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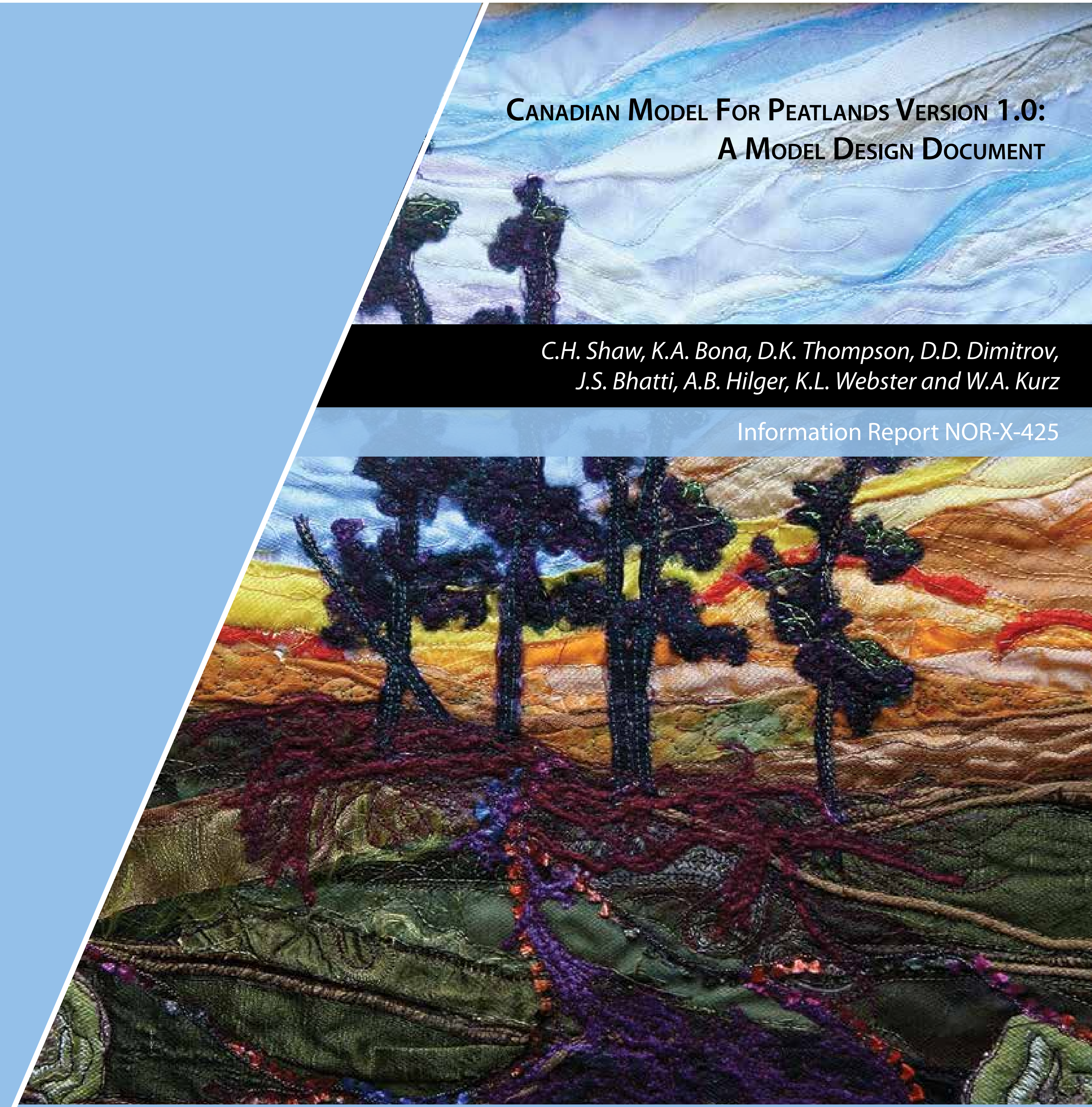

Canadian Model For Peatlands Version 1.0: A Model Design Document

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Canadian Model For Peatlands Version 1.0: A Model Design Document

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Canadian Forest Service
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ABSTRACT

A three-year forested peatland modeling project, funded by the Canadian Boreal Forest Agreement, was developed in response to the need for national-scale greenhouse gas estimates from the extensive peatlands in Canada's forested area. This document describes the design plan for one component of the project: version 1.0 of the Canadian Model for Peatlands (CaMP v1.0). The CaMP v1.0 will be developed as a module for the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS), which is used to meet national and international greenhouse gas reporting requirements but currently only accounts for upland forest systems. The CaMP is intended to simulate carbon (C) stock changes and emissions in the top 100 cm of peat, which 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. The CaMP will be compatible with the newest modeling framework of the CBM-CFS and is designed for application at multiple scales (site level to national level) and for spatially referenced (polygon based) and spatially explicit (raster based; ≥ 30 m resolution) modeling approaches. The CaMP will simulate annual growth and decay of live and dead C pools (originating from a woody layer [roots, stems, and foliage], a moss layer [feather moss and sphagnum], and a sedge layer [roots and foliage]), which will eventually be transferred to an oxic peat layer (acrotelm) and then a water-saturated peat layer (catotelm). The CaMP will be calibrated and tested for 11 peatland categories, representing different combinations of tree canopy cover (forested, treed, or open) and wetland classification (bog, poor fen, rich fen, or swamp). These peatland categories will be mapped for Canada in another component of the project to allow for national-scale estimates of peatland C emissions and removals. Methane emissions will be modeled as a proportion of the total C emitted that is a function of water table depth. The CaMP v1.0, described here, will be built assuming a static water table estimated for each combination of peatland category and ecozone. Version 2.0 of the CaMP will include a dynamic water table modeled as a function of a regional drought code and include moisture and temperature modifiers to decay and growth functions with the aim of providing future predictions of peatland C budgets in response to climate change, including permafrost thaw. It will also include modeling of natural and anthropogenic disturbance effects.

RÉSUMÉ

Un projet de modélisation des tourbières boisées de trois ans, financé par l’Entente sur la forêt boréale canadienne, a été développé en réponse à la nécessité d’estimer les gaz à effet de serre à l’échelle nationale dans les vastes tourbières de la région boisée du Canada. Ce document décrit le plan de conception pour une composante du projet : la version 1.0 du Modèle canadien en matière de tourbières (MCaT). La version 1.0 du MCaT sera développée comme module pour le Modèle du bilan du carbone du secteur forestier canadien (MBC-SFC3), qui est utilisé pour répondre aux exigences nationales et internationales de reddition de compte sur les gaz à effet de serre, mais qui ne représente actuellement que les systèmes forestiers des hautes terres. Le MCaT est destiné à simuler les changements et les émissions de stocks de carbone (C) dans les 100 cm supérieurs de la tourbe, qui sont les plus sensibles aux changements climatiques et édaphiques et les plus sensibles aux perturbations anthropiques et naturelles, pour des périodes contemporaines (de 1990 à aujourd’hui) et futures (de 10 à 100 années à venir). Le MCaT sera compatible avec le cadre le plus récent de modélisation du MBC-SFC3 et est conçu pour une application à plusieurs échelles (de l’échelle d’un site et à l’échelle nationale) et pour des approches de modélisation à référence spatiale (en polygones) et spatialement explicite (raster; ≥ 30 m de résolution). Le MCaT permettra de simuler la croissance annuelle et la décomposition des réservoirs vivants et morts de carbone (provenant d’une couche ligneuse [racines, tiges et feuillage], d’une couche de mousse [plume de mousse et de sphaigne] et d’une couche de carex [racines et feuillage]), qui seront ultérieurement transférées à une couche oxique de tourbe (acrotelme), puis à une couche de tourbe saturée d’eau (catotelme). Le MCaT sera étalonné et testé pour 11 catégories de tourbières, représentant différentes combinaisons de couverts forestiers (tourbières forestière, arborée ou ouverte), et de classification de zones humides (tourbières ombrotrophe, minérotrophe pauvre, minérotrophe riche ou marécage). Ces catégories de tourbières seront cartographiées pour le Canada dans un autre volet du projet afin de permettre des estimations à l’échelle nationale des émissions et des éliminations de carbone dans les tourbières. Les émissions de méthane seront modélisées en tant que proportion du total émis de carbone, qui dépend de la profondeur de la nappe phréatique. La version 1.0 du MCaT, décrite ici, sera construite en supposant une nappe phréatique statique estimée pour chaque combinaison de catégories de tourbière et d’écozone. La version 2.0 du MCaT comprendra un tableau d’eau dynamique modélisé en fonction du code de la sécheresse régionale et comprendra des modificateurs d’humidité et de température rattachés aux fonctions de décomposition et de croissance dans le but de fournir des prévisions pour l’avenir des budgets de carbone dans les tourbières en réponse aux changements climatiques, y compris le dégel du pergélisol. Il comprendra également la modélisation des effets perturbateurs naturels et anthropiques.

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INTRODUCTION

Peatlands are wetlands with more than 40 cm depth of peat development (National Wetlands Working Group 1997). The International Peatland Society (IPS) defines peat as a "heterogeneous mixture of more or less decomposed plant material that has accumulated in a water saturated environment in the absence of oxygen" (IPS 2016). Canada contains the world's second largest area of peatlands (after Russia), covering approximately 13% of the Canadian land area (Tarnocai et al. 2011), of which approximately 96% (1050 × 103 km^2) is in Canada's boreal zone (Kurz et al. 2013; Tarnocai 2006). Peatlands in the boreal zone alone contain 137 Pg of organic carbon (C) (Kurz et al. 2013), representing approximately 93% of all peatland C stored in Canada (Tarnocai 2006). Canada's peatlands provide many important ecosystem services, such as water storage, wildlife habitat, and C sequestration.

The importance of boreal peatlands to the Canadian and global C balance has been widely recognized (Gorham 1991). Boreal peatlands have been studied extensively through experimental work, as reviewed in Roulet et al. (2007), Limpens et al. (2008), and Yu (2012), and through process-based modeling, as reviewed in Farmer et al. (2011), Wu et al. (2012), and Schuldt et al. (2013). Many studies have investigated the C balance of peatlands as influenced by land-use change (afforestation, deforestation), management practices in forestry and peat harvesting (Daigle and Gautreau-Daigle 2001; Rochefort and Daigle 2000), climate change (Strack and Waddington 2007), permafrost thaw (Chasmer et al. 2012), and the increase in fire frequency (Wieder et al. 2009) and intensity (Thompson et al. 2015). However, national-scale distributions and net greenhouse gas balances of peatlands are still poorly understood, and this lack of understanding must be addressed to satisfy growing international pressure for better C accounting of peatlands within managed forests. Recent comments from the United Nations Framework Convention on Climate Change (UNFCCC) expert review team on Canada's greenhouse gas inventory recommended that representation of deep organic soils be improved. Currently the National Forest Carbon Monitoring, Accounting and Reporting System, of which the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS) is the core model, does not include peatlands, and Canada's National Inventory Report (accessed February 2016 at http://unfccc.int/national_reports/annex_i_ghg_inventories/national_inventories_submissions/items/8812.php) to the UNFCCC only reports on peatlands managed for peat extraction. Therefore, the greenhouse gas balances of forested peatlands should be determined to improve the completeness and accuracy of the reporting of emission and removal estimates from Canada's managed forests.

