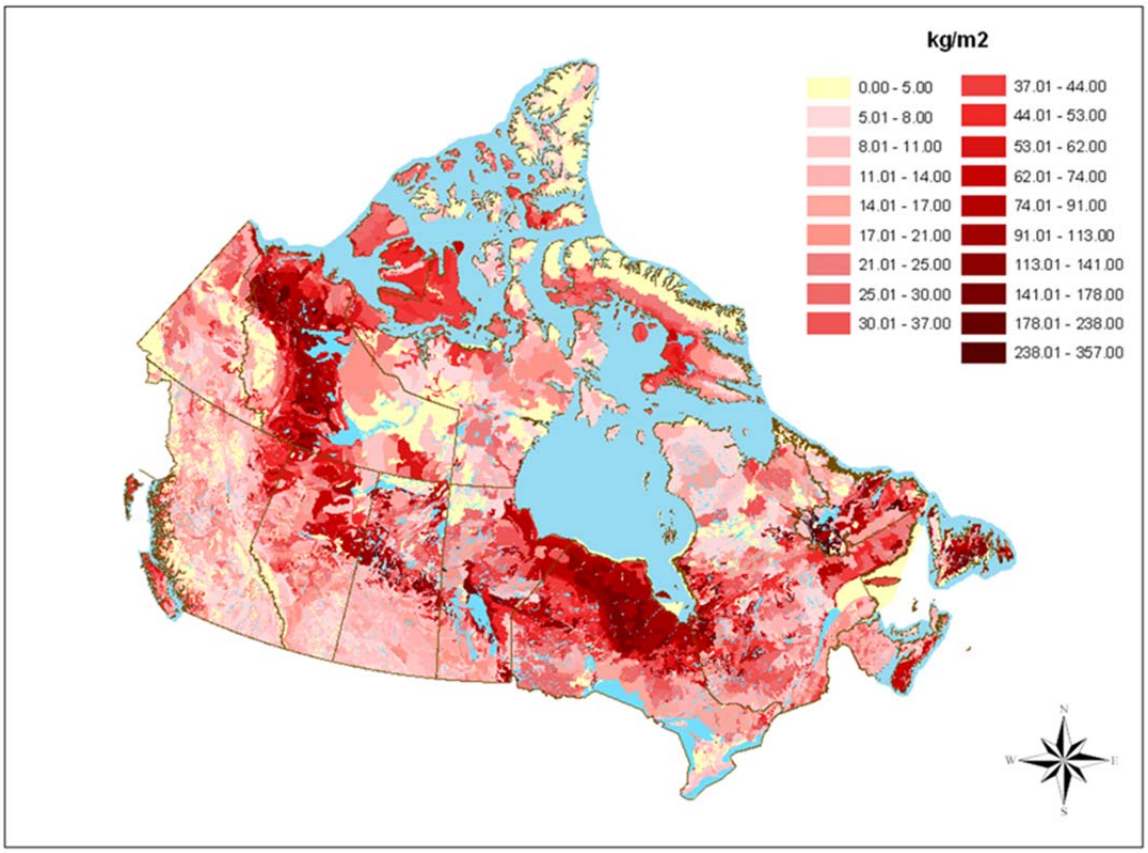

Figure 2. Density of soil C in Canada (Source: Tarnocai and Lacelle 1996).

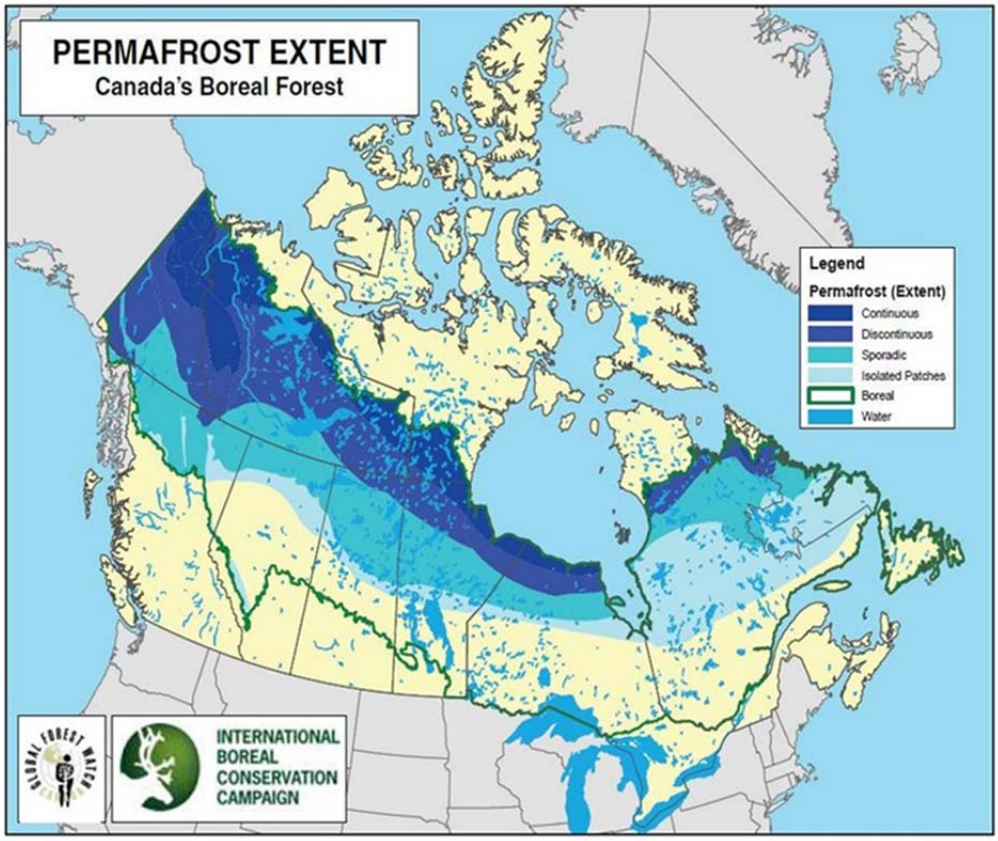

Figure 3. The extent of Canada's permafrost in the boreal (Source: International Boreal Conservation Campaign mapping of Brown 1998).

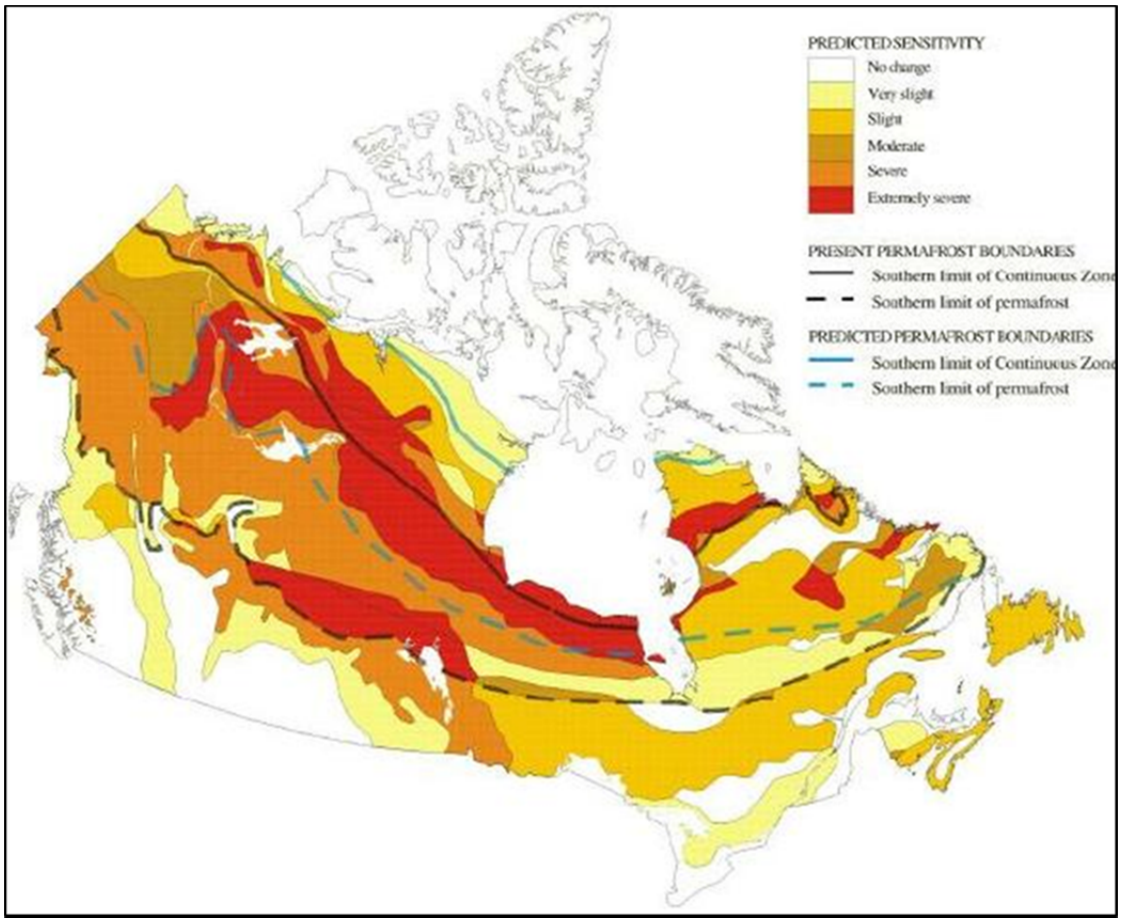

Figure 4. Sensitivity of soil C to climate change (Source: Tarnocai 2006).