A comprehensive way to model the peatland C greenhouse gas balance at the national scale in Canada is to develop a peatland module for the CBM-CFS, which is the existing tool used for national estimation and reporting of C stocks and stock changes in Canada's managed forest area (Kurz et al. 1992, 2009; Stinson et al. 2011). In the first C budget of the Canadian forest sector (Kurz et al. 1992), peatlands were included assuming one C accumulation rate for all peatlands. Recognizing that representation of peatlands must be improved, Natural Resources Canada staff began discussions on how to build a CBM-CFS peatland module in 1994 (Kurz, W.A.; Apps, M.J.; Bellan, D.; Gignac, D.; Hogg, E.; Seburn, D.; Warner, B.; Wein, R.; Vitt, D.; Zoltai, S.C. 1994. A carbon dynamics model of Canadian peatlands. Unpublished draft design document) but the work did not progress because of organizational constraints at that time. Since then, the global importance of peatlands as C stores has been repeatedly recognized and was recently highlighted in "A Blueprint for Forest Carbon Science in Canada 2012–2020" (Bernier et al. 2012) as a top priority. Meanwhile, reviews of detailed observations and simulations conducted in different peatland types and peatland-forest transition zones have enhanced our understanding of C cycling processes and their ecological controls (e.g., Roulet 2000; Vitt et al. 2000; Lai 2009; Sulman et al. 2010; Yu 2012; McLaughlin and Webster 2013).

A three-year forested peatland modeling project, funded by the Canadian Boreal Forest Agreement, was developed in response to the need to improve C accounting in Canadian peatlands. This document describes the design plan for one component of the project: version 1.0 of the Canadian Model for Peatlands (CaMP v1.0). The CaMP v1.0 will be developed as a module for the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS), which is used to meet national and international greenhouse gas reporting requirements but currently only accounts for upland forest systems. Estimation of peatland C stock changes for Canada requires a standardized spatial representation of peatland categories for the nation and a simulation model that can be applied to the spatial units. As part of the peatland modeling project a unified map of peatland categories will be built using existing regional and national mapping products and published data. The peatland categories that will be mapped are those useful for reporting purposes and for which sufficient data are available to parameterize a simple simulation model for peatland C dynamics that will be called the Canadian Model for Peatlands (CaMP). The CaMP will be built as a module (i.e., a sub-model) for the newest version of the CBM-CFS and will be designed to fit within the current temporal and spatial constraints of the CBM-CFS. In this document we describe the design plan for CaMP v1.0, which will be a simple model of peatland C stocks and stock changes using a static water table. We describe different peatland categories that will be modeled with the CaMP and the key components of the CaMP, including pools, model drivers, and parameters. We also describe:

- how the CaMP will be constrained to fit within the current CBM-CFS framework,
- how methane emissions will be modeled,
- how the static water table will be estimated for different peatland categories and ecozones,
- how peatland C stocks will be initialized, and
- how the CaMP will be evaluated against available data.

Version 2.0 of the CaMP (CaMP v2.0) will include a dynamic water table as well as the more complex effects of edaphic and climatic factors on decay and growth functions. We give an overview of version 2.0 in the section of the present document entitled “Future Steps for Version 2.0 of the CaMP”; full specifications will be given in a separate design document.

MODEL CONSTRAINTS

The CaMP will be designed in close collaboration with the Canadian Forest Service Carbon Accounting Team (CAT) and will have conceptual and structural similarities to the CBM-CFS (Kurz et al. 2009) for implementation as a module in the next generation of the CBM, which is currently under development. The modeling approach for moss productivity and turnover within the CaMP will be consistent with that used in MOSS-C (Bona et al. 2016), a module developed for the CBM-CFS to include mosses in upland forests with deep organic layers (Fig. 1). Consistency among the CaMP and MOSS-C modules and the CBM-CFS for reporting purposes will be ensured either by mapping the modules' outputs to the CBM-CFS outputs or by adding new outputs to the CBM-CFS in cases where additional pools or fluxes must be included in the modules (Bona et al. 2016, Fig. 1). These outputs, in turn, are congruous with the Intergovernmental Panel on Climate Change tables for international reporting purposes as described in Table 2 in Kurz et al. (2009) (Fig. 1).

The CaMP will be built to simulate C stock changes and emissions in the top 100 cm of peat, which was deemed the biogeochemically dynamic portion of the peat. Below 100 cm the peat decomposes very slowly, has little to no root growth, has minimal intra-annual variation in temperature or moisture, and is minimally affected by natural and anthropogenic disturbances (Beer and Blodau 2007; Morris and Waddington 2011). Constraining the modeling effort to the top 100 cm also makes model initialization, calibration, and validation at the regional and national scale attainable given the

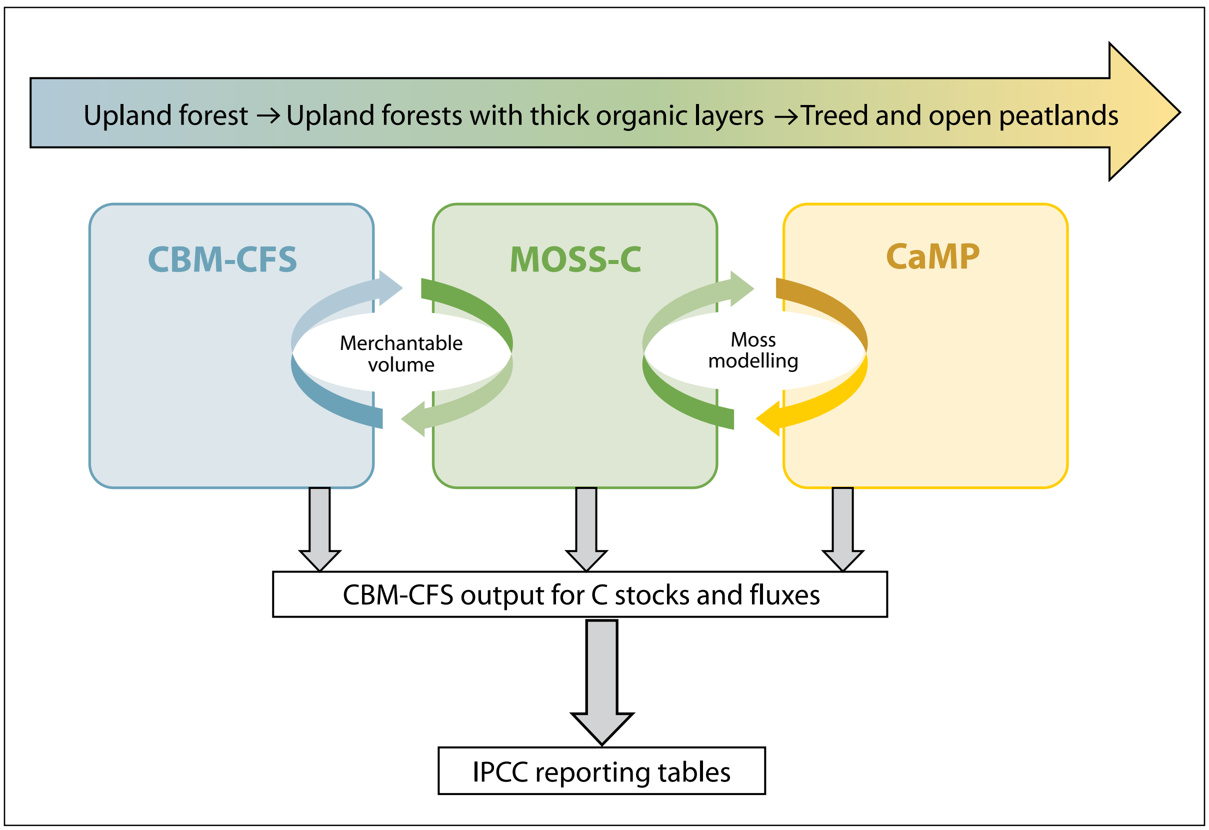

Figure 1. The relationships between the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS), the MOSS-C module, and the Canadian Model for Peatlands (CaMP) module. The CBM-CFS and MOSS-C are linked by relationships between merchantable yield curves in the CBM-CFS and moss productivity in MOSS-C. MOSS-C and the CaMP are linked through a unified approach to moss modeling. All three produce outputs that feed into standardized output file formats for the CBM-CFS that in turn can be compiled into Intergovernmental Panel on Climate Change (IPCC) reporting tables.

limitations on available data. The CaMP v1.0 will be designed to model peatland C fluxes to the atmosphere (i.e., CO_2, CH_4) on the basis of a predicted water table, peatland C stocks, decay, and transfers between pools. The total modeling forecast period following initialization (spin-up) will be 10 to 100 years, which is consistent with the contemporary time frame of the CBM-CFS. The CaMP is being developed so that it can be applied to individual peatland sites, but its primary application will be for regional and national predictions for national and international reporting purposes. It will be useful for both spatially referenced (polygon based) and spatially explicit (raster based; ≥ 30 m resolution) approaches that can be used with the CBM-CFS.

PEATLAND CATEGORIES FOR MODELING WITHIN THE CaMP

Upland forest types are already represented in the CBM-CFS, and upland forests with deep organic layers will be represented in the CBM-CFS by the MOSS-C module (Bona et al. 2016, Fig. 1). Here, we define the peatland categories for the CaMP that can be described, mapped, and modeled with currently available data.

The Canadian Wetland Classification System (National Wetlands Working Group 1997) is the foundation for wetland classification in Canada and is the basis of the Canadian Wetland Inventory (Warner and Rubec 1997). The classification system includes five main wetland classes (bog, fen, swamp, marsh, and shallow water), with sub-classes based on key vegetation layers (moss, herb, shrub, and tree [either coniferous or deciduous]). While many provinces have adopted this classification system, early work to define or map peatlands or wetlands was reported using coarser separations (e.g., treed versus non-treed) than those adopted in the Canadian Wetland Classification System. For our modeling purposes, we have defined forested, treed, and open peatland categories (Table 1). Forested types are defined to be consistent with Canada's definition of forest land, which in turn is consistent with the Intergovernmental Panel on Climate Change standards as implemented for Canada's national and international reporting (Stinson et al. 2011). Forested categories only include sites with large trees (potential height ≥ 5 m and > 25% cover at maturity). Forested peatlands that are potentially transitional to upland black spruce sites with shallow peat layers (such as the CaMP forested bog category) can be modeled using MOSS-C within the CBM-CFS; however, further testing of MOSS-C will be needed to confirm this approach. Treed peatlands are dominated by small trees (potential height < 5 m, 10–25% cover), and open peatlands are dominated by a shrub layer that can contain tree species and sparse small trees (potential height < 5 m, < 10% cover) (Table 1). There are 11 CaMP peatland categories (Table 1), seven of which are termed treed or open and will be modeled within the CaMP and four of which are termed forested and will be modeled within the CBM-CFS with MOSS-C enabled, or within the CaMP.

The basic modeling unit for upland forests in the CBM-CFS is the "forest stand" (Kurz et al. 2009), which is characterized in the model by unique combinations of classifiers (forest age, land class, productivity, stocking, forest type, site quality, maturity, management). We will name the analogous basic modeling unit in the CaMP the "peatland site". Each peatland site will be characterized by three classifiers: peatland category, ecozone (ESWG 1996), and province or territory. The complementary work being done on the mapping component of this project will ensure that the MOSS-C and the CaMP are appropriately applied to upland or peatland sites.

Table 1. Definition of peatland types and the Canadian Model for Peatlands (CaMP) peatland categories

		Potential tree growth at maturity		
Type	Definition	CaMP category	Cover (%)	Height (m)
Swamp	Swamps are minerogenous wetlands dominated by trees and/or shrubs that generally cover > 30% of the area. Peat (formed in situ) is therefore mainly derived from wood but there is often organic matter accumulated from lateral transfers, setting swamps apart from forested or treed bogs and fens. Swamps can be on organic or mineral soils. Swamps on organic soils that have > 40 cm of organic layer (or peat) are categorized as peatlands. In contrast, mineral wetland swamps (with < 40 cm organic layer depth) can be on a variety of soil parent materials ranging from sand to clay, but they are frequently on Gleysols. Swamps develop peat through basin filling where the original system was a fen or a marsh or through paludification where the original ecosystem was an upland forest. Swamps can be dominated by conifers, hardwoods, shrubs, or mixed wood/shrub. Swamps include a wide range of nutrient regimes.	Forested swamp	> 25	≥ 5
		Treed swamp	10–25	< 5
Bog	Bogs are raised or level with surrounding areas and are dominated by sphagnum moss. They are characterized as being ombrogenous; therefore, they receive water solely from precipitation, fog, or snow melt and are not influenced by groundwater or run-off from the surrounding terrain. Water is low in dissolved minerals and generally acidic (ranging from pH of 4.0 to 4.8). Peat accumulated in bogs is > 40 cm in depth and is mainly from sphagnum moss mixed with woody debris from ericaceous shrubs, and, if trees are present, they are black spruce.	Forested bog	> 25	≥ 5
		Treed bog	< 10	< 5
		Open bog	10–25	< 5
Fen	Fens are characterized by the flow of geogenous water from groundwater and/or various surface water sources such as lakes, streams, run-off, or spring melt. Differences in water sources and mode of water transport (e.g., via channels or open pools) create different fen surface characteristics and nutrient statuses. Peat accumulated in fens is > 40 cm in depth and is mainly derived from sedges and brown moss, as they are dominated by graminoids, dominated by bryophytes, or contain a mixture of both.			
Poor fen	Water sources are low in base-cations, with little to no alkalinity and a high concentration of hydrogen ions leading to a poor nutrient status. Generally these fens have a pH < 5.5. Poor fens can be seen as intermediates between bogs and rich fens, and they share elements of both. They are dominated by graminoids, with some sphagnum moss cover (usually > 20% cover).	Forested rich fen	> 25	≥ 5
		Treed rich fen	10–25	< 5
		Open rich fen	< 10	< 5
Rich fen	Rich fens are fed by water sources that tend to be alkaline, with a pH generally > 5.5, leading to a richer nutrient status. Rich fens are dominated by sedges and brown mosses, and in contrast to poor fens, they tend to contain no or very little sphagnum moss (usually < 20%) or ericaceous shrubs.	Forested rich fen	> 25	≥ 5
		Treed rich fen	10–25	< 5
		Open rich fen	< 10	< 5

THE CaMP POOLS AND PARAMETERS

Like the CBM-CFS, the CaMP will simulate internal C transfers (among modeled pools) and external transfers (to the forest products sector) and gaseous C emissions to the atmosphere. The approach is similar to that used for the CBM-CFS with biomass and dead organic matter (DOM) pools, inputs to biomass pools from growth curves or estimates of net primary productivity (NPP), C transfers from biomass to DOM pools through annual mortality, and C transfers between DOM or peat pools or the atmosphere through decay (Fig. 2). This section describes the pools, productivity inputs, and parameters with a static water table in the absence of disturbances. Dissolved organic C (DOC) and dissolved gaseous C (also known as dissolved inorganic C [DIC]) pools occur within peatlands. These pools were suggested for consideration during a 1994 workshop (Kurz, W.A.; Apps, M.J.; Bellan, D.; Gignac, D.; Hogg, E.; Seburn, D.; Warner, B.; Wein, R.; Vitt, D.; Zoltai, S.C. 1994. A carbon dynamics model of Canadian peatlands. Unpublished draft design document) but will not be included in the CaMP at this stage. Modeling DOC and DIC requires modeling lateral hydrological fluxes and leaching into the ground, processes that are not included in the CaMP because of the difficulty of parameterizing groundwater flow at a national scale.

Model Pools

The CBM-CFS has pools that are used to represent stand-level C stocks and stock changes in forest stands from trees (merchantable and non-merchantable sized) and in the DOM pools derived from trees (Fig. 2). The model is appropriate for stands containing sufficient volume from merchantable-sized trees to be represented by a yield curve. Although non-merchantable-sized trees are represented in the CBM-CFS their C stocks are predicted from the merchantable-sized tree volume or biomass (Boudewyn et al. 2007). The CBM-CFS structure can contribute to the modeling of forested peatland categories with merchantable-sized trees (forested CaMP categories, Table 1) but the majority of treed peatlands only have trees of a non-merchantable size. In this and subsequent sections we refer to such trees as small-sized trees, which are defined as having a potential height of < 5 m at maturity (Table 1). The CaMP pool structure will be used to represent peatlands dominated by different vegetation categories: small-sized trees as well as shrubs, sedges and mosses. Live biomass pools from these vegetation categories will be accounted for and the C from their litter will flow through specific DOM pools. The DOM pools will then flow into an acrotelm pool once they are deemed to be buried as peat or, in the case of roots, decayed for at least one year. Part of the acrotelm C pool will eventually flow into a water-saturated catotelm pool. The acrotelm and catotelm represent two distinct layers in undisturbed peatlands that are determined by the long-term average hydrological regime. The acrotelm is the upper layer of a peat, in which organic matter decomposes aerobically and more rapidly than in the underlying, anaerobic, catotelm. The thickness of the acrotelm limits the depth to which aerobic respiration can occur. The catotelm is the bottom layer of peat that is below the water table in all but drought conditions (Verry 1984). Under anaerobic conditions, microbial activity and peat decomposition are very slow. The catotelm is composed of relatively decomposed, compacted peat where water movements are slow. A normalized median depth of the static water table (see section entitled "Simulation of a Static Water Table") will be used to determine the boundary between the acrotelm and catotelm pools. The water table depth estimate will subsequently be used to determine the relative depth of the acrotelm and catotelm (keeping in mind the 100-cm total depth limit that the CaMP will model). This peat depth will also be used to estimate a mean bulk density for the acrotelm and catotelm pool using data from Tarnocai et al. (2005), which will be important in determining C transfer rates due to a changing water table in version 2.0 of the CaMP.

The CaMP includes live and dead pools for woody layer stems/branches, roots, and foliage (Fig. 2) to simulate input, turnover, and decay dynamics differentiated by peatland categories. The relative proportion of woody plant types (small trees and large shrubs vs. small shrubs) and hardwood or softwood dominance for

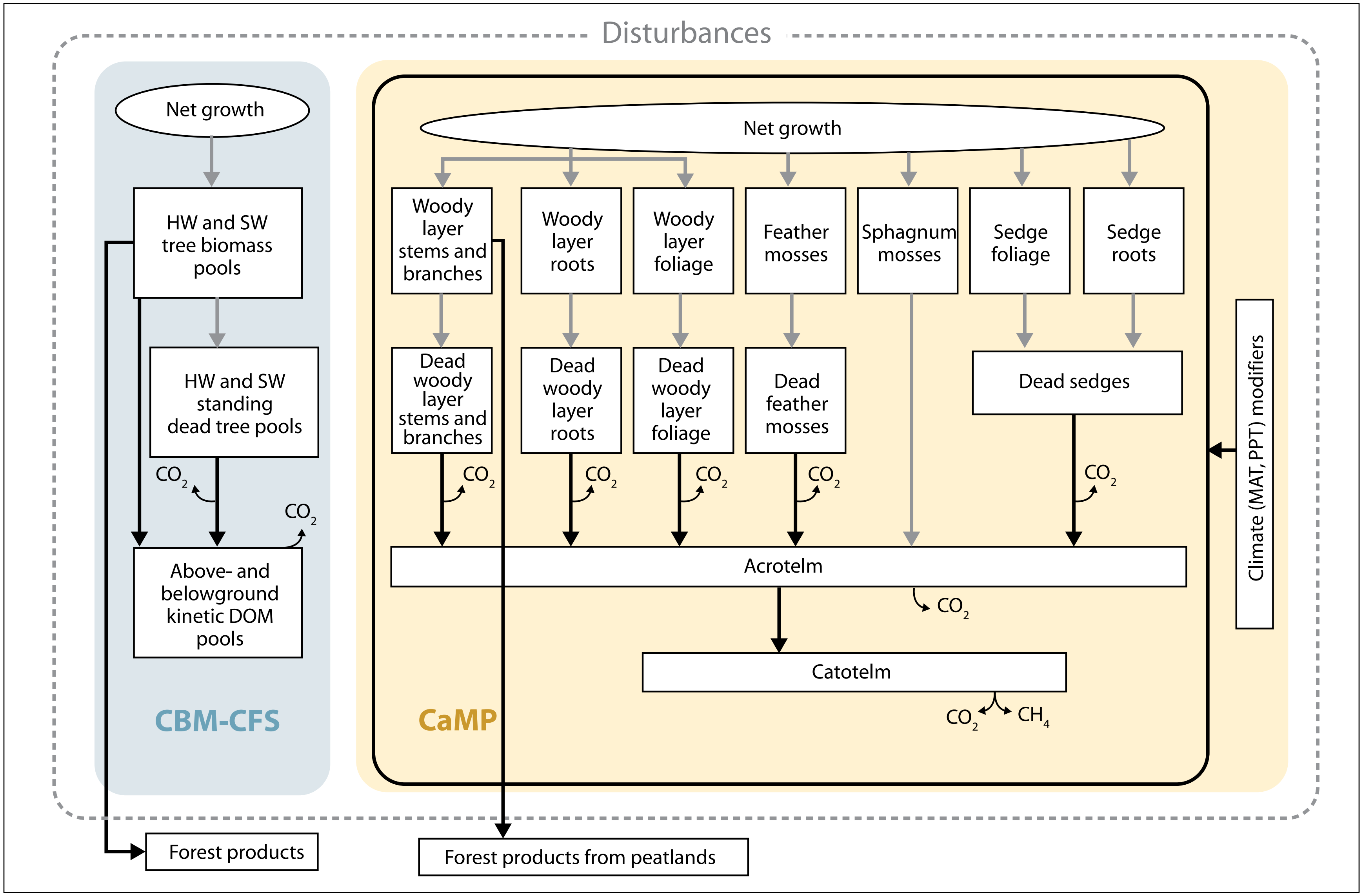

Figure 2. The modeling structure of the Canadian Model for Peatlands version 1.0 (CaMP v1.0) with a static water table (yellow), alongside a simplified structure of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS) (blue). Ellipses enclose inputs that drive the models. The top row of boxes represent biomass pools and all boxes below them represent dead organic matter (DOM) or peat (acrotelm and catotelm) pools. Gray arrows represent transfers of carbon (C) into and out of biomass pools because of annual growth or mortality, respectively. Straight black arrows represent direct transfers of C from the acrotelm to the catotelm, and out of the woody layer stems and branches pool to forest products from peatlands. In the simplified representation of the CBM-CFS, straight black arrows represent transfers of C from trees to forest products and transfers of C from trees to DOM pools from disturbances like wildfire. Straight black arrows combined with curved black arrows represent C removed from a DOM or peat pool because of decay and indicate the fate of the C emitted to the atmosphere as CO_2 or CH_4 (curved arrows) or transferred (straight arrows) 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 affect both the CaMP and the CBM-CFS. HW = hardwood, MAT = mean annual temperature, PPT = precipitation, SW = softwood.

different peatland categories will help to reflect differences in foliage turnover and decay rates (Moore et al. 2005).