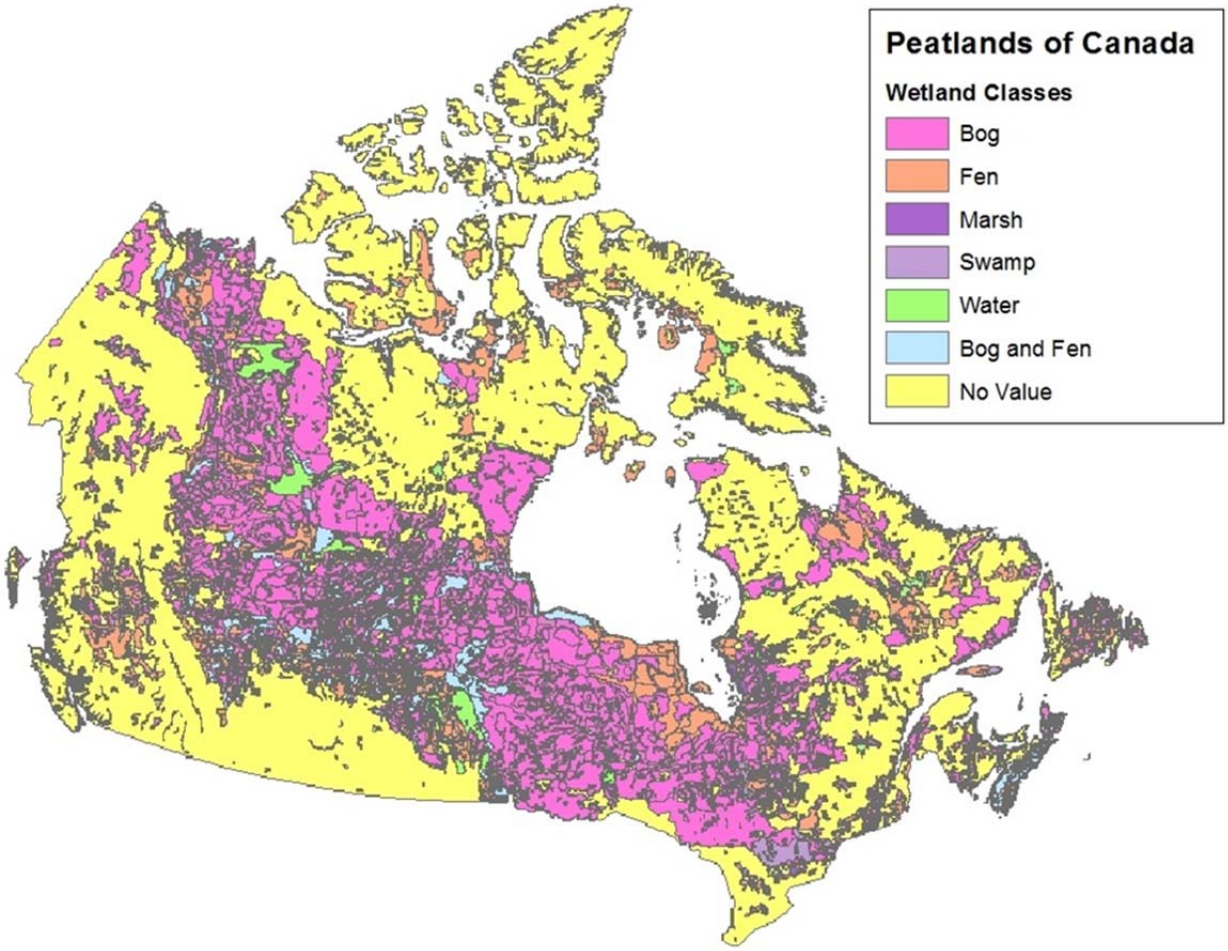

Figure 5. Dominant peatland types in Canada (Source: Tarnocai et al. 2011).

2.2 Key science questions and objectives

The objective of this project is to develop and implement a peatland module for the CBM-CFS that will estimate C emissions and removals from forested peatlands in the boreal region and for managed and unmanaged forests nationally.

Key questions that this research will address include:

1. What are the key peatland types to include in a national peatland C dynamics module?
2. What is the distribution and extent of these peatland types nationally?
3. What are the key processes needed to model peatland C emissions and removals?
4. What data are needed to calibrate the key processes and validate module outputs?
5. What data are available to calibrate the key processes and validate the module outputs?
6. What are the estimated peatland C emissions and removals in the managed and unmanaged forest areas of Canada?
7. How do impacts of natural and anthropogenic disturbances affect peatland C cycling processes and estimates of peatland emissions and removals?

The expected outcomes of this work will be:

1. A better understanding of C dynamics within forests on organic soils and boreal peatlands, including permafrost peatlands, and their distribution across the country.
2. National estimates of emissions and removals of C dioxide, methane, and (in the case of fire) N_2O that incorporate the distribution of different types of forested peatlands and their greenhouse gas budgets, given regional climate.
3. Improved knowledge of the impacts of disturbance caused by human activities and climate change on forested peatland C budgets.
4. Identification of key data and knowledge gaps contributing to uncertainty in estimation of peatland C budgets.

2.3 Model focus

The focus of the CaMP peatland module for the CBM-CFS is a simplified model that is one dimensional (vertical flux) and forest focused. The primary focus of the CaMP will be on understanding changes in C fluxes, and secondarily on changes in C stocks.

It is acknowledged that lateral fluxes of C to other systems exist (e.g., losses of dissolved C to aquatic systems), but once they leave the forest-peatland system they are considered losses from the ecosystem, so their associated C is not double-counted. Detailed feedbacks (e.g. CO_2 fertilization effects) will not be considered within the model.

2.4 Overall project strategy (phased approach)

The project will proceed in a phased approach. Phase 1 will produce a simplified model at a coarse spatial resolution. Phase 2 will reflect the adaptive learning based on the results of Phase 1. For example, complexities in the model related to hydrology (static to dynamic), inclusion of permafrost processes, interactions of C cycling processes, disturbance activities, and refinement of spatial resolution of peatland coverage will be considered in Phase 2.

2.5 Key project deliverables

The expected key project deliverables for Phase 1 include:

1. This workshop report outlining approaches and options for module development and for integrating spatial data layers.
2. A classification system of peatland types based on plant functional groups hierarchically designed so that categories can be expanded as spatial peatland data layers are better refined or as data parameters for different peatland types become available.
3. Algorithms for the CBM-CFS peatland C module – CaMP Version 1, which will model peatland C dynamics with a static water table and without disturbances.
4. A national map of peatland types and permafrost using an ensemble of existing spatial data, with identification of gaps in coverage.
5. Estimates of C budgets for different forested peatland types using extrapolated climate data, for the boreal zone and in the managed forest.
6. Estimates of annual national peatland C sequestration and emissions, for the boreal zone and in the managed forest from 1990 to present.

3. Scoping issues

3.1 Temporal scale

To be consistent with the current CBM-CFS model structure, we propose to model at annual time steps for periods ranging from years to a few centuries. Since many peatland processes vary seasonally, a "modifier" approach will be used to account for inter-annual effects of seasonal water table draw-down on C cycling processes for version 2 of the CaMP. Future versions of the module may explicitly model at seasonal, monthly or daily time-scales.

3.2 Spatial scale and approach

We will include peatlands within the managed and unmanaged forest of Canada, recognizing that there is particular interest in predictions and reporting requirements for forested peatlands in the managed portion of the boreal forest region of Canada. We will use a spatially-referenced or, at the sub-national scale, spatially-explicit (30 m resolution) approaches. Initial (Phase 1) estimates are likely to be made using the spatially-referenced approach that is currently supported in the CBM-CFS in which polygons are delineated with information on the percentage of peatland types. Revised estimates (Phase 2) will aim to adopt the spatially-explicit approach (pixel referenced) that is under development within the new modelling structure of the CBM-CFS version 4.

4. Peatland classification

4.1 The aquatic to terrestrial continuum

Wetlands are wet terrestrial ecosystems where, over the long term, net primary productivity exceeds organic matter decomposition, resulting in peat accumulation. Wetlands can be classified as shallow open water, marsh, swamp, fen or bog (Figure 6). Peatlands are wetlands that have greater than 40 cm of peat and can include swamps, fens and bog types. These three peatland types will be the focus of the peatland module for the CBM-CFS. This compliments the existing upland forest focus of the CBM-CFS and a new module for moss C dynamics (Bona et al. 2016) that will be used to represent C dynamics of mineral soil with thick moss-derived organic layers.

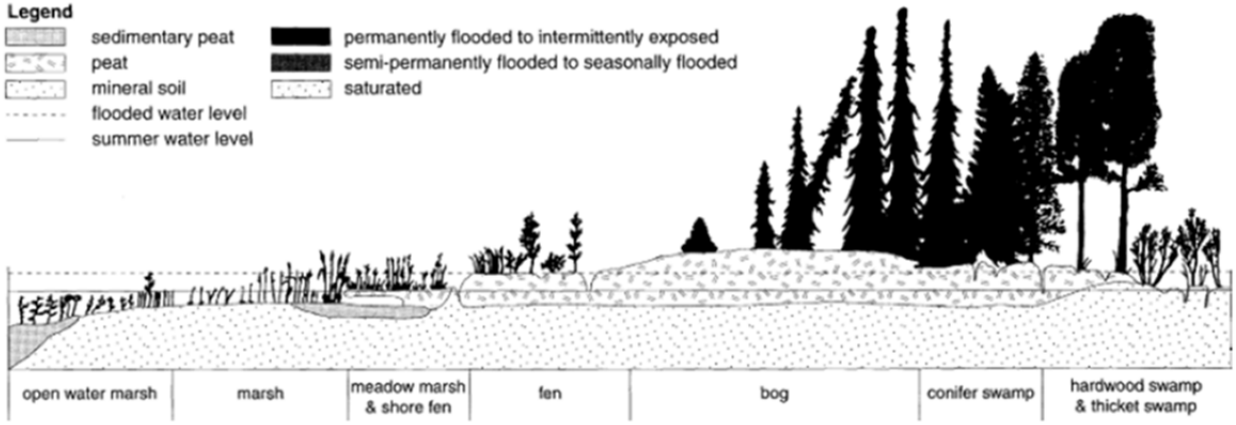

Figure 6. The open water to forest transition in peatland types (Source: Smith, undated publication).

4.2 Peatland initiation and diversification

In the northern hemisphere, peatlands became widely established in the time following deglaciation. Peatlands initiation, whether it was immediately after deglaciation or at some later point in time, occurs by either paludification or terrestrialization (Figure 7). Paludification (or "swamping") occurs when peat forms on previously drier, vegetated habitats over mineral soils and in the absence of a body of water, due to a rise in the regional water table. Terrestrialization can form peatlands over shallow bodies of water, gradually filling the basin with vegetation that develops floating or grounded peat mats.

Once formed, many factors (including hydrology, vegetation and flora, substrate, hydroseral succession, permafrost and fire) drive processes that result in diversification of the peatlands into different types.

1. Hydrology: Peatlands require a constant, long-term water supply either from precipitation (ombrogenous = bogs) or ground and surface waters (geogenous, having minerals = fens) to maintain the wet conditions that promote peat development. This hydrology is driven by geologic setting and by regional climate (temperature and precipitation) driving inputs and distribution of water on the landscape.
2. Vegetation and flora: The trees, shrubs, bryophytes and lichens respond to hydrological conditions, creating characteristic species assemblages with different peatland types. In turn, shifts in species from non-vascular to vascular can increase evaporative losses and further decrease the water table. There are different plant functional forms within peatlands (e.g., lichen, brown mosses, feather mosses, Sphagnum mosses, grasses, herbs, shrubs and trees

[deciduous and/or evergreen]) (Figure 6). Different peatland types have characteristic vegetation (plant functional types) assemblages.