Sedges have a prominent role in rich fens; accordingly, data must be compiled for the sedge pool to account for their growth, turnover, and decay dynamics, which are typically much more rapid than those of other vascular plants and (non-vascular) mosses (Szumigalski and Bayley 1996; Laiho 2006). The sedge foliage pool (Fig. 2) includes all sedge aboveground biomass measured in the field, that is mainly foliage but could also include other plant parts. It is important to track sedge root biomass separately from sedge foliar biomass in part because of the former's unique effect on methane emission rates (e.g., Chanton et al. 2005, Noyce et al. 2014), the dynamics of which may be incorporated into version 2.0 of the CaMP.

Mosses in the CaMP will be represented by the same feather moss and sphagnum pools used in MOSS-C (Bona et al. 2016). The feather moss fast pool in MOSS-C (Bona et al. 2016) will be added to the dead feather mosses pool in the CaMP, and the combined sphagnum fast and feather moss slow pools in MOSS-C will be added to the "acrotelm" pool, which represents aerobic peat in the CaMP. The sphagnum slow pool in MOSS-C will be added to the CaMP anaerobic peat and named "catotelm" (Fig. 2). Sphagnum litter will be the only DOM-derived C that does not have its own separate dead pool tracked before flowing into the acrotelm; it will instead flow directly to the acrotelm. This is due to the way sphagnum mosses grow in a continuum from live to dead, making it difficult to define a clear dead sphagnum moss pool (as opposed to dead woody debris or sedge foliage). Since dead vegetation litter pools are defined as being transferred to the acrotelm once buried by mosses or sufficiently incorporated into the peat, and since sphagnum mosses bury themselves as they grow, C derived from sphagnum moss litter will be immediately incorporated into the acrotelm layer.

Productivity and Net Growth

Biomass pools in the CaMP (Fig. 2) will receive C inputs from net growth and productivity data, and productivity estimates will be organized at the level of the classifier sets consisting of peatland category and ecozone. Generating those values requires a different approach for the woody layer pools than for moss and sedge pools, because of differences in the biology of these components. For mosses and sedges, with annually renewed aboveground biomass, productivity values derived from literature sources will be used to estimate average annual productivity by peatland category and ecozone. For woody layer pools, biomass curve sets used to calculate annual net growth increments will be created using data from the published literature.

Representation of woody plant net growth over time for each peatland category and ecozone would use a set of growth curves that includes one curve for small trees and one curve for low shrubs. For open peatlands only a low shrub curve would be applied. The method for development of growth curves for small trees on organic soils is yet to be determined but conceptually would be based on ground plot biomass and productivity data for treed peatlands from the literature and databases (e.g., National Forest Inventory biomass and tree-ring data), in conjunction with a national-scale tree biomass model (Paré et al. 2013). The species-specific curves will be combined with information about the variability in species and tree cover percent associated with different peatland categories and ecozones from the literature and peatlands databases (e.g., Zoltai et al. 2000; Riley 1994a, 1994b, 2011; Riley and Michaud 1989); curves for small trees will be generated for each peatland category and ecozone. Thus, differences in the average biomass and composition of the woody vegetation among peatland categories and ecozones will be reflected in their growth curve sets.

Where the hardwood component in treed peatlands is largely tall shrubs, curves could be estimated by establishing a maximum biomass (Campbell et al. 2000) together with a time to maximum biomass, with the latter estimated at 20 years from a peatland reestablishment study (Wieder et al. 2009). Biomass curves for small shrub species (largely ericaceous species in bogs) could also be estimated from maximum biomass by peatland category and ecozone available in the literature (Campbell et al. 2000), along with time to maximum biomass, which is estimated at three years (Johnston et al. 2015). The resulting growth increments will be scaled by the percent cover values for shrubs by peatland category and ecozone.

Allometric relationships from the literature will be used to derive foliar, woody aboveground (AG) and belowground (BG; i.e., roots) contributions to total productivity. For small trees and tall shrub species, estimates could be derived from biomass partitioning equations previously developed for non-merchantable trees (Boudewyn et al. 2007). For low shrub species almost all of AG annual productivity is foliage production and, typically, about half of AG biomass is foliage (Reader and Stewart 1972; Grigal et al. 1985). Also, there are strong allometric relationships between AG biomass and BG productivity of low shrubs (Murphy et al. 2009; Murphy and Moore 2010) that can be used to estimate the contribution of BG parts to total productivity.

Productivity estimates for the foliage pool of sedges will use NPP and biomass values collected from the literature (e.g., Campbell et al. 2000; Saarinen et al. 1996) and averaged by peatland category and ecozone. Root productivity will be added by using an expansion factor (also derived from literature data [e.g., Wallén 1986, 1992; Murphy et al. 2009; Murphy and Moore 2010; Kosykh et al. 2008]). Since we constrain turnover of biomass to 100% or less (see subsection entitled "Mortality and turnover of biomass pools"), productivity estimates for sedge foliage may need to be adjusted to account for mortality and regrowth of sedges within the growing season. For example, one study found that sedge foliage productivity estimates doubled when intra-season mortality was taken into account (Bernard and Gorham 1978). Similar considerations may not apply to inferring productivity of roots, which can contribute eight times more biomass than foliage (e.g., poor fen, Moore et al. 2002) but for which intra-seasonal turnover may typically be less than 100% yr^{-1} (Saarinen 1996). These differences in characteristics for the foliar and root components of sedges mean that the foliage to root biomass ratio may not be representative of the foliage to root productivity ratio. However, strong relationships have been reported between AG biomass and BG productivity (Murphy and Moore 2010) and these could be used to infer the latter from more abundant literature data for AG biomass (Campbell et al. 2000). We will not implement a lag in recovery of sedge NPP values after fire disturbances, because of high survival rates of BG sedge parts that are submerged in water and are therefore protected from fire, allowing for rapid regrowth from rhizomes (Norton and De Lange 2003).

Productivity of moss pools (feather moss and sphagnum) will be estimated from literature values of NPP and percent cover (e.g., Campbell et al. 2000; Gunnarsson 2005; references in Bona et al. 2016) by peatland category and ecozone. Site-specific percent cover values for sphagnum and feather moss may also be estimated as a function of tree canopy cover as in the MOSS-C module (Bona et al. 2016); however, this function would need to be recalibrated and tested for peatland sites if the appropriate data are obtained. To represent the time required for recovery of moss NPP following fire, a lag period could be implemented as described for the MOSS-C module (Bona et al. 2016), where the lag time was set to 10 years (Benscoter and Vitt 2008). Percent cover values for sphagnum and feather moss will also be incorporated into the productivity rates for each.

Mortality and Turnover of Biomass Pools

Turnover (annual mortality) rates for biomass pools will be based on literature values for biomass components. Where turnover rates are not available, turnover rate estimates may be based on the relationship between NPP and biomass, that is, turnover equals NPP divided by biomass. The relationship between AG biomass and AG NPP was reported by Moore et al. (2002) for herb/sedge, shrub, and tree components from the analysis of a number of publications for northern peatlands. Using their and other values we can then solve for turnover by peatland category and ecozone. For feather moss and sphagnum pools, production is assumed to be equal to biomass and annual turnover is assumed to be 100% as in Bona et al. (2016). Although this may not be accurate on a year to year basis, it is a reasonable assumption as an average over the large temporal scale of this model. The assumption that total AG moss NPP is equal to moss litter input is also supported in peatland models such as that developed by Frolking et al. (2002) and Frolking et al. (2010).

Base Decay Rates and Transfer Rates

As in the CBM-CFS, the base decay rates, k (yr^{-1}), in the CaMP represent the proportions of DOM or peat pools that are removed from a pool because of decomposition independent of changes in environmental conditions (Table 2). These base decay rates can then be modified by factors such as moisture and temperature to produce an applied decay rate used in the model to simulate the effect of climate on decomposition. Decay rates reported in the literature are most often applied decay rates observed at the moisture and temperature conditions of the study site. The development of appropriate base decay rates from literature values will require compilation and analysis of applied decay rates. Base decay rates for the dead woody layer and the dead sedge pool will be derived from literature values.

It is yet to be determined how the base decay rates for the acrotelm and catotelm pools in the CaMP, and the flow of C between the acrotelm and catotelm pool that simulates the process of C accumulation in peat, will be calculated. Values for base decay rates could be drawn from the literature for different peatland categories and ecozones and the physical transfer rate from the acrotelm to catotelm pool could be calculated from the long-term peat accumulation rate (long-term apparent rate of C accumulation, LARCA) of 20–30 g C m^{-2} yr^{-1} in North America (Frolking et al. 2001). Analyses would have to be completed to ensure that the base decay rates are appropriately derived from literature data to match the definition of the modeled pools and to enable separation of decay from transfer and emission to the atmosphere as modeled in the CaMP. Alternatively, base decay rates could be calibrated along with other parameters for multiple pools simultaneously using a probabilistic inversion approach (Hararuk et al. 2015) if sufficient data were available to constrain and validate the parameters.

Net Methane Emission

Methane (CH_4) has a global warming potential that is 21 times that of carbon-dioxide for a 100-year time scale (Solomon et al. 2007), and it is therefore an important gas to consider when modeling C emitted to the atmosphere. This is especially true when modeling wetlands because peatlands are the largest contributor of natural CH_4 emissions globally (Kirschke et al. 2013).

Predictions of global and national CH_4 emissions using natural wetland models are highly variable and uncertain (Kirschke et al. 2013). Modeling methane emissions from peatlands can be challenging because of the large

Table 2. Base decay rates (*d*) and the proportion of decayed material that is transferred to a downstream pool (p_t) or released to the atmosphere as CO_2 (p_a = 100% – p_t) in the Canadian Model for Peatlands with a static water table (Fig. 2). Values will vary by peatland category and ecozone depending on vegetation composition. A methane (CH_4) emission will be simulated from the catotelm pool only, by proportioning p_a into CO_2 and CH_4 based on a relationship with water table depth (Fig. 3).

DOM or peat pool	Decay parameters		Physical transfer parameters			Source
	Base decay rate [yr^{-1}]	Q10	p_t	p_a	Pool receiving decaying material	
Dead woody layer stems and branches	0.1435	2	0.17	0.83	Acrotelm	Kurz et al. 2009
Dead woody layer foliage	0.355	2.65	0.185	0.815	Acrotelm	Kurz et al. 2009
Dead woody layer roots	tbd	tbd	tbd	tbd	Acrotelm	tbd
Dead sedges	tbd	tbd	tbd	tbd	Acrotelm	tbd
Acrotelm	tbd	1	tbd	tbd	Catotelm	tbd
Catotelm	tbd	1	1.0	1.0	n/a	tbd

DOM = dead organic matter.
n/a = not applicable.
tbd = to be determined.

temporal and spatial variability among reported flux rates and their dependence on a variety of complex processes (Arneth et al. 2010; Wania et al. 2010). Methane is first produced during anaerobic decomposition by methanotrophs within a peatland's water-saturated zone. It is then emitted to the atmosphere through three potential pathways: (1) diffusion, (2) ebullition, and/or (3) plant-mediated transport. The amount of CH_4 that reaches the atmosphere can be reduced if it is oxidized by aerobic methanotrophs in the oxic layers of peat. The proportion of CH_4 that is oxidized will be driven by the mechanism and timing of CH_4 transport through the oxic peat layers. Therefore, CH_4 flux can be generally described as the difference between its production and oxidation, the latter depending on the pathway CH_4 takes to the atmosphere.

There are several process-based wetland models that predict CH_4 production, and oxidation in detail, such as a natural wetlands model (Cao et al. 1996), the Wetland-DNDC model (Zhang et al. 2002), the LPJ Wetland Hydrology and Methane model (Wania et al. 2010), and the more recent TRIPLEX-GHG model (Zhu et al. 2014). These models predict CH_4 production and oxidation separately as a function of soil temperature, pH, and redox potential for individually tracked peat cohorts. Several of these models also predict CH_4 transport by using complex functions for CH_4 diffusion and ebullition through soil layers that are based on soil porosity, hydrology, and CH_4 solubility gradients or by using an aerenchyma factor to predict plant-mediated transport (Zhang et al. 2002; Wania et al. 2010; Zhu et al. 2014). Therefore, these CH_4 wetland emission models require several coupled equations representing a number of processes and a large number of parameters that are not available for national-scale modeling with the CaMP. Some methane wetland models (such as the one based on rice paddies; Cao et al. 1996) use a slightly more simplistic approach by modeling CH_4 production as a function of temperature and water table position, and CH_4 oxidation as a function of sedge gross primary productivity because an increase in plant growth would increase the oxidative rhizosphere offered by the plants. While this approach is more manageable, it assumes that the wetland is constantly inundated with water and it is based on grass- or sedge-dominant systems such as rice paddies (or fens) that may not be appropriate for all of the peatland categories included in the CaMP.

Since parameters to drive process-based methane wetland models across several peatland categories and regions in Canada are not available, a simplistic approach is required for the CaMP. Instead of modeling production and oxidation separately, the CaMP will predict total CH_4 flux. Methane emission will be modeled as net CH_4 (kg C m^{-2}) as a proportion of total net C emissions (CH_4 + CO_2) (kg C m^{-2}), partitioned from litter mass loss from the DOM C. The main drivers for CH_4 production are substrate availability and redox potential (Nilsson and Öquist 2009). This means that the depth at which CH_4 is produced, especially relative to the water table depth, will be highly important as it controls the degree of litter freshness in the anoxic zone. Furthermore, increasing the depth of the oxic layer will increase the probability that the CH_4 will be oxidized before reaching the atmosphere. We propose a scheme in which the net CH_4 to total C emission quotient (Q) is at a maximum value of 0.47 when the water table is at the peat surface and at a minimum value of 0 when the water table is at its lowest, which in this case will be the maximum depth of 100 cm that the CaMP will model (Fig. 3). These maximum and minimum net CH_4 quotients are derived from cited values in peatland and rice paddy CH_4 emissions models (Cao et al. 1996; Wania et al. 2010; Zhu et al. 2014) and are also in agreement with values from a literature review of 16 peer-reviewed journal articles citing over 240 CH_4:CO_2 emission ratios (Nilsson and Öquist 2009).

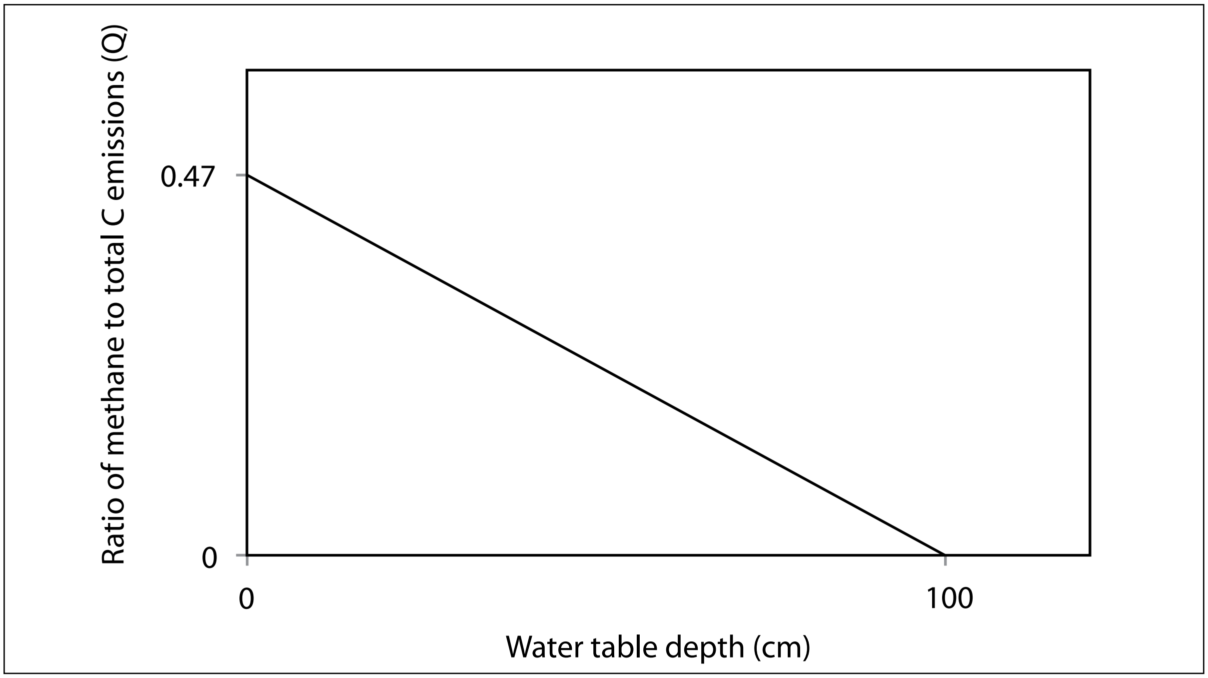

Figure 3. The proposed relationship between water table depth and the ratio between methane (CH_4) and total C emissions (Q = [CH_4 emissions]/[CH_4 emissions + CO_2 emissions]) used to predict methane flux in the Canadian Model for Peatlands version 1.0 (modified from Kurz, W.A.; Apps, M.J.; Bellan, D.; Gignac, D.; Hogg, E.; Seburn, D.; Warner, B.; Wein, R.; Vitt, D.; Zoltai, S.C. 1994. A carbon dynamics model of Canadian peatlands. Unpublished draft design document).

SIMULATION OF A STATIC WATER TABLE

Few geographically expansive measurements of peatland water table exist in boreal Canada; most observations of water table are for "point" locations over prolonged periods of time (e.g., Barr et al. 2012). One-time water table measurements were taken as part of the peatland survey work in western Canada (Zoltai et al. 2000) as well as northern Ontario (Riley and Michaud 1989). While a simple average water table per ecozone and peatland category can be estimated from databases of peat cores, water table depth needs to be normalized by the seasonal water balance deficit at the time of sampling, as water tables in peatlands are largely a function of the seasonal difference between evapotranspiration and precipitation inputs, with additional groundwater inputs in fens (Roulet and Woo 1986; Rouse 1998; Lafleur et al. 2005). If this normalization is not performed, historical measurements of water table that happened to be taken during drought periods could be misconstrued as being average values for the region. For single peatlands, a strong linear relationship exists between the water table and the drought code component of the Canadian Fire Weather Index system (Waddington et al. 2012). This linear relationship is the net result of two opposing forces: (1) a more rapid decline in water table per unit of evaporation due to peat specific yield (the decline in water table per unit of evaporation); and (2) a decrease in transpiration and surface evaporation with increasing water table. Specifics on these feedbacks can be found in Waddington et al. (2014). Geographically extensive historical water table measurements such as from Zoltai et al. (2000) and Riley and Michaud (1989) could be normalized by the drought code (which has been mapped in Canada at 3-km resolution on a daily basis since 1980) and stratified by ecozone and peatland category to derive a simple weather-driven peatland water table model. A single annual static water table value for use in annual time-step C accounting modeling would probably reflect the annual maximum water table depth rather than an average value, as even brief exposure of peat to oxic conditions above the water table increases decomposition rates by approximately a factor of 10 (Scanlon and Moore 2000). Moreover, by determining the drought code across Canada at drought conditions (for instance, the 95th percentile of the drought code over the 35-year record) consistent with the definition of the acrotelm–catotelm boundary following Verry (1984), this simple drought code driven water table model could also be used to approximate the depth of the acrotelm in moss-dominated systems. Using the maximum water table depth will, however, underestimate the amount of CH_4 emissions modeled, because CH_4 will only be emitted from the water-saturated peat layer. Therefore, median water table depth will be used to estimate the median acrotelm depth for a growing season.

INITIALIZATION OF THE CaMP

Before commencing simulations we need to initialize the dead woody layer pools and peat pools in the CaMP in a way that takes into account water table. To initialize the peat pools, water table depth for the growing season will be modeled from the 95th percentile of the daily calculation of the drought code from a 35-year (1980–2015) climate record and will be used to estimate the acrotelm depth. A look-up table of peat C density in the acrotelm and catotelm will be generated using data from Tarnocai et al. (2005) and will provide specific combinations of peat C density across differing peatland categories and ecozones. Combining depth and density values will yield a C stock estimate for the upper 100 cm. Moreover, modeling bulk density will become important in later versions of the CaMP where dynamic water table simulations are performed as the rate of C transfer in relation to water table flux is dependent on peat bulk density.

MODEL EVALUATION AND AVAILABLE DATA

Estimates of peatland C emissions with a static water table (version 1.0) and dynamic water table (version 2.0) will be tested against available observations at several sites across the country, with sensitivity and statistical analyses conducted to evaluate model performance. Data from peatland experimental sites (Table 3) with multi-year measurements of C emissions and removals will be used to evaluate performance of the CaMP v1.0 by comparing modeled outputs with measurements of selected pools and fluxes.

A national-scale validation will be conducted by comparing modeled output for each peatland category and ecozone with estimates based on the area for each peatland category by ecozone from the peatlands of Canada database (Tarnocai et al. 2005) and average bog and fen net ecosystem exchange (NEE) and CH_4 estimated from field-observed values. NEE and CH_4 are typically reported as growing season maximums; therefore, annual NEE and CH_4 rates will be estimated by taking into account the non-growing season and patterns of emissions throughout the growing season.