3. Substrate: Differences in surficial geology (e.g., acidic granite on the Boreal Shield and carbonate-rich sedimentary bedrock on the Boreal Plain) affect the nutrient richness of geogenous peatlands.
4. Hydroseral succession: Peat accumulation gradually lifts the surface above the influence of groundwater, decreasing moisture and nutrients.
5. Permafrost aggradation and degradation: Permafrost formation affects the elevation of peat, creating a similar effect to hydroseral succession. When permafrost thaws, the reduction in elevation results in slumping and a return to wetter conditions.
6. Fire disturbance: Peatland fires remove surface organic layers and decrease vascular plant biomass, resulting in a higher water table and wetter conditions.

While each of these factors is important for peatland development, the time scale of change is typically very long for many of them (e.g., for hydroseral succession and permafrost aggradation) and other factors may occur infrequently, but when they do occur they create large changes to peatland structure and function (e.g., permafrost collapse and fire).

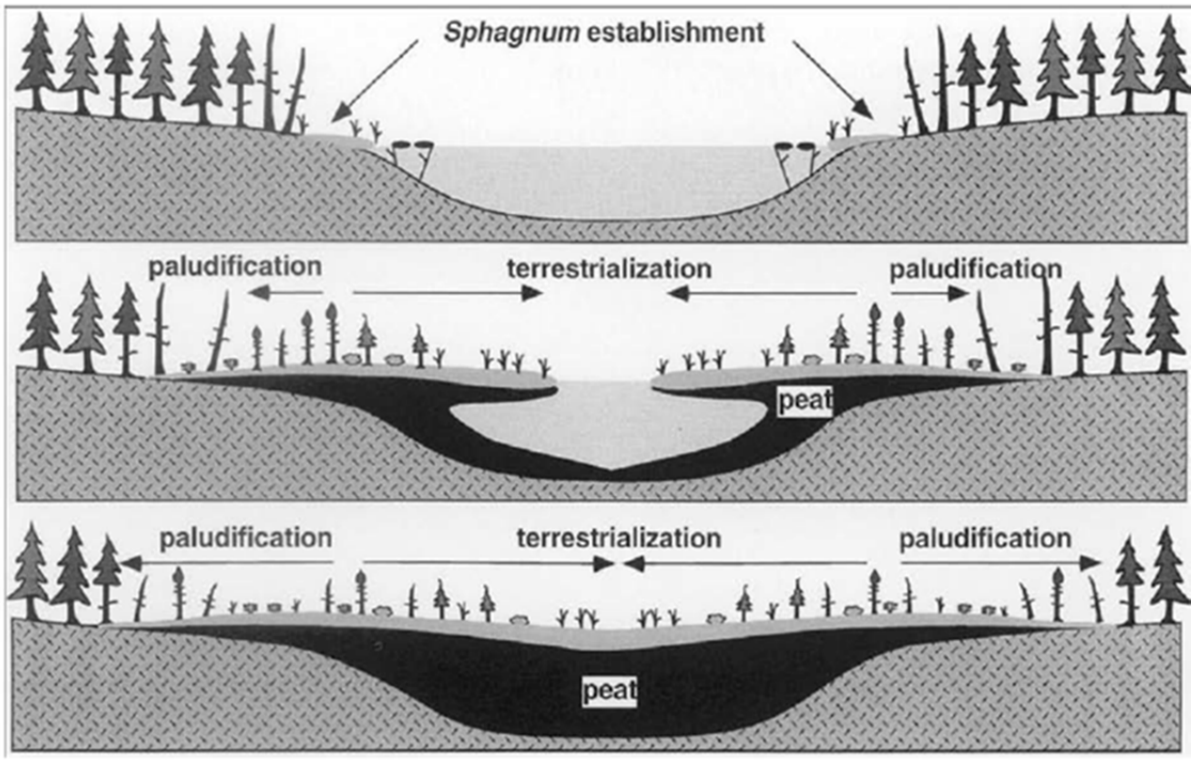

Figure 7. Peatland development processes of terrestrialization and paludification (Source: Klinger 1996).

4.3 Peatland classification system

A peatland classification system is necessary to group similar peatland forms across the continuum of conditions they occupy. Having a classification system that defines all possible classes is ideal, but has the disadvantage of needing an enormous number of pre-defined classes. A realistic peatland classification system should be comprehensive in the classes included, scientifically sound in how those classes are delineated, and practically oriented so that it can meet the needs of a variety of users.

The Canadian Wetland Classification system (CWCS) is the foundation for wetland classification in Canada and is the basis of the Canadian Wetland Inventory (CWI) (Figure 8). The classification includes the five main wetland classes (bog, fen, swamp, marsh and shallow water), and sub-classes are defined based on key vegetation layers (moss, herb, shrub and tree [either coniferous or deciduous]). While many provinces have adopted this classification, early work to define or map peatland types pre-dated the classification and in some instances wetlands are reported using coarser classes (e.g., treed versus non-treed wetland) than the CWCS. Some provinces report at higher resolution than the CWCS categories, particularly when specialized wetland habitats are identified as priority areas. For example, Ducks Unlimited has an enhanced wetland classification system that is similar to the CWCS and CWI systems, but with additional swamp classes, with rich and poor fen differentiated.

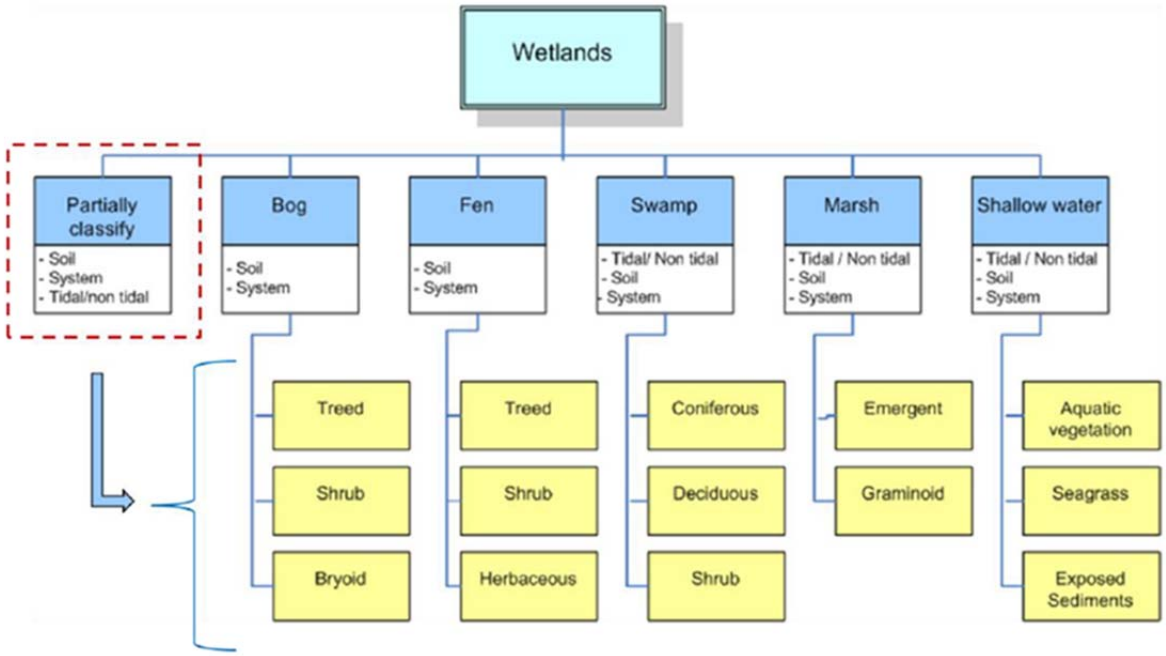

Figure 8. Canadian Wetland Inventory wetland class hierarchy with major classes in blue, modifiers in white, and secondary classes in yellow (Source: Environment Canada 2012).

4.4 Mappable and meaningful categories

The categories of peatland types that will be included within the CaMP include forested (potential to reach >25% tree cover and >5m height at maturity), treed (potential to reach 10-25% tree cover and <5m height at maturity) and open (<10% tree cover and <5m height at maturity) bog, poor fen, and rich fen, and forested and treed swamp (Shaw et al. 2016). These categories are consistent with CWCS classes and appropriate for C budgeting, as they represent the major vegetation pools that control net primary production, litter production and peat depth that influence hydrology and impact on primary production and decomposition.

5. Key processes of the model and model review

5.1 Commonalities and differences in C modelling between forest and peatland systems

Similar to C cycling in forests, peatland C cycling involves interactions among ecosystem components of soil, vegetation and atmosphere operating within the regional landscape. Carbon transfers within and among these components vary over time and are influenced by internal (stand dynamics, plant growth) and external (hydrology and disturbance) drivers. Whether the balance of C is emitted to the atmosphere or sequestered as a function of the difference between net primary production and heterotrophic respiration, with the rates of each a function of many interacting factors. A key driver of C cycling within peatlands is the presence of a water table, which creates an anaerobic (reducing environment) zone within peat below the water table (catotelm) and an aerobic zone (oxidized environment) above the water table (acrotelm), which affects many physical (e.g., temperature) and chemical (e.g., oxidation-reduction potential) characteristics and biological (e.g., rooting depth) processes.

Figure 9 summarizes the key pools and fluxes within peatlands. Carbon is stored in live biomass (e.g., leaves, stems, roots), dead organic matter (e.g., litter, coarse woody debris), soil (e.g., peat and mineral soil) and dissolved organic carbon (DOC). Carbon enters, leaves or transfers through the system via photosynthesis, autotrophic respiration, heterotrophic respiration, decomposition, as well as DOC export and gas transport (diffusion, ebullition, or plant mediated).

There are several important features of peatlands that may need special consideration within the module.

1. Hydrology: Influences soil moisture, water table depth, water balance and decomposition.
2. Soil temperature: Influences decomposition and productivity.
3. Plant functional type (tree, shrub, moss, and sedge): Influences biomass and litter production rates and litter quality.
4. Organic matter quality: Influences decomposition.
5. Oxidation-reduction potential: Influences pathway of decomposition (aerobic vs. anaerobic).
6. Transport pathways for methane (ebullition, diffusion, plant mediated): Influences methane emissions.
7. Disturbance: Influences productivity, decomposition and direct C releases (fire).
8. Permafrost: Influences productivity and decomposition.

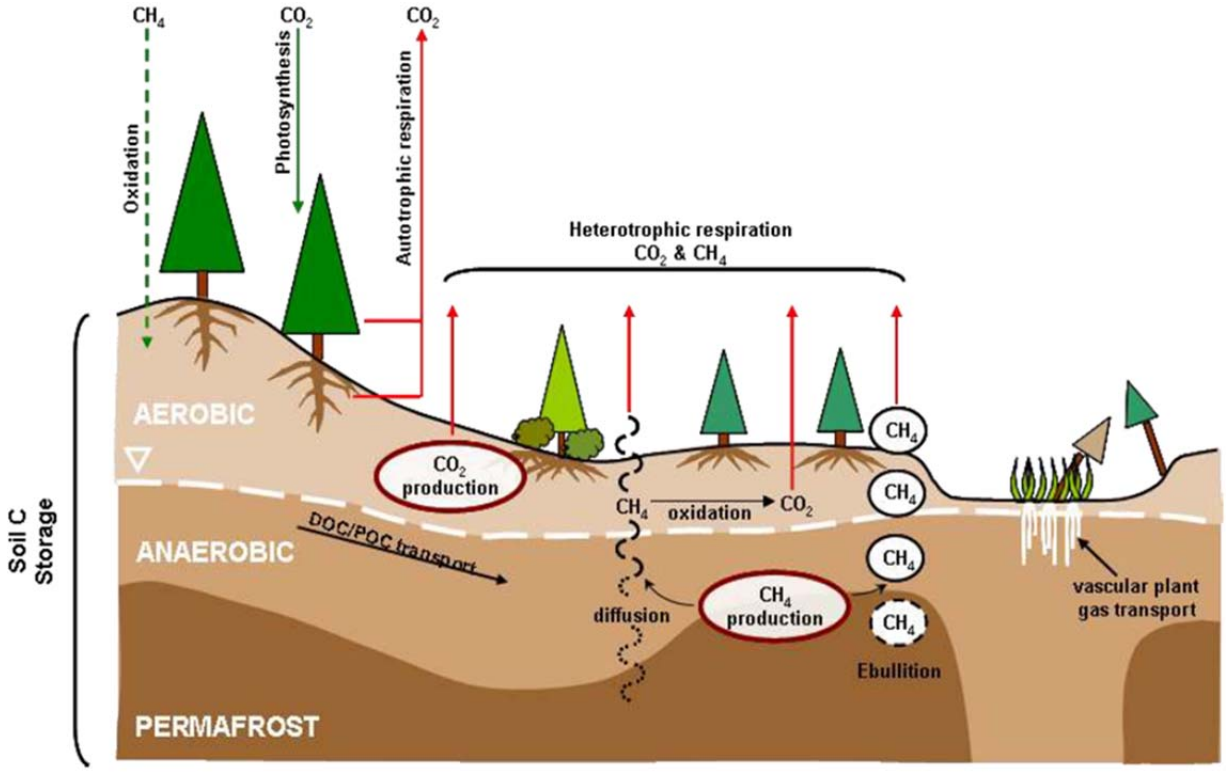

Figure 9. Key pools and fluxes within peatlands (Source: Jagtar Bhatti).

5.2 Insights from existing peatland models

Different peatland C models were reviewed and summarized (Table 1). Currently a single model suitable for applying at a national scale does not exist. Most of the peatland models are data and parameter intensive process-based models that are applied at point scales. Much can be learned by examining how key processes have been dealt with in each of these models, however to have a national-scale modelling capability requires a simplified approach. Potential options for simplifying processes include:

1. Capturing statistical distributions of characteristics instead of explicitly modelling processes.
2. Simplified processes (e.g., water budget versus static water table versus dynamic water table, 3D to 1D representation).
3. Characterize responses based on peatland types from empirical measurements.
4. Process-based modelling of peatland types under different climate regimes with outputs scaled from point to landscape.

Table 1. Summary of characteristics of commonly used peatland models.

Model	Gases simulated	Hydrology	PFT[1]	Type	Inputs	Disturbances	Uncertainties
Holocene Peat Model	None – C accumulation rate	Yes	Simulated PFTs (12)	Process-based	Weather, PFTs productivity, soil moisture, WT[2], peat hydrological properties, peat depth, BD[3], soil T[4].	No	Yearly time step over millennia scale. Simulates total loss of C and not GHG[5]; thermal variables affect or modify peat decay.
McGill Wetland Model	CO_2	No	PFTs as input	Process-based using pool approach	Incoming short wave radiation, atmospheric [CO_2], air and soil T, soil water content, WT, BD	No	Underestimating growing season peaks in CO_2 production; lacking plant water relations.
ECOSSE	CO_2, N_2O, CH_4	WT as input	Simulated PFTs	Process-based using pool approach	Weather, # soil organic layers, C content, BD, soil pH, texture and other basic properties, WT depth, vegetation	Yes	
PEATLAND	CO_2, CH_4	WT as input	Simulated PFTs	Process-based using pool approach	WT, Air T, soil properties, vegetation	No	Data requirement is very high; very sensitive to low soil moisture content.
DNDC	CO_2, N_2O, CH_4	WT as input or simulated	Simulated PFTs	Process-based using pool approach	Weather, soil physical properties, soil water and T, N deposition	Yes, along with effect on soil environment	Data requirement is very high; CH_4 emissions are highly sensitive to water.
Ecosys	CO_2, N_2O, CH_4, NH_3, NO	WT simulated	Simulated PFTs	Process-based using pool approach	Weather (P, air T, RH, wind speed, shortwave radiation), soil parameter (hydraulic and thermal conductivities, OC, pH), chemical and biogeochemical transformations.	Yes, along with effect on soil environment	Data requirement is very high; uncertainty with interacting parameters; computational limitations.

Model	Gases simulated	Hydrology	PFT[1]	Type	Inputs	Disturbances	Uncertainties
TEM (Terrestrial Ecosystem Model)	Include permafrost CO_2, CH_4 and N_2O are considered	See McGuire et al. 2012. Biogeosciences	Simulated PFTs	Process-based	Spatially explicit with monthly data on climate, vegetation soil and elevations.	Yes	Very high sensitivity to radiation factor with respect to plant functional productivity during growing season.
NEST (Northern Ecosystem Soil Temperature	Soil T, permafrost	See Zhang et al. 2012. Global Change Biology	Vegetation type considered	Process-based	Climate, topography, vegetation, snow depth, snow density, forest floor, peat layers and mineral soils.	No	It is one dimensional so lateral flow of heat and water has been ignored.

1.PFT; plant functional type
2. WT; water table
3. BD; bulk density
4. T, temperature
5. GHG; greenhouse gas

6. Model conceptual design and linkages to the CBM-CFS

6.1 Current version of the CBM-CFS

The CBM-CFS (Kurz et al. 2009) is one of the main components of the National Forest Carbon Monitoring and Reporting System (NFCMARS) (Kurz and Apps 2006) used for international reporting and projecting (Figure 10,11) from 1990 to present (Stinson et al. 2011). CBM-CFS is an operational-scale model of forest C dynamics based on growth and yield curves and contains detailed forest inventory information along with knowledge and mapping of disturbance events (harvesting and natural disturbances such as fire and insects) including land-use changes (deforestation, afforestation). The model represents 22 C pools and transfers.

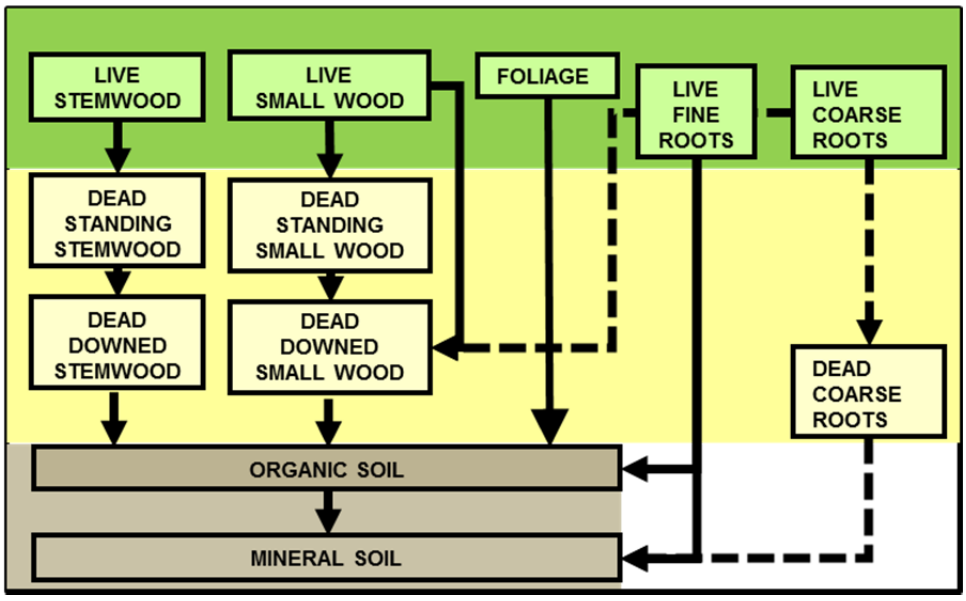

Figure 10. Simplified pool structure of the CBM-CFS3.

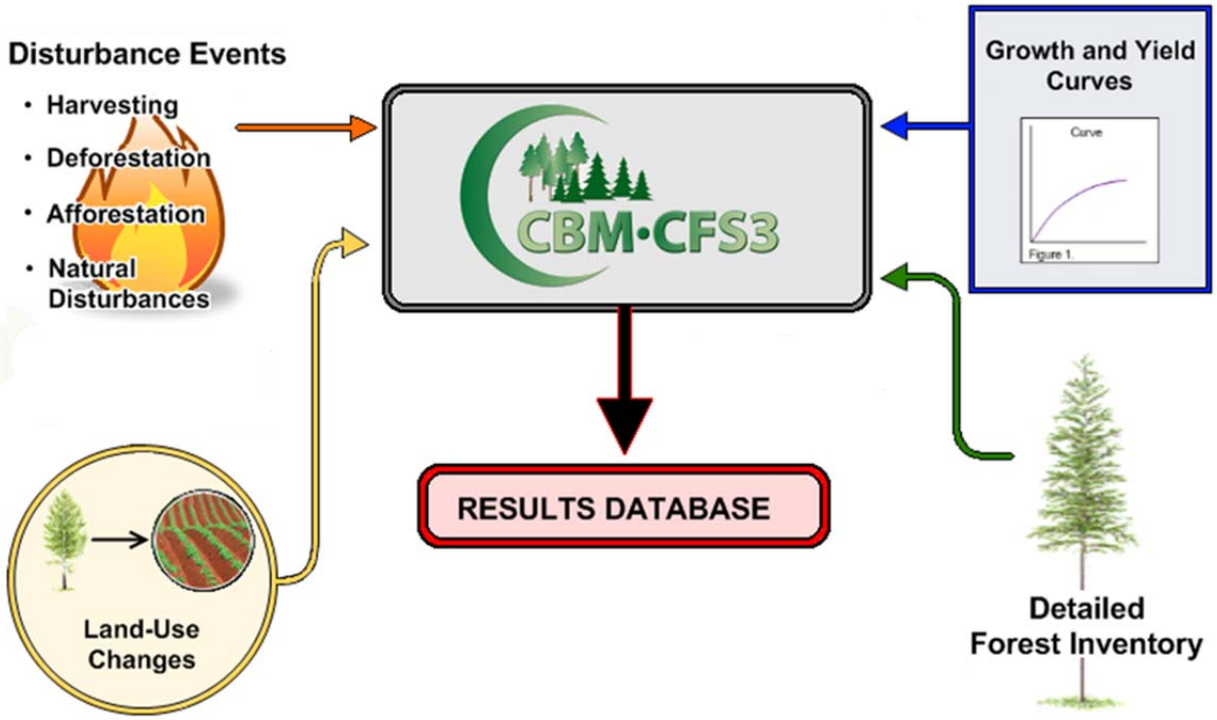

Figure 11. Components of the NFCMARS (Source: CFS Carbon Accounting Team).