Table 3. List of validation sites, their location, peatland types, and available data

Site name	Ecozone or jurisdiction	Peatland type	Data	Years	Reference
White River	Boreal Shield, Ontario	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)	McLaughlin et al. unpublished data
Victor Mine	Hudson Plains, Ontario	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)	McLaughlin et al. unpublished data
BOREAS study region North and south	Saskatchewan and Manitoba	Rich fen Bog	Water table, biomass, CO_2, CH_4, NEE	1994–1997 (CO_2, CH_4, NEE)	Sonnenta et al. 2009
Mackenzie Valley	Alberta and Northwest Territories	Bog Peat plateau Poor fen	CO_2, CH_4, NEE, water table, biomass	2007–2010 (water table, productivity, CO_2, CH_4, NEE)	Bhatti et al. unpublished data
Sandhill Fen	Saskatchewan	Rich fen Bog	Water table, biomass, CO_2, CH_4, NEE	2007–2010 (water table, productivity, CO_2, CH_4, NEE)	Sonnenta et al. 2009

NEE = net ecosystem exchange.
BOREAS = Boreal Ecosystem-Atmosphere Study.

FUTURE STEPS FOR VERSION 2.0 OF THE CaMP

Version 2.0 of the CaMP will include all the features of the CaMP v1.0 and in addition it will (1) provide modeling of annual water table dynamics and their effect on peat C dynamics and growth of the woody layer, mosses, and sedges, (2) address the effects of temperature on peat C dynamics, the growth of the woody layer, mosses, and sedges, and (3) natural and anthropogenic disturbances, including permafrost thaw within peatlands. A separate design document will be developed for the CaMP v2.0; however, the CaMP v1.0 will include some conceptual and structural features that will enable rapid development of the CaMP v2.0.

In the CaMP v2.0, more features will be added to the static water table from version 1.0 (Fig. 2) to produce a dynamic water table (Fig. 4) with additional pools and fluxes to enable modeling of C dynamics with interannual change in water table depth. The same relationship that predicts water table depth as a function of drought code in version 1.0 will be used in version 2.0, except that drought code distribution will be updated annually on the basis of current climate data or modeled climate data for simulation of future scenarios. Two additional pools will be used to accommodate change in decay rates resulting from the movement of the water table up into the acrotelm (the anaerobic acrotelm pool) or movement down into the catotelm (the aerobic catotelm pool (Fig. 4). Carbon will be transferred in and out of the anaerobic acrotelm or aerobic catotelm pools in response to water table movement, and base decay rates for the new pools will be intermediate to those for the acrotelm and catotelm pools. These new pools will be built into the CaMP v1.0 so that they are available in the model structure for parameterization in

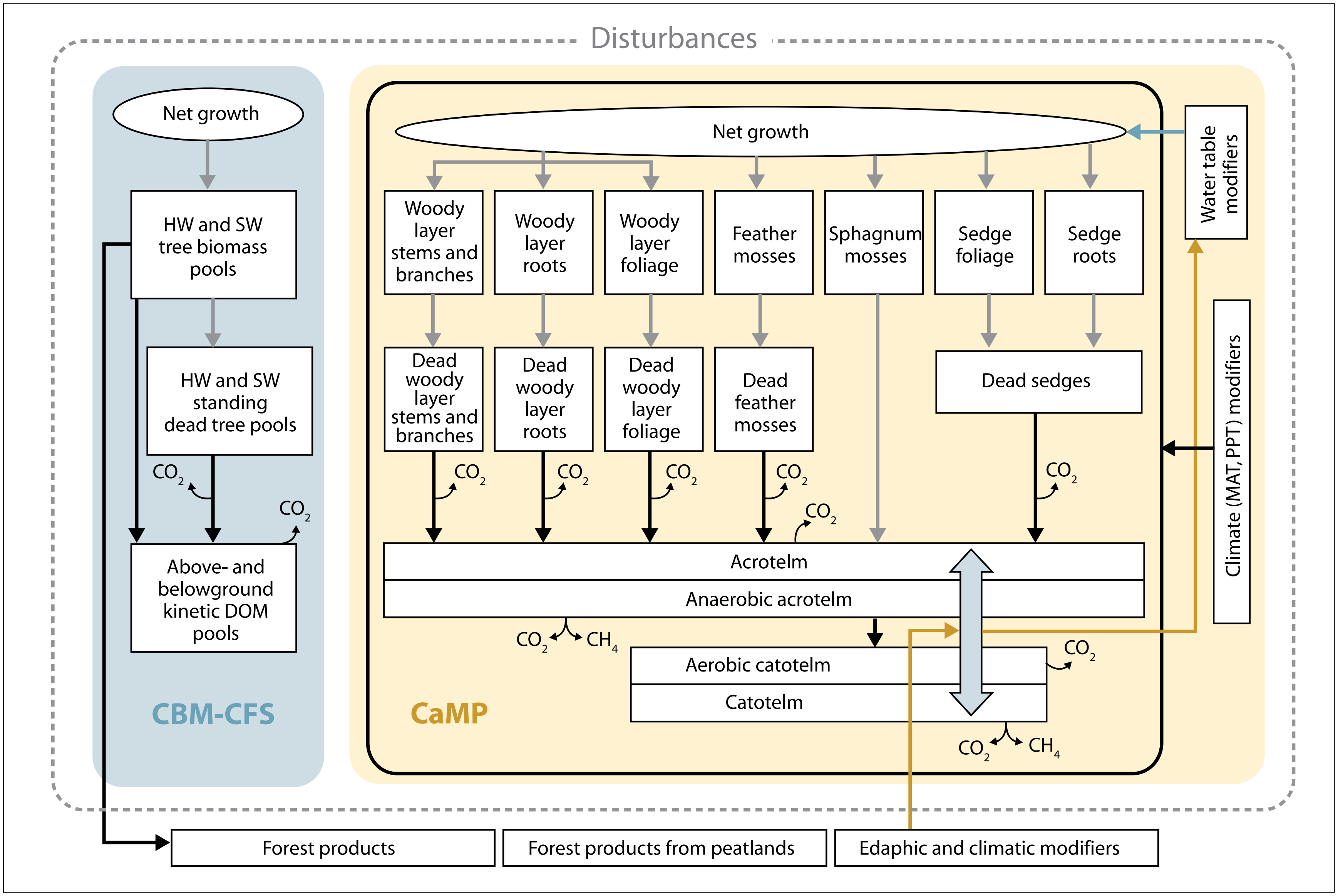

Figure 4. The modeling structure of the Canadian Model for Peatlands version 2.0 (CaMP v2.0) with a dynamic water table. The structure is the same as for the static water table of CaMP v1.0 (Fig. 2) with the addition of pools, fluxes, and transfers to accommodate a fluctuating water table (blue two-way arrow) that can be influenced by edaphic and climatic modifiers (brown arrow). Water table rise will cause a transfer of C from the acrotelm to the anaerobic acrotelm pool; a water table drop, because of drainage, will cause a transfer of C from the catotelm to the aerobic catotelm pool. Changes in the water table in turn influence water table modifiers (solid blue arrow) on productivity or on the growth, mortality, or decomposition functions for other pools. HW = hardwood, MAT = mean annual temperature, PPT = precipitation, SW = softwood.

the development of the CaMP v.2.0. Adjustment of decay rates of peat pools owing to shifts between aerobic and anaerobic conditions can be derived from literature sources, for example, Scanlon and Moore (2000). As with version 1.0, CH_4 emissions will only be possible under anaerobic conditions in version 2.0.

There are several ways in which the modeling of CH_4 emissions in the CaMP v1.0 could be modified to increase the model's complexity and explanatory power in the CaMP v2.0. First, since litter quality, soil temperature, and redox potential all tend to decrease very sharply with peat depth (Moore and Basiliko 2006; Lloyd et al. 1998), an exponential decay relationship may be more appropriate than the proposed linear relationship (Fig. 3) and is therefore worth testing. Second, an aerenchyma factor could be used as a modifier to the proposed function with the aim of simulating increased CH_4 flux in sedge-dominated peatlands owing to plant-mediated transport. The aerenchyma factor could be calculated on the basis of sedge productivity, or an estimated constant could be fixed depending on the peatland category.

Two of the most challenging and new tasks for developing the CaMP v2.0 will be including the effect of climatic and water table modifiers to growth and decay functions, and the effect of permafrost and permafrost thaw on peatlands. Introducing climatic modifiers to the CaMP v2.0 is challenging because modifiers need to be applied at annual time steps and at the landscape scale but the majority of temperature and moisture modifiers used in peatland models have been developed for specific sites and for application at fine time scales; therefore, they would need to be annualized and tested for use in the CaMP v2.0. Alternatively, new modifiers at the appropriate temporal and spatial scale for implementation in the CaMP v2.0 could also be developed and tested. Including permafrost effects will require simulation of soil thermal regimes for peatland categories over the large boreal areas with continuous and discontinuous permafrost. The CaMP v2.0 could be integrated with the existing specialized permafrost model Northern Ecosystem Soil Temperature (NEST), which has been used to simulate one-dimensional ground thermal dynamics, associated thawing/freezing, and permafrost conditions (Zhang et al. 2012). Alternatively, essential permafrost algorithms of the NEST model could be incorporated into the CaMP with the assumption that lateral heat transfer in peat is negligible because of its large lateral thermal inertia, thereby reducing three-dimensional thermal simulations to one-dimensional thermal simulation. Either approach could result in simulation of the soil thermal regime at permafrost peatland sites that would have to be spatially separated from non-permafrost peatland sites.

The remaining challenge for the CaMP v2.0 will be to include the effects of natural and anthropogenic disturbances. One possible approach is to develop specialized disturbance matrices such as those used in the CBM-CFS (Table 5 in Kurz et al. 1992). These disturbance matrices would define C stock changes for each of the modeled C pools and the resulting C emissions, for different combinations of disturbance scenarios and peatland categories.

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LITERATURE CITED

Arneth, A.; Harrison, S.P.; Zaehle, S.; Tsigaridis, K.; Menon, S.; Bartlein, P.J.; Feichter, J.; Korhola, A.; Kulmala, M.; O'Donnell, D.; Schurgers, G.; Sorvari, S.; Vesala,T. 2010. Terrestrial biogeochemical feedbacks in the climate system. Nat. Geosci. 3(8):525–532. doi: 10.1038/ngeo905.

Barr, A.G.; Van der Kamp, G.; Black, T.A.; McCaughey, J.H.; Nesic, Z. 2012. Energy balance closure at the BERMS flux towers in relation to the water balance of the White Gull Creek watershed 1999–2009. Agric. For. Meteorol. 153:3–13. doi: 10.1016/j.agrformet.2011.05.017.

Beer, J.; Blodau, C. 2007. Transport and thermodynamics constrain belowground carbon turnover in a northern peatland. Geochim Cosmochim. Acta 71:2989–3002.

Benscoter, B.W.; Vitt, D.H. 2008. Spatial patterns and temporal trajectories in bog ground layer composition along a post-fire chronosequence. Ecosystems 11(7):1054–1064.

Bernard, J.M.; Gorham, E. 1978. Life history aspects of primary production in sedge wetlands. Pages 39–51 *in* R.E. Good, D.E. Whigham, and R.L. Simpson, editors. Freshwater wetlands. Academic Press, New York.

Bernier, P.–Y.; Kurz, W.A.; Lemprière, T.C.; Ste-Marie, C. 2012. A blueprint for forest carbon science in Canada 2012–2020. Nat. Resour. Can., Can. For. Serv., Ottawa, ON. 52 p. Also available at <http://cfs.nrcan.gc.ca/publications?id=34222>.