The model builds on over 25 years of Canadian Forest Service (CFS) science and allows forest managers to assess C implications of forest management on GHG sources and sinks. The model is referenced to 635 spatial analysis units (geographic intersection of terrestrial ecozones, political boundaries and forest management units) comprising approximately 2.7 million stands which are aggregated to 18 reporting zones at the ecozone scale (Figure 12).

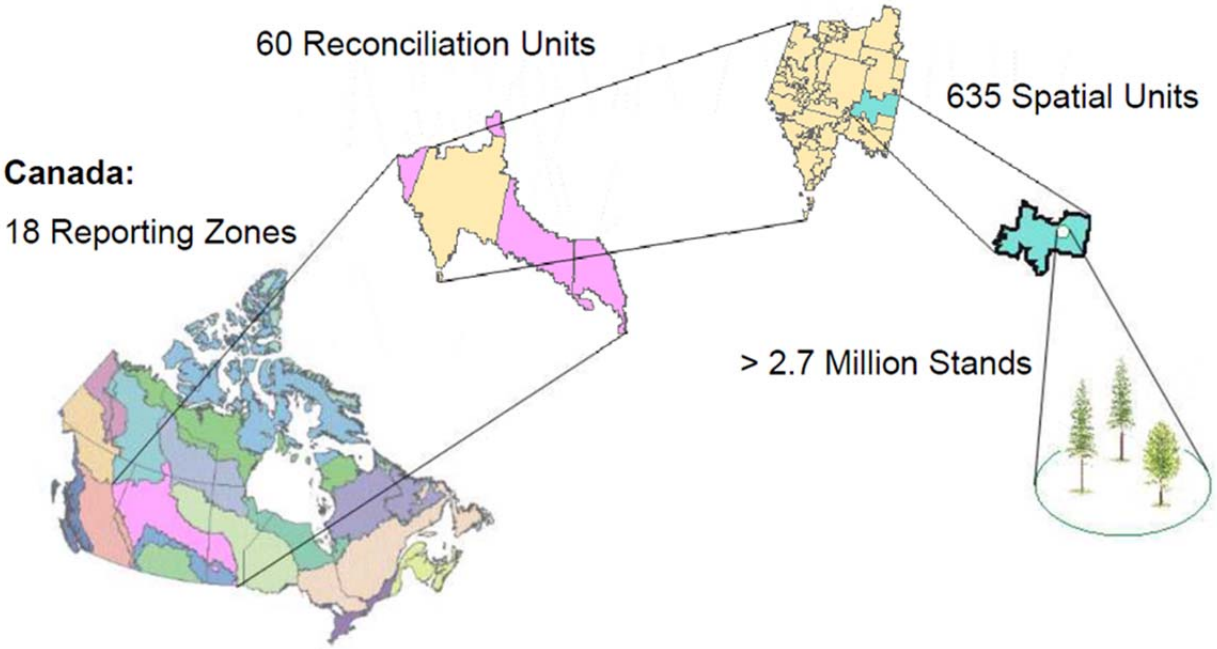

Figure 12. Spatial structure within the CBM-CFS3 model (Source: CFS Carbon Accounting Team).

6.2 Next generation of the CBM-CFS

The current version of the CBM-CFS is 3.0. The next version, CBM-CFS 3.5, currently under development, will introduce new computing technology. It will have a next generation modelling platform with parallel processing, faster performing algorithms, and with processes represented in separate, but interacting, modules. The new modular approach allows more versatility and flexibility while achieving computational efficiencies. Modules will draw on shared spatial data layers (e.g., climate, environment, disturbances, etc.) and interact with an overall integration module that checks for conservation of mass and updates all C pools (referenced to 5 IPCC C pools), and will track and summarize fluxes by category.

The CBM-CFS 3.5 will be event-driven, using a variable time step (1 year or less) approach. It will be possible to run the model using either spatially-explicit (e.g. 30 m resolution) or spatially-referenced (polygon) implementations. Issues related to implementation of spatially-linked (i.e., contagion) processes such as fire spread and lateral fluxes still have to be sorted out. A prototype design and development of CBM-CFS 3.5 is currently in progress.

The CBM-CFS 4.0 will represent new C science applied in a modular approach that will facilitate data assimilation, sensitivity and uncertainty analyses. For example, the empirical growth model could be replaced with a process-based growth model that includes growth sensitivity to environmental change. The CBM-CFS 4.0 will be the version in which the peatland module will eventually reside.

Concurrent to changes in the CBM-CFS are changes to the NFCMARS. The NFCMARS 2.0 will be a new reporting system including all anthropogenic impacts that reduces reliance on provincial/territorial inventory data and increases reliance on national-scale remote sensing products for both the managed and unmanaged forest. The remote sensing products will be at high resolution with spatially-explicit representation of anthropogenic and natural disturbance impacts. Outputs from the peatland module will be incorporated into the NFCMARS 2.0 reporting with the plan to inform national GHG estimation and reporting, once the required testing, peer-review and other expert reviews have been completed.

6.3 Overall modular approach and integration

The CBM-CFS currently models forests on mineral soil. Its peatland module (Canadian Model for Peatlands– CaMP) will address C emissions and removals for systems with deep organic layer (peat) development having a water table, by modelling peatland C fluxes (CO_2, CH_4) that are coupled to simulated hydrology, peatland biomass, and C transfers into and out of the peatland. The CaMP can run as a stand-alone program or as part of CBM-CFS. Estimates will be made at spatial and temporal scales compatible with those of the CBM-CFS. The CaMP will maintain a program structure that will easily allow for the incorporation of more detailed processes-based modelling approaches to be incorporated in the future with improved understanding of peatland processes and their controls. The program structure will also allow finer (i.e., sub-national) spatial (landscape, site) and temporal (monthly, daily) scale predictions to be made as required.

6.4 Summary of modelling categories

The CaMP will be designed and applied for peatland types; specifically forested, treed and open bogs, poor fens, and rich fen, plus forested and treed swamps. These peatland types will vary in the amount and presence of tree, shrub, sedge and moss components. Since these peatland types vary in their plant

functional types and hydrologic, nutrient and pH regimes, they will be represented by peatland type-specific decay and transfer rates.

6.5 Summary of the peatland module

The CaMP will be designed in close collaboration with the Canadian Forest Service Carbon Accounting Team (CAT) with conceptual and structural similarities to the CBM-CFS3 (Kurz et al. 2009) for implementation as a module in the next generation of the CBM (CBM-CFS4) currently under development. For the first model version, the CaMP will be applied at the national-scale, for managed and unmanaged forest areas, consistent with both spatially-referenced and spatially-explicit CBM-CFS approaches (spatial resolutions in the future anticipated as low as 30 m). The CaMP will operate at an annual time step, over a modelling time-frame of years to a century or more, after the C pool initialization model spin up. To meet challenges of modelling at a national scale, the CaMP will have a simplified process representation (i.e., 1 dimensional representation) of hydrological and thermal processes, using a mix of empirical and process-based algorithms. The model will draw on data readily available or derivable at a national scale. The CaMP is intended to simulate carbon fluxes in the top 100 cm of peat that is most responsive to climatic and edaphic change and most susceptible to anthropogenic and natural disturbances, over contemporary (1990 to present) and future (10 to 100 years ahead) time frames. A summary of the key features of the CaMP is presented below and the reader is encouraged to reference the CaMP module design document (Shaw et al. 2016) for more detailed information.

Several new pools, fluxes, parameters, modifiers and algorithms that do not exist in the current version of the CBM-CFS3 will be part of the new CaMP (Figures 13a, b). New plant types for the peatland module include a woody layer (shrubs and small trees), sedges and moss. Inclusion of these new plant types in the CaMP will require estimates of their net growth as a main model driver. Where possible, the CaMP will draw on either the moss module or the conceptual development of Bona et al. (2016) for forest mosses. Additional dead organic matter (DOM) pools will also be required for inputs from the new biomass pools and for the acrotelm and catotelm peat pools. DOC and dissolved inorganic carbon (DIC) pools will not be simulated in the CaMP at this time, but may be included in the future.

New fluxes and their rates will be required to account for biomass turnover and litterfall transfers from the woody layer (stems and branches, roots and foliage), sedges (roots and foliage) and moss (sphagnum and feather moss) biomass pools, as well as DOM and peat pool base decay rates and proportions for partitioning of decayed C between transfer to downstream DOM or peat pools and the atmosphere. In version 2.0 (V2.0) of the CaMP temperature and moisture modifiers will be introduced for woody layer, sedge, and moss growth, along with moisture modifiers for microbial decay within the aerobic and anaerobic pools. In version 1.0 (V1.0), the net emission of methane (CH_4) released to the atmosphere will be simulated as a function of the water table depth following Kurz et al. (1994), with added complexity in future versions of the model including a modifier to reflect the impact of plant mediated transport.

Hydrology is an over-riding driver of many peatland processes. A specifically designed hydrology algorithm for simulating water table depth will be a key part of the CaMP module and will drive the moisture modifiers either directly or through simulated soil water contents as a function of the water table depth. V1.0 of the CaMP will simulate a static water table, while V2.0 will have a dynamic water table. By direct modelling of the water table depth, both approaches avoid simulations of lateral water

flows and thereby reduce the complex three dimensional hydrological modelling to a one dimensional simulation within each model unit. For the static water table approach, an average water table depth can be predicted as a function of the Canadian Fire Weather Index systems Drought Code (Waddington et al. 2012). Extensive historical water table measurements from Zoltai et al. (2000) will be normalized by the Drought Code (which has been mapped in Canada on a daily basis since 1980) and stratified by ecozone and peatland type in order to derive a simple weather-driven peatland water table model. For the dynamic water table approach, the water table will be estimated based on the Drought Code, and then temporally scaled using aboveground environmental and ecological controls such as vegetation surface characteristics, terrain parameters, and climate parameters.