Bona, K.A.; Shaw, C.; Fyles, J.; Kurz, W. 2016. Modeling moss-derived carbon in black spruce forests. Can. J. For. Res. doi: 10.1139/cjfr-2015-0512. <http://www.nrcresearchpress.com/doi/abs/10.1139/cjfr-2015-0512#.VuLr3ubeDZj>.

Boudewyn, P.; Song, X.; Magnussen, S.; Gillis, M.D. 2007. Model-based, volume-to-biomass conversion for forested and vegetated land in Canada. Can. For. Serv., Pac. For. Cent., Victoria, BC. Inf. Rep. BC-X-411. Also available at <http://cfs.nrcan.gc.ca/publications?id=27434>.

Cao, M.; Marshall, S.; Gregson, K. 1996. Global carbon exchange and methane emissions from natural wetlands: Application of a process-based model. J. Geophys. Res. 101(D9):14,399–14,414. doi: 10.1029/96JD00219/pdf.

Campbell, C.; Vitt, D.H.; Halsey, L.A.; Campbell, I.D.; Thormann, M.N.; Bayley, S.E. 2000. Net primary production and standing biomass in northern continental wetlands. Nat. Resour. Can., Can. For. Serv., North. For. Cent., Edmonton, AB. 63 p. Also available at <http://cfs.nrcan.gc.ca/publications?id=11646>.

Chanton, J.P. 2005. The effect of gas transport on the isotope signature of methane in wetlands. Org. Geochem. 36(5):735–768.

Chasmer, L.; Kenward, A.; Quinton, W.; Petrone, R. 2012. CO_2 exchanges within zones of rapid conversion from permafrost plateau to bog and fen land cover types. Arct. Antarct. Alp. Res. 44(4):399–411. doi: org/10.1657/1938-4246-44.4.399.

Daigle, J.-Y.; Gautreau-Daigle, H. 2001. Canadian peat harvesting and the environment. 2nd ed. Canadian sphagnum peat moss. Sustaining Wetlands Issues Pap. No. 2001-1. Secretariat to the North American Wetlands Conservation Council Committee, Ottawa. ON. 45 p. Also available at <http://nawcc.wetlandnetwork.ca/Can%20Peat%20Harvesting%202001-1.pdf>.

[ESWG] Ecological Stratification Working Group. 1996. A national ecological framework for Canada. Agric. Agri-Food Can., Res. Branch, Environ. Can., Ecozone Anal. Branch, Ottawa, ON. <http://ecozones.ca/english/>. Accessed 28 May 2015.

Farmer, J.; Matthews, R.; Smith, J.U.; Smith, P.; Singh, B.K. 2011. Assessing existing peatland models for their applicability for modeling greenhouse gas emissions from tropical peat soils. Curr. Opin. Environ. Sustain. 3(5):339–349. doi: 10.1016/j.cosust.2011.08.010.

Frolking, S.; Roulet, N.T.; Moore, T.; Richard, P.J.H.; Lavoie, M.; Muller, S.D. 2001. Modeling northern peatland decomposition and peat accumulation. Ecosystems 4:479–498. doi: 10.1007/s10021-001-0105-1.

Frolking, S.; Roulet, N.T.; Moore, T.R.; Lafleur, P.M.; Bubier, J.L.; Crill, P.M. 2002. Modeling seasonal to annual carbon balance of Mer Bleue bog, Ontario, Canada. Glob. Biogeochem. Cycles 16(3):4-1–4-21. doi: 10.1029/2001GB001457.

Frolking, S.; Roulet, N.T.; Tuittila, E.; Bubier, J.L.; Quillet, A.; Talbot, J.; Richard, P.J.H. 2010. A new model of Holocene peatland net primary production, decomposition, water balance, and peat accumulation. Earth Syst. Dynam. 1(1):1–21.

Gorham, E. 1991. Northern peatlands: Role in the carbon cycle and probable responses to climatic warming. Ecol. Appl. 1(2):182–195.

Grigal, D.F.; Buttleman, C.G.; Kernik, L.K. 1985. Biomass and productivity of the woody strata of forested bogs in northern Minnesota. Can. J. Bot. 63(12):2416–2424.

Gunnarsson, U. 2005. Global patterns of sphagnum productivity. J. Bryol. 27(3):269–279.

Hararuk, O.; Smith, M.J.; Luo, Y. 2015. Microbial models with data-driven parameters predict stronger soil carbon responses to climate change. Glob. Change Biol. doi: 1111/gcb. 12827.

[IPS] International Peatland Society. Accessed 27 April. 2016 at http://www.peatlands.org/

Johnston, D.; Turetsky, M.R.; Benscoter, B.; Wotton, B.M. 2015. Fuel load, structure and potential fire behaviour in black spruce bogs. Can. J. For. Res. 45(7):888–899. doi: 10.1139/cjfr-2014-0334.

Kirschke, S.; Bousquet, P.; Ciais, P.; Saunois, M.; Canadell, J.G.; Dlugokencky, E.J.; Bergamaschi, P.; Bergmann, D.; Blake, D.R.; Bruhwiler, L.; Cameron-Smith, P.; Castaldi, S.; Chevallier, F.; Feng, L.; Fraser, A.; Heimann, M.; Hodson, E.L.; Houweling, S.; Josse, B.; Fraser, P.J.; Krummel, P.B.; Lamarque, J.-F.; Langenfelds, R.L.; Le Quere, C.; Naik, V.; O'Doherty, S.; Palmer, P.I.; Pison, I.; Plummer, D.; Poulter, B.; Prinn, R.G.; Rigby, M.; Ringeval, B.; Santini, M.; Schmidt, M.; Shindell, D.T.; Simpson, I.J.; Spahni, R.; Steele, L.P.; Strode, S.A.; Sudo, K.; Szopa, S.; van der Werf, G.R.; Voulgarakis, A.; van Weele, M.; Weiss, R.F.; Williams, J.E.; Zeng, G. 2013. Three decades of global methane sources and sinks. Nat. Geosci. 6(10):813–823. doi: 10.1038/ngeo1955.

Kosykh, N.; Koronatova, N.; Naumova, N.; Titlyanova, A. 2008. Above- and below-ground phytomass and net primary production in boreal mire ecosystems of Western Siberia. Wetl. Ecol. Manag. 16(2):139–153. doi: 10.1007/s11273-007-9061-7.

Kurz, W.A.; Apps, M.J.; Webb, T.M.; McNamee, P.J. 1992. The carbon budget of the Canadian forest sector: Phase I. For. Can., Northwest Reg., North. For. Cent., Edmonton, AB. Inf. Rep. NOR-X-326. 105 p. Also available at <http://www.cfs.nrcan.gc.ca/pubwarehouse/pdfs/11881.pdf>.

Kurz, W.A.; Dymond, C.C.; White, T.W.; Stinson, G.; Shaw, C.H.; Rampley, G.J.; Smyth, C.; Simpson, B.N.; Neilson, E.T.; Trofymow, J.A.; Metsaranta, J.; Apps, M.J. 2009. CBM-CFS3: A model of carbon-dynamics in forestry and land-use change implementing IPCC standards. Ecol. Model. 220(4):480–504. doi: 10.1016/j.ecolmodel.2008.10.018.

Kurz, W.A.; Shaw, C.H.; Boisvenue, C.; Stinson, G.; Metsaranta, J.; Leckie, D.; Dyk, A.; Smyth, C.; Neilson, E.T. 2013. Carbon in Canada's boreal forest — a synthesis. Environ. Rev. 21(4):260–292. doi: 10.1139/er-2013-0041.

Lafleur, P.M.; Hember, R.A.; Admiral, S.W.; Roulet, N.T. 2005. Annual and seasonal variability in evapotranspiration and water table at a shrub covered bog in southern Ontario, Canada. Hydrol. Process. 19(18):3533–3550. doi: 10.1002/hyp.5842.

Lai, D.Y.F. 2009. Methane dynamics in northern peatlands: a review. Pedosphere 19(4):409–421.

Laiho, R. 2006. Decomposition in peatlands: reconciling seemingly contrasting results on the impacts of lowered water levels. Soil Biol. Biochem. 38(8):2011–2024. doi: 10.1016/j.soilbio.2006.02.017.

Limpens, J.; Berendse, F.; Blodau, C.; Canadell, J.G.; Freeman, C.; Holden, J.; Roulet, N.; Rydin, H.; Schaepman-Strub, G. 2008. Peatlands and the carbon cycle: from local processes to global implications – a synthesis. Biogeosciences 5(5):1475–1491. doi: 10.5194/bg-5-1475-2008.

Lloyd, D.; Thomas, K.L.; Benstead, J.; Davies, K.L.; Lloyd, S.H.; Arah, J.R.M.; Stephen, K.D. 1998. Methanogenesis and CO_2 exchange in an ombrotrophic peat bog. Atmos. Environ. 32(19):3229–3238.

McLaughlin, J.; Webster, K. 2013. Effects of a changing climate on peatlands in permafrost zones: a literature review and application to Ontario's Far North. Ont. Minist. Nat. Resour. Sault Ste. Marie, ON. No. CCRR-34. <http://files.ontario.ca/environment-and-energy/aquatics-climate/stdprod_108463.pdf>.

Moore, T.; Basiliko, N. 2006. Decomposition in boreal peatlands. Pages 125–143 *in* R.K. Weider and D.H. Vitt, editors. Boreal peatland ecosystems, Ecol. Stud. 188. Springer, Berlin.

Moore, T.R.; Bubier, J.L.; Frolking, S.E.; Lafleur, P.M.; Roulet, N.T. 2002. Plant biomass and production and CO_2 exchange in an ombrotrophic bog. J. Ecol. 90(1):25–36.

Moore, T.R.; Trofymow, J.A.; Siltanen, M.; Prescott, C.; CIDET Working Group. 2005. Patterns of decomposition and carbon, nitrogen, and phosphorus dynamics of litter in upland forest and peatland sites in central Canada. Can. J. For. Res. 35(1):133–142. doi: 10.1139/X04-149.

Morris, P. J.; Waddington, J. M. 2011. Groundwater residence time distributions in peatlands: Implications for peat decomposition and accumulation. Water Resour. Res. 47, W02511. doi: 10.1029/2010WR009492.

Murphy, M.T.; Moore, T.R. 2010. Linking root production to aboveground plant characteristics and water table in a temperate bog. Plant Soil 336(1–2):219–231. doi:10.1007/s11104-010-0468-1.

Murphy, M.; Laiho, R.; Moore, T.R. 2009. Effects of water table drawdown on root production and aboveground biomass in a boreal bog. Ecosystems 12(8):1268–82. doi:10.1007/s10021-009-9283-z.

National Wetlands Working Group. 1997. The Canadian wetland classification system. 2nd ed. B.G. Warner and C.D.A. Rubec, editors. University of Waterloo, Waterloo, ON. 68 p. Also available at <http://www.gret-perg.ulaval.ca/fileadmin/fichiers/fichiersGRET/pdf/Doc_generale/Wetlands.pdf>.

Nilsson, M.; Öquist, M. 2009. Partitioning litter mass loss into carbon dioxide and methane in peatland ecosystems. Pages 131–144 *in* A.J. Baird, L.R. Belyea, X.Comas, A.S. Reeve, and L.D. Slater, editors. Carbon cycling in northern peatlands. Am. Geophys. Union, Washington, DC.