Permafrost is a condition that affects a large area of Canada's peatlands. As part of V2.0 of the module development soil thermal regime will be simulated by integrating with the Northern Ecosystem Soil Temperature (NEST) model (Zhang et al. 2003) or incorporating algorithms of NEST or of other models within the CaMP. NEST is an established model with well tested algorithms to simulate one dimensional ground thermal dynamics associated with thawing and freezing of permafrost.

Land-use changes affecting peatlands will also be part of the CaMP V2.0 development. Fluxes of material removed due to tree or peat harvesting will also be included, as will biomass losses due to fire disturbance or flooding (e.g., from hydroelectric reservoir creation). Disturbance matrices will be developed to accommodate peatland-specific disturbance types that impact C emissions and removals

6.6 Running the peatland module

The CaMP will be parameterized with peatland type-specific data derived from literature and databases. These parameters control the model fluxes of mortality C transfers, detritus C decay and redistributions, and physical detritus transfers. A sensitivity analysis of the module parameters will be done to determine which factors have the greatest impact on CO_2 emissions and removals and CH_4 emissions. Details about peatland type-specific data derived from literature and databases can be found in Section 8 of this document).

Initialization of the CaMP will be done by running the module, calibrated for each peatland type. The CaMP will initialize its biomass pools, DOM pools and peat pools in a way that takes into account previous disturbance effects (Kurz et al. 1992; 2009). The model C pools will be initialized by using a peatland carbon database (Tarnocai et al. 2005) for which the C density in the acrotelm and catotelm of various depth ranges will be calculated for different combinations of peatland types and ecozones. The combined knowledge of the peat layers C density along with the layer depth up to 100 cm (previously determined by the water table depth) will allow for calculation of the initial C peat in the peat pools. The CaMP will then simulate one or several cycles ending with the last known site-destroying disturbance, and then the model will perform under contemporary conditions and/or future scenarios.

Following initialization, module simulations will be run for each peatland site from time of last disturbance to the current year. Estimates of national peatland C emissions will be produced by aggregating all peatland sites for: (1) a historical period using a long-term average (static) water table, (2) the contemporary period (1990 to present) using a dynamic water table and known disturbance history, and; (3) future periods using a dynamic water table, projected climate and disturbance scenarios.

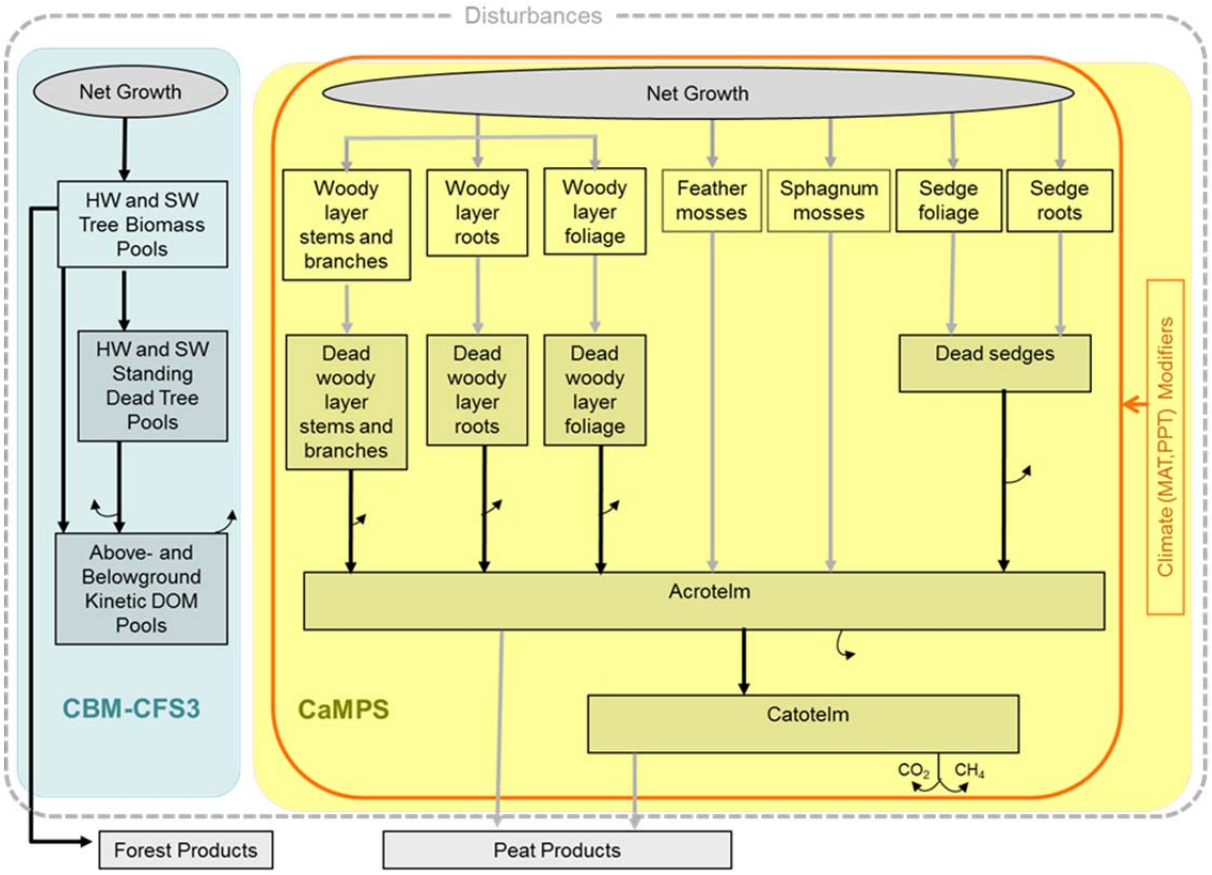

Figure 13a. The modeling structure of the Canadian Model for Peatlands (CaMP) version 1.0 with a static water table (yellow), alongside a simplified structure of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) (blue). Ellipses represent inputs that drive the model. The top row of boxes represent biomass pools and all boxes below them represent dead organic matter (DOM) or peat (Acrotelm and Catotelm) pools. Gray arrows represent transfers of C into and out of biomass pools due to growth or mortality, respectively. Other direct transfers of C are from the Actotelm to the Catotelm, and out of the peat pools to the Peat Products pool. Black arrows represent C removed from a DOM or peat pool due to decay, and the fate of that C which is emitted as CO_2 (curved arrow) (or CH_4 in the case of the Catotelm) or transferred (straight arrow) to downstream pools. Climate modifiers can feed back on growth, mortality, and decomposition functions for any of the pools in the CaMP and disturbances can impact both the CaMP and the CBM-CFS3. AG, aboveground; MAT, mean annual temperature; PPT, precipitation; Vfast, very fast.

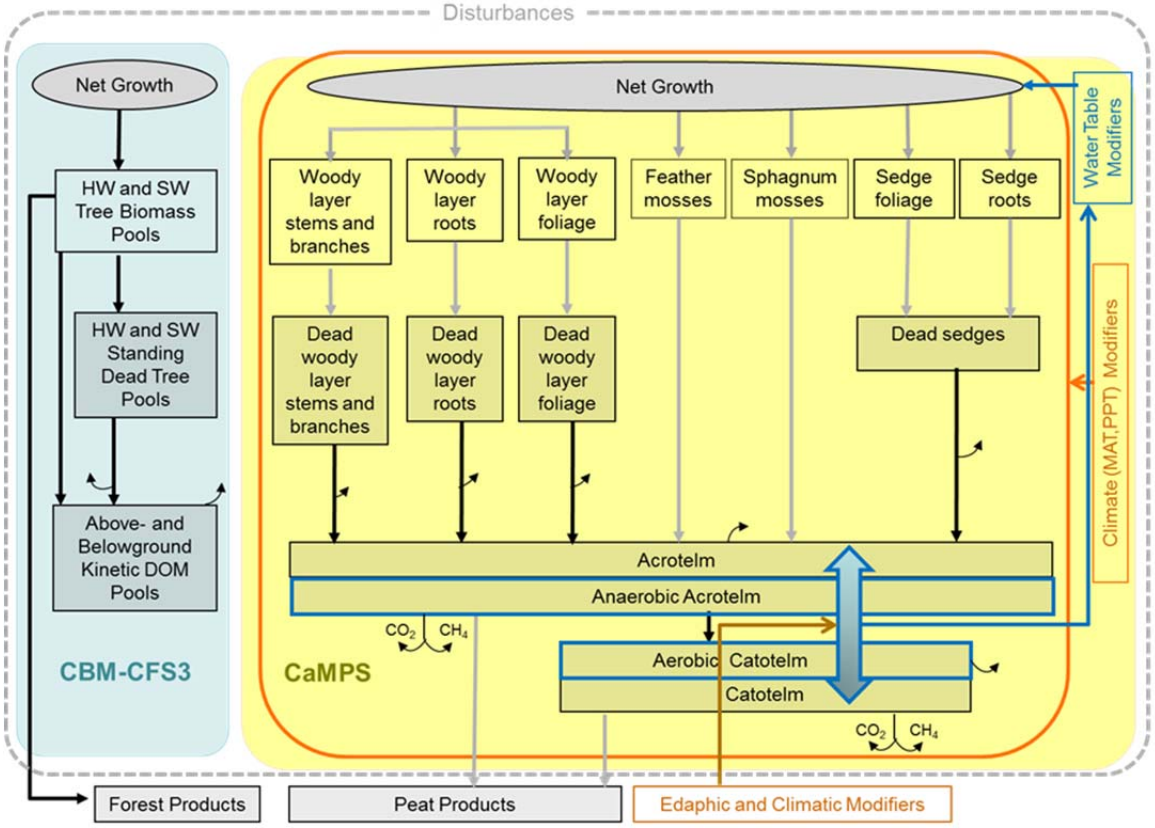

Figure 13b. The modelling structure of the Canadian Model for Peatlands (CaMP) version 2.0 with a dynamic water table. The structure is the same as the CaMP with a static water table (Figure 2) with the addition of a fluctuating water table (blue 2-way arrow) that can be influenced by edaphic and climatic modifiers (brown arrow). Changes in the water table in turn influence water table modifiers (solid blue arrow) on productivity. See Figure 6 for details on implementation of a fluctuation water table.

7. Spatial layers

7.1 Information content and suitability for the task

Successful modelling of C emissions from peatlands at a national scale requires maps of key peatland types at a national scale. A variety of peatland map products have been produced for Canada (Table 2). Ideally, we would like a spatially-explicit representation of all peatland types at a fine resolution (30 m) indicating the key aboveground components of each peatland type (e.g., open, treed or forested). In reality these ideal data exist in relatively few areas. Spatial data from various sources were acquired and each data source was judged for its utility for this project according to the following criteria:

1. Spatial extent: Do the data cover the entire country, a specific ecoregion, province or territory, or local region?
2. Coverage type: Is the coverage spatially explicit or spatially referenced (i.e. does it quantify the extent and location of peatland types within a defined region)?
3. Peat types: Which peat categories are mapped?
4. Spatial resolution: What is the resolution (pixel size) of the data?
5. Data type: Are the data in raster or vector format?

A rating scale was developed based on these criteria (Table 2). Many of the map products were determined to be only of medium utility for the purpose of this project. The Ducks Unlimited (DU) wetland product represented the highest quality spatial data. However, at present we only have data that cover a small pilot area. The total extent of the DU data, while not national, covers a large portion of the western boreal forest (Figure 14).

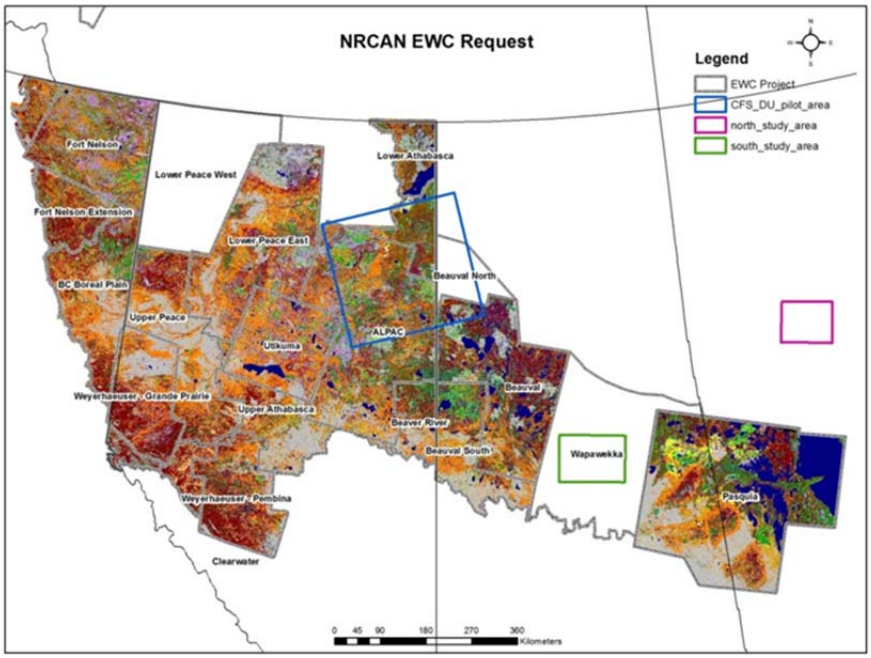

Figure 14. Pilot area (rectangle at the AB/SK border) requested from Ducks Unlimited and extent of their mapped product across western Canada.

The best national product is the Peatlands of Canada Database that has spatially-referenced representation of fen, bog and swamp areas. The Environment Canada National Wetland Inventory Maps will likely supersede this map as the best national product when it becomes publicly available. The spatial mapping sub-project will attempt to synthesize the best available national peatland map by synthesizing other spatial (e.g., EOSD) and aspatial (e.g. Western Canada Peatland Database) data sources to delineate the key peatland types.

Amalgamation of data layers differing in resolution and quality will result in some areas having higher accuracy of peatland identification and thus higher confidence in the estimates produced than areas with lower accuracy of peatland identification. Efforts will be made to address uncertainty and error in areas where coverage is of low quality. The pilot area in which DU provided the high resolution mapping data will serve as a test area for comparing map products and to evaluate our ability to combine map products to improve peatland type and cover representation.

Table 2. Summary of spatial data sets and the components captured in the layers and rating of the data layer utility for this project. Numbers in bracket in column headings represents scores assigned to the column. An 'X' indicates the presence of information meeting our criteria in the dataset. Dataset utility for this project: high represents datasets with score of 11-14, medium represents datasets with score of 7-10, and low represents datasets with score of < 7.

Dataset	Contact/ Source	Dataset Attributes	Desired Wetland Classes				Spatial Extent				Coverage Description		Spatial Resolution		Data Type		Data Utility		
			Fen	Bog	Swamp	Marsh	Canada	Provincial	Regional	Boreal	Occurrence	Spatially Explicit	≤ 30m	> 30m	Vector	Raster	Low	Medium	High
Peatlands of Canada Database	Geogratis or data.gc.ca Tarnocai et al. 2005.	Bog, Fen, Marsh, Swamp, Water, Bog &Fen	X	X	X	X	X				X		X		X			X	
Attribute codes: B=Bog, S=Swamp, F= Fen, X= Fen and Bog, W= Water, Q= No Value. Polygons are assigned to one of the wetland classes but contain information on the percentage of each wetland class present in each polygon.																			
Soil Landscapes of Canada	Ag Canada (Peter Schut, CanSIS).	Bog, Fen, Marshland, Tundra - high shrub, tundra- medium shrub, tundra - low shrub, tundra-broken herb-low shrub, meadow - wet. Swamp	X	X	X	X	X				X			X	X		X		
This dataset has three features, all vectors: hydro (containing land, ocean, and freshwater), prov (containing prov boundaries), and slc_v2r2. Slc_v2r2 is what contains the soil boundary polygons. It must be linked to a number of attribute tables to have meaning. There is a vegetation class table (veget_e) that contains the attributes given above. [The pmdep table provides the Swamp class.]																			
Western Canada Peatland Database	Vitt et al. 2000	Bog, Fen, Marsh, Swamp, Shallow Open Water, Non-Wetland. (*see below)	X	X	X	X			X			X	X		X			X	
Wetland classes are subdivided by four categories/divisions. The first division includes the categories noted above. Attribute codes in order are: B, F, M, S, W, and Z or MINL (while the paper indicates Z in the actual data set it is represented by the field attribute MINL). This data set could be divided into Treed fens and Non-Treed fens if desired. There is also a class PEAT which represents both Bog and Fen in each polygon. Each class (as defined by the four divisions) has a % cover for each polygon.																			

Dataset	Contact/ Source	Dataset Attributes	Desired Wetland Classes				Spatial Extent				Coverage Description		Spatial Resolution		Data Type		Data Utility		
			Fen	Bog	Swamp	Marsh	Canada	Provincial	Regional	Boreal	Occurrence	Spatially Explicit	≤ 30m	> 30m	Vector	Raster	Low	Medium	High
Environment Canada compiled DB	Shari Hayne (shari.hayne@ec.gc.ca)																		
It was indicated in email correspondence that collection of data was still ongoing and nothing was yet available but that a small sample would be sent.																			
Permafrost Zones of Canada	Brown 1998	Major class groups: Continuous permafrost, Discontinuous permafrost, Isolated permafrost, and Sporadic permafrost					X				X			X	X		X		
Dataset has a total of 13 classes based on the above four 4 major classes. No wetland classes.																			
National Forest Inventory (KNN mapping)	Beaudoin et al. 2014						X					X		X 250		X		X	
No wetland classes. Rasters are available as: 1. veg, 2. non veg, 3. treed veg, and 4. non-treed veg. Rasters for trees are available as Genus groups and individual Species for all trees in Canada. For each raster the attributes are represented as % cover in each raster cell. Original dataset can only be opened in ArcGIS 10																			
Far North Landcover Map	Adam Hogg	open fen, treed fen, open bog, treed bog, swamp, marsh, water	X	X	X	X			X			X	X			X		X	
This layer has been joined with the Wetlands Ontario dataset. See below.																			
Forest Resource Inventory (FRI) dataset	Adam Hogg	tall treed							X			X	X		X		X		
This layer has been joined with the Wetlands Ontario dataset. See below.																			

Dataset	Contact/ Source	Dataset Attributes	Desired Wetland Classes				Spatial Extent				Coverage Description		Spatial Resolution		Data Type		Data Utility		
			Fen	Bog	Swamp	Marsh	Canada	Provincial	Regional	Boreal	Occurrence	Spatially Explicit	≤ 30m	> 30m	Vector	Raster	Low	Medium	High
Ducks Unlimited (NWT, YK, AB, SK, MB)	Al Richard (a_richard@ ducks.ca, 780-930-1254)	19 enhanced wetland classes	X	X	X	X			X			X	X			X			X
19 enhanced wetland classes collapsed into Fen, Bog, Swamp, Marsh. Can separate Treed Fen if desired.																			
Southern Peatlands-Manitoba Habitat Heritage Corp (part of NWI)	Stephen Carlyle (scarlyle@ mhhc.mb.ca 204-784-4355	Bog, Fen, Swamp, Marsh, Open Water	X	X	X	X			X			X	X			X		X	
Labrador-Minipi Lake and NE Avalon (part of NWI) NFLD	Mathew Mahoney (mathew. mahoney@ ec.gc.ca)	Bog, Commercial Peatland, Fen, Marsh, Open Water, Shallow Water, Swamp, Treed Peatland	X	X	X	X			X			X	X		X			X	
mxp that can only be opened in ArcGIS 10.																			
National Lake Map	Mike Wulder and Joanne White	Water bodies					X												

Dataset	Contact/ Source	Dataset Attributes	Desired Wetland Classes				Spatial Extent				Coverage Description		Spatial Resolution		Data Type		Data Utility		
			Fen	Bog	Swamp	Marsh	Canada	Provincial	Regional	Boreal	Occurrence	Spatially Explicit	≤ 30m	> 30m	Vector	Raster	Low	Medium	High
EOSD dataset	Mike Wulder (CFS) & Morgan Cranny (NRCan)	Wetland Herb, Wetland Shrub, Wetland Treed					X					X	X			X		X	
From Geobase document: Land Cover, cira 2000-vector Data Product Specifications Ed 1.0 (www.geobase.ca/doc/specs/pdf/GeoBase_LCC200V_product_specifications_en.pdf). The original code list and raster equivalents: Wetland Treed = 81 - now 2, Wetland Shrub = 82 - now 3, Wetland Herb = 83 - now 4																			
Wetlands Ontario																			
This is a merge of three datasets: Wetlands Ontario, Forest resource Inventory, and Far North Landcover Map. The raster attributes are as follows: 0=Bog, 1=Fen, 2=Swamp, 3=Marsh, 4=Treed Peatland, 5=Unknown, 6=Open Water. Most of the middle/south part of Ontario is labeled unknown as this is an ongoing mapping project.																			