Nonton, D.A.; De Lange, P.J. 2003. Fire and vegetation in a temperate peat bog: Implications for the management of threatened species. Conserv. Biol. 17(1):138–148. doi: 10.1046/j.1523-1739.2003.01131.x.

Noyce, G.L.; Varner, R.K.; Bubier, J.L.; Frolking, S. 2014. Effect of Carex rostrata on seasonal and interannual variability in peatland methane emissions. J. Geophys. Res. Biogeosci. 119(1):24–34. doi: 10.1002/2013JG002474.

Paré, D.; Bernier, P.; Lafleur, B.; Titus, B.D.; Thiffault, E.; Maynard, D.G.; Guo, X. 2013. Estimating stand-scale biomass, nutrient contents, and associated uncertainties for tree species of Canadian forests. Can. J. For. Res. 43(7):599–608. doi: 10.1139/cjfr-2012-0454.

Reader, R.J.; Stewart, J.M. 1972. The relationship between net primary production and accumulation for a peatland in southeastern Manitoba. Ecology 53(6):1024–1037. doi: 10.2307/1935415.

Riley, J.L. 1994a. Peat and peatland resources of northeastern Ontario. Ontario Geological Survey, Sudbury, ON. Misc. Pap. 153. 186 p. Also available at <http://www.geologyontario.mndmf.gov.on.ca/mndmfiles/pub/data/imaging/MP153/MP153.pdf>.

Riley, J.L. 1994b. Peat and peatland resources of southeastern Ontario. Ontario Geological Survey, Sudbury, ON. Misc. Pap. 154. 167 p. Also available at <http://www.geologyontario.mndmf.gov.on.ca/mndmfiles/pub/data/imaging/MP154/MP154.pdf>.

Riley, J.L. 2011. Wetlands of the Ontario Hudson Bay lowland: An Ontario overview. Nature Conservancy of Canada, Toronto, ON. 156 p.

Riley, J.L.; Michaud, L. 1989. Peat and peatland resources of Northwestern Ontario. Ontario Geological Survey, Sudbury, ON. Misc. Pap. 144. <Also available at <http://www.geologyontario.mndmf.gov.on.ca/mndmfiles/pub/data/imaging/MP144/MP144.pdf>.

Rochefort, L.; Daigle, J.-Y., editors. 2000. Sustaining our peatlands. Proc. 11th Int. Peat Congr. Canadian Society of Peat and Peatlands and the International Peat Society, Edmonton, AB.

Roulet, N.T. 2000. Peatlands, carbon storage, greenhouse gases, and the Kyoto protocol: prospects and significance for Canada. Wetlands 20(4):605–615.

Roulet, N.T.; Lafleur, P.M.; Richard, P.J.H.; Moore, T.R.; Humphreys, E.R.; Bubier, J. 2007. Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland. Glob. Change Biol. 13(2):397–411. doi: 10.1111/j.1365-2486.2006.01292.x.

Roulet, N.T.; Woo, M.K. 1986. Hydrology of a wetland in the continuous permafrost region. J. Hydrol. 89(1):73–91.

Rouse, W.R. 1998. A water balance model for a subarctic sedge fen and its application to climatic change. Clim. Change 38(2):207–234.

Saarinen, T. 1996. Biomass and production of two vascular plants in a boreal mesotrophic fen. Can. J. Bot. 74:934–938.

Scanlon, D.; Moore, T. 2000. Carbon dioxide production from peatland soil profiles: the influence of temperature, oxic/anoxic conditions and substrate. Soil Sci. 165(2):153–160.

Schuldt, R. J., Brovkin, V.; Kleinen, T.; Winderlich, J. 2013. Modeling Holocene carbon accumulation and methane emissions of boreal wetlands – an Earth system model approach. Biogeosciences 10(3):1659–1674. doi:10.5194/bg-10-1659-2013.

Solomon, S., Qin, D., Chen, M.Z., Marquis, M., Averyt, K.B., Tigno, M., H.L. Miller, editors. 2007. Climate change 2007: the physical sciences basis. Contribution of Working Group 1 to the Fourth Assessment Report of the International Panel on Climate Change. Intergovernmental Panel on Climate Change, Cambridge Univ. Press, New York, NY. <Also available at <https://www.ipcc.ch/publications_and_data/publications_ipcc_fourth_assessment_report_wg2_report_impacts_adaptation_and_vulnerability.htm>.

Sonnenta, O; Vanderkamp, G; Barr, A; Chen, J. M. 2009. On the relationship between water table depth and water vapor and carbon dioxide fluxes in a minerotrophic fen. Glob. Change Biol. 16(6): 1762–1776. doi: 10.1111/j.1365-2486.2009.02032.x

Stinson, G.; Kurz, W.A.; Smyth, C.E.; Neilson, E.T.; Dymond, C.C.; Metsaranta, J.M.; Boisvenue, C.; Rampley, G.J.; Li, Q.; White, T.M; Blain, D. 2011. An inventory-based analysis of Canada's managed forest carbon dynamics, 1990 to 2008. Glob. Change Biol. 17(6):2227–2244. doi: 10.1111/j.1365-2486.2010.02369.x.

Strack, M.; Waddington, J.M. 2007. Response of peatland carbon dioxide and methane fluxes to a water table drawdown experiment. Glob. Biogeochem. Cycles 21(1):GB1007. doi: 10.1029/2006GB002715.

Sulman, B.N.; Desai, A.R.; Saliendra, N.Z.; Lafleur, P.M.; Flanagan, L.B.; Sonnentag, O.; Mackay, D.S.; Barr, A.G.; van der Kamp, G. 2010. CO_2 fluxes at northern fens and bogs have opposite responses to inter-annual fluctuations in water table. Geophys. Res. Lett. 37:L19702. doi: 10.1029/2010GL044018.

Szumigalski, A.R.; Bayley, S.E. 1996. Decomposition along a bog to rich fen gradient in central Alberta, Canada. Can. J. Bot. 74(4):573–581.

Tarnocai, C. 2006. The effect of climate change on carbon in Canadian peatlands. Glob. Planet. Change 53(4):222–232. doi: 10.1016/j.gloplacha.2006.03.012.

Tarnocai, C.; Kettles, I.M.; Lacelle, B. 2005. Peatlands of Canada database. Digital database, Research 21 Branch, Agriculture and Agri-Food Canada, Ottawa, ON.

Tarnocai, C.; Kettles, I.M.; Lacelle, B. 2011. Peatlands of Canada. Geological Survey of Canada, Open File 6561 (digital database); CD-ROM. Also available at <http://geoscan.nrcan.gc.ca/starweb/geoscan/servlet.starweb?path=geoscan/fulle.web&search1=R=288786>.

Thompson, D.K.; Wotton, B.M.; Waddington, J.M. 2015. Estimating the heat transfer to an organic soil surface during crown fire. Int. J.Wildland Fire 24(1):120. doi: 10.1071/WF12121.

Verry, E.S. 1984. Microtropography and water table fluctuation in a sphagnum mire. Proc. 7th Int. Peat Cong. 18–24 June 1984, Dublin, Ireland. Irish National Peat Committee and the International Peat Society, Dublin, Ireland. 2:11–31. Also available at <http://www.treesearch.fs.fed.us/pubs/13031>.

Vitt, D.H.; Halsey, L.A.; Bauer, I.E.; Campbell, C. 2000. Spatial and temporal trends in carbon storage of peatlands of continental western Canada through the Holocene. Can. J. Earth Sci. 37(5):683–693. doi: 10.1139/e99-097.

Waddington, J.M.; Morris, P.J.; Kettridge, N.; Granath, G.; Thompson, D.K.; Moore, P.A. 2014. Hydrological feedbacks in northern peatlands. Ecohydrology 8:113–127. doi: 10.1002/eco.1493.

Waddington, J.M.; Thompson, D.K.; Wotton, M.; Quinton, W.L.; Flannigan, M.D.; Benscoter, B.W.; Baisley, S.A.; Turetsky, M.R. 2012. Examining the utility of the Canadian Forest Fire Weather Index System in boreal peatlands. Can. J. For. Res. 42:47–58. doi: 10.1139/X11-162.

Wallén, B. 1986. Above and below ground dry mass of the three main vascular plants on hummocks on a subarctic peat bog. Oikos 46(1):51–56. doi: 10.2307/3565379.

Wallén, B. 1992. Methods for studying below-ground production in mire ecosystems. Suo 43(4–5):155–162.

Wania, R.; Ross, I.; Prentice, I.C. 2010. Implementation and evaluation of a new methane model within a dynamic global vegetation model: LPJ-WHyMe v1.3.1. Geosci. Model Dev. 3:565–584. doi: 10.5194/gmd-3-565-2010.

Warner, B.G.; Rubec, C.D.A. editors. 1997. The Canadian wetland classification system. 2nd ed. Wetlands Res. Cent., Univ. Waterloo, Waterloo, ON. 68 p. Also available at <http://www.gret-perg.ulaval.ca/fileadmin/fichiers/fichiersGRET/pdf/Doc_generale/Wetlands.pdf>.

Wieder, R.K.; Scott, K.D.; Kamminga, K.; Vile, M.A.; Vitt, D.H.; Bone, T.; Xu, B.; Benscoter, B.W.; Bhatti, J.S. 2009. Postfire carbon balance in boreal bogs of Alberta, Canada. Glob. Change Biol. 15(1):63–81. doi: 10.1111/j.1365-2486.2008.01756.x.

Wu, J.; Roulet, N.T.; Nilsson, M.; Lafleur, P.; Humphreys, E. 2012. Simulating the carbon cycling of northern peatlands using a land surface scheme coupled to a wetland carbon model (CLASS3W-MWM). Atmos.-Ocean 50(4):487–506. doi: 10.1080/07055900.2012.730980.

Yu, Z.C. 2012. Northern peatland carbon stocks and dynamics: a review. Biogeosciences 9(10):4071–4085. doi: 10.5194/bg-9-4071-2012.

Zhang, Y.; Li, C.; Trettin, C.C.; Li, H.; Sun, G. 2002. An integrated model of soil, hydrology, and vegetation for carbon dynamics in wetland ecosystems. Glob. Biogeochem. Cycles 16(4):1061. doi: 10.1029/2001GB001838.

Zhang, Y.; Sachs, T.; Li, C.; Boike, J. 2012. Upscaling methane fluxes from closed chambers to eddy covariance based on a permafrost biogeochemistry integrated model. Glob. Change Biol. 18(4):1428–1440. doi: 10.1111/j.1365-2486.2011.02587.x.

Zhu, Q.; Liu, J.; Peng, C.; Chen, H.; Fang, X.; Jiang, H.; Yang, G.; Zhu, D.; Wang, W.; Zhou, X. 2014. Modelling methane emissions from natural wetlands by development and application of the TRIPLEX-GHG model. Geosci. Model Dev. 7:981–999. doi: 10.5194/gmd-7-981-2014.

Zoltai, S.C.; Siltanen, R.M.; Johnson, J.D. 2000. A wetland data base for the western boreal, subarctic, and arctic regions of Canada. Nat. Resour. Can., Can. For. Serv., North. For. Cent., Edmonton, AB. Inf. Rep. NOR-X-368E. 28 p. Also available at <http://cfs.nrcan.gc.ca/publications?id=12183.>