8. Library of plot data for model initialization, testing relationships, calibration and evaluation.

A list of field data sets for use in parameterizing, calibrating and validating the model is provided in Table 3. The key attributes available in each data set and relevant to our modelling project are given. Criteria for judging utility of the data set are based on how many of the relevant variables are included. At present, none of the data sets contain all of the variables required therefore multiple data sets must be evaluated, integrated and interpreted for suitability for use in the model and for the different peatland functional types. Model pools and parameters are rarely, if ever, equivalent to pools and parameters measured in the field. Therefore, most data collected in the field and included in this list must be converted and reinterpreted to be useable for the pools and parameters in the model.

Table 3. Summary of point source field data sets, the components to be captured in the database and rating of the data content and utility for this project. An 'X' indicates the data set has been examined and the presence of information meeting our criteria. The number in the column "potential value ranking" is the number of "X"s counted for a source and represents the breadth of data types within a source.

Datasets	Contact and/or Reference	Depth to water table	Water table date measured	Peat depth	Wetland type	Cover% by veg layer	Bulk Density	Organic Matter density	Organic Carbon	Peat density	pH	Soil chemistry	Peat core age data	Fluxes of CH_4/CO_2	AG biomass and partitioning	AG:BG biomass ratios	BG biomass and partitioning	Productivity/Turnover rates	Time to max biomass	Disturbance interval	AG litter decay and transfer rates	BG Litter Decay and Transfer rates	Acrotelm Peat Decay (rates, Q10)	Catotelm peat decay (rates, Q10)	Short-term peat accumulation rates	Long-term peat accumulation rates	Evapo-transpiration	Utility ranking
Eco-atlas of Canada	Geogratis[1]																										X	1
Peatlands of Canada db	Tarnocai et al. 2005[2], Tarnocai et al. 2011																											0
Western Canada Peatlands Database	Halsey et al. 2003 [3]	x	x	x	x	x					x	x																7
	Zoltai et al. 2000 [4]	x	x	x	x	x	x		x	x	x	x																10
	Vitt et al. 2000[5,15]																											NR[16]
MacKenzie Basin	Beilman et al. 2008[6,15]																											NR
Riley Data	Riley 1994, 2011[7], Riley and Michaud 1989	x		x					x		x	x																5
Northern Circumpolar db	Hugelius et al. 2013a[8] and Hugelius et al. 2013b[8]								x																			1
Misc basal peat data from GSC	MacDonald et al. 2006[9]												x															1
Lehigh peat core database	Loisel et al. 2014[10]						x	x	x	x			x															5

Datasets	Contact and/or Reference	Depth to water table	Water table date measured	Peat depth	Wetland type	Cover% by veg layer	Bulk Density	Organic Matter density	Organic Carbon	Peat density	pH	Soil chemistry	Peat core age data	Fluxes of CH_4/CO_2	AG biomass and partitioning	AG:BG biomass ratios	BG biomass and partitioning	Productivity/Turnover rates	Time to max biomass	Disturbance interval	AG litter decay and transfer rates	BG Litter Decay and Transfer rates	Acrotelm Peat Decay (rates, Q10)	Catotelm peat decay (rates, Q10)	Short-term peat accumulation rates	Long-term peat accumulation rates	Evapo-transpiration	Utility ranking
McLaughlin Data	McLaughlin and Webster 2013[11,15]																											NR
	Akumu and McLaughlin 2013[12]			X			X		X	X																		4
Biomass & productivity data	Campbell et al. 2000[13]				X										X			X										3
	Other source lit[13]				X											X	X		X	X								5
Decay data	Thormann et al. 2001[14] and other literature sources				X																X	X						3
Mer Bleue	Murphy et al. 2009[15] and other related				X										X	X	X											4
	Moore et al. 2002[15]				X									X	X	X		X							X			6
NFI	G Stinson & G Russo [15]																											NR
Canadian Forest Ecosystem Classification	K Chapman and K Baldwin[15]																											NR
ABMI	http://www.abmi.ca/home/data/welcome-data-portal.html or abmiinfo@ualberta.ca[15]																											NR

[1] captured data
[2] captured spatial db, not point-source data
[3] captured 3 tables, 100 sites

[4] captured 3 tables: 626 sites
[5] db w 818 records not found (but includes Zoltai et al. 2000 626 sites)
[6] data not yet captured (request - J Bhatti): 203 ground sample sites;
[7] datasets obtained from EDR_database OFRI
[8] datasets in points and polygons,
[9] captured 83 records for core location, age, look to original refs for type, depth data
[10] captured 30 of 96 Canadian core files
[11] data not captured
[12] captured Victory mine 27 sites, publication pending
[13] captured all tables
[14] captured tables
[15] data not captured
[16] not ranked

9. Model evaluation and uncertainty analyses

Data from peatland experimental sites (Table 4) with multi-year measurements of C emissions and removals will be used for initial evaluation of module outputs by providing measurements of selected pools and fluxes that can be used in comparisons with model projections.

Model sensitivity and uncertainty analyses will be conducted in a future project phase to quantify the sensitivity of model outputs to parameter inputs. Uncertainty analyses using Monte-Carlo simulations with simultaneous variations of parameters across a range of values will be used to estimate the overall uncertainty in model predictions.

Table 4. List of evaluation sites, their location, peatland types and data.

Site name	Location	Peat types	Data	Years
White River	Mixedwood Boreal Shield, ON	Rich fen Intermediate fen Poor fen	CO_2, CH_4, NEE, water table, biomass	2004-present (water table) 2009-2012 (CO_2, CH_4, NEE)
Victor Mine	Hudson Plain, ON	Rich fen Intermediate fen Poor fen Bog Palsa	Water table, Biomass, CO_2, CH_4, NEE	2010-present (water table) 2011-present (flux tower CO_2, CH_4, NEE for bog and fen)
Arctic Fen and forested bog Churchill MB	Subarctic fen and forested wetlands	Poor fen and forested bogs	Water table, heat fluxes, Biomass, CO_2, NEE	1994 to 1998
BOREAS North	Boreal Plains	Poor fen	Leaf area, Heat fluxes, water table, CO_2, CH_4 fluxes	1994, 1995, 1996
BOREAS South	Boreal Plains	Rich Fen	Leaf area, Heat fluxes, water table, CO_2, CH_4 fluxes	1994, 1995, 1996 2004 to 2008
BOREAS South	Boreal Plains	Bog	Leaf area, Heat fluxes, water table, CO_2, CH_4 fluxes.	1994, 1995, 1996
Alberta Fluxnet sites	Boreal Plains	Fen and Bog	Leaf area, Heat fluxes, water table, CO_2, CH_4 fluxes.	2004 to 2008
Mackenzie Valley	AB, NWT	Bogs and Collapse scars	Leaf area, Heat fluxes, water table, CO_2, CH_4 fluxes. (Static measurements)	2008 to 2010
Peat transect	SK	Bog and rich fen	Leaf area, Heat fluxes, water table, vegetation changes, Biomass both above ground and below ground, decomposition	2002 to 2005

10. Planned Phase 1 (year 1 and 2) activities

The following are activities and deliverables from phase 1 of the project:

10.1 Spatial database of peatland types

A survey of peatland spatial layers available will be conducted. Permission will be sought to obtain data layers relevant to the project and compile them into a Geodatabase. Layers will be synthesized to produce a "best available" layer of key peatland types identified for input to the module. Criteria will be developed to assess the utility of the data layers for this project. Gaps and uncertainties in the data layers will be assessed.

10.2 Point source field databases and validation data areas

A survey of point based field data of peatland properties will be conducted. Permission will be sought to obtain data relevant for the project for calibration, parameterization and testing purposes.

10.3 Module

A module design document for the CaMP that includes a revised pool structure, algorithms, and data requirements that accounts for the unique processes that occur within peatlands will be written. The design document will include a list of parameters needed for each peatland type.

10.4 Spatial distribution of wetland categories and emission factors

Using emission factors from previously-published field studies from different peatland types across Canada and the area of peatland types taken from the Peatlands of Canada Database, initial national estimates of methane emission and gross and net carbon dioxide emissions will be prepared to improve on the existing values (Kurz et al. 1992, Moore and Roulet 1995, Roulet 2000).

10.5 CaMP with static water table simulation

The CaMP version 1.0 module will be coded using the assumption of a static water table. The module will be tested and evaluated with data from the validation database. Using "best available" peatland layer from 10.1 the CaMP will be run at a national scale to derive estimates of emissions and removals of carbon dioxide and methane from peatlands.

10.6 Model documentation and publication of results

The details of the CaMP module will be documented and the initial results obtained with the module will be summarised in a short report. One or more manuscripts on the methods and results will be prepared for submission to scientific peer review.

11. Phase 2 (year 3) activities

The following are activities and deliverables from phase 2 of the project:

11.1 CaMP with dynamic water table simulation

Version 2.0 of the CaMP will be implemented using a dynamic water table algorithm. The module will be tested and evaluated with data from the validation database. Using "best available" peatland layer from 10.1 The CaMP will be run at a national scale to derive estimates of emissions and removals of carbon dioxide and methane from peatlands.

11.2 Permafrost

Approaches to integrate the Northern Ecosystem Soil Temperature (NEST) model or implementation of key algorithms taken from NEST or other models will be investigated. Incorporation of soil temperature would allow a future version of the CaMP to simulate permafrost dynamics.

11.3 Activity data

Fire, permafrost thaw, insect infestation, forest harvesting, peat harvesting, flooding from hydroelectric development, industrial development and associated infrastructure and peat removal from mining are key activities that affect pools and fluxes within peatlands. A survey of available data layers describing these activities will be compiled and permission sought to obtain the data layers.

11.4 Representation of anthropogenic and natural disturbance

A survey of the literature and consultation with experts will be conducted to create the disturbance matrices for disturbance types within peatland systems.

11.5 National estimates of peatland C emissions and removals

Using the “best available” layer of peatland types, a dynamic water table and simulation of soil temperature (permafrost) with disturbance matrices, the model will produce historical, contemporary and future scenario-based estimates of national peatland C emissions and removals. These can be included in future international reporting, once peer-review and other due diligence processes have been completed.

11.6 Model documentation and publication of results

The details of the CaMP module from phase 2 will be documented and the results obtained with the revised module will be summarised in a short report. One or more manuscripts on the methods and results will be prepared for submission to scientific peer review.

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