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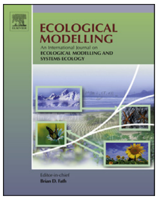

Constraining the organic matter decay parameters in the CBM-CFS3 using Canadian National Forest Inventory data and a Bayesian inversion technique

Oleksandra Hararuk[a,*], Cindy Shaw[b], Werner A. Kurz[a]

[a] Pacific Forestry Centre, Natural Resources Canada, Canadian Forest Service, Victoria, BC, V8Z 1M5, Canada
[b] Northern Forestry Centre, Canadian Forest Service,5320 122nd Street Edmonton, AB, T6H 3S5, Canada

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ABSTRACT

Forests are an important component of the global carbon (C) cycle: they can capture and retain large amounts of C annually, depending on stand characteristics, climate, and disturbance regimes. With climate and disturbance regimes shifting, it is important to be able to accurately represent the corresponding changes in forest C dynamics with well-calibrated models. The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) is a widely used model for simulating C dynamics in managed forests at stand, regional, and national levels. Here, we use a Bayesian Markov Chain Monte Carlo (MCMC) technique to calibrate the parameters in the CBM-CFS3 by assimilating C stocks of six deadwood and soil pools estimated from data collected from 635 plots within the Canadian National Forest Inventory. Calibration led to most improvement in the simulation of C stocks in small and fine woody debris, reducing RMSE by 54.3%, followed by the snag stems (RMSE reduced by 23.2%), and coarse woody debris (13%). The calibrated parameters resulted in increased rates of C cycling in fine and coarse woody debris and the soil organic layer, distinct C dynamics in hardwood and softwood dominated stands, and increased temperature sensitivity of the C contained in the mineral soil. While parameter calibration considerably improved the simulation of the small and fine woody debris and snags stem pools, model representation of the branch snag, coarse woody debris, soil organic layer, and mineral soil pools were not substantially improved. Lack of substantial improvements in the calibrated model performance indicated the need for including additional processes in C dynamics simulation or a change in the modelling paradigm. We illustrate the potential need to include a lignin effect on deadwood decay and suggest further exploration of the effects of tree species, soil types, and mosses on performance of the CBM-CFS3.

1. Introduction

Forests are an important component of the global carbon (C) cycle: they store 45% of terrestrial C, contribute to approximately 50% of annual terrestrial global net primary production and can retain large amounts of C annually (Bonan, 2008; Field and Raupach, 2004). The amount of C forests capture and store is dependent on forest stand characteristics (e.g., age, species), climate, and disturbance regimes (Chen et al., 2013; Pregitzer and Euskirchen, 2004; Vanderwel et al., 2016). Over the past century, climate and disturbance regimes have been changing (Alexander et al., 2006; Seidl et al., 2011), and it became essential to estimate how these changes will affect forest C stocks and dynamics.

Estimation and prediction of a system's C stocks and fluxes is often done with simulation models such as the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). The CBM-CFS3 simulates the dynamics of living and dead organic matter in Canada's managed forest area. It has been widely used to estimate C stocks and dynamics at stand (Metsaranta and Kurz, 2012), regional (Amichev et al., 2016), and national (Kurz and Apps, 2006; Pilli et al., 2013; Pilli et al., 2016; Stinson et al., 2011; Zamolodchikov et al., 2013) scales, as well as to evaluate the effects of disturbances and management practices on forest C stocks and dynamics (Amichev et al., 2012; Boisvenue et al., 2012; Boucher et al., 2012; Kurz et al., 2008; Luckai et al., 2012; Man et al., 2013; Pilli et al., 2015; Sharma et al., 2013; Taylor et al., 2008).

With increasing use of the CBM-CFS3 to estimate national C budgets and the effects of disturbance regimes or management

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[*] Corresponding author. Current address: 21,111 Lakeshore Road, St. Anne-de-Bellevue, Quebec H9 × 3V9, Canada.
E-mail address: ohararuk@gmail.com (O. Hararuk).

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practices on forest C dynamics, it is necessary to ensure that the model performs well across various stand types and climates, and to improve the model if its performance is poor. Shaw et al. (2014) evaluated the CBM-CFS3 at 696 ground plots from Canada's National Forest Inventory (NFI), and found that the CBM-CFS3 simulated aboveground live biomass well, but the simulated deadwood and soil pools were often poorly correlated with the NFI estimates, which indicated the need for improvements in simulating deadwood and soil dynamics in the CBM-CFS3.

One of the strategies for achieving model improvement is to add more processes observed in nature. Thus it was suggested that the CBM-CFS3 could be improved by including C dynamics in mosses (Bona et al., 2013; Kurz et al., 2013; Shaw et al., 2014), stratification of model parameters by species and soil types (Shaw et al., 2008; Shaw et al., 2015), the effect of earthworms on soil C dynamics (Cameron et al., 2015; Kurz et al., 2013), the burial of deadwood by bryophytes (Hagemann et al., 2010), and the effects of drought on organic matter decay (Davidson et al., 2006; Davidson et al., 2012; Smyth et al., 2011). However, including more processes will increase model complexity, which may lead to overfitting. Therefore, before including new processes, an additional stage is needed in the model development that will comprehensively evaluate model performance across the realistic parameter space, thus helping to justify the increase in model complexity or a change in the modelling paradigm.

Data assimilation allows informing the parameters in a model with the available observations to improve model performance without altering its structure. This method has been widely used in C cycle research to constrain the parameters in models and gain information about C dynamics at site (Keenan et al., 2012; Xu et al., 2006), regional (Zhou and Luo, 2008), and global (Hararuk et al., 2014; Smith et al., 2013) scales. In this study we use Bayesian inversion (Besag et al., 1995) to inform parameters in the CBM-CFS3 with observations from Canada's NFI to (1) improve the model's performance (reduce RMSE and increase the explained variance in the NFI estimates); (2) gain more knowledge about C dynamics by analyzing the calibrated parameter estimates; and (3) evaluate the necessity for modifications to the CBM-CFS3 structure.

2. Methods

2.1. Overview of the CBM-CFS3

The CBM-CFS3 simulates C dynamics in ten live tree biomass pools and eleven deadwood and soil pools at annual time steps [see Table 2 in Kurz et al. (2009) for a full description]. Biomass pools are calculated by transforming merchantable volumes obtained from yield curves into biomass using the relationships described in Boudewyn et al. (2007). Biomass pools transition into deadwood and soil pools via litterfall, tree mortality or disturbance events. Deadwood and soil pools decay at an exponential rate, with the rate dependent on the pool type and mean annual temperature. Fraction *f* of the decayed pool is transferred to soil pools and fraction *1- f* is transferred to the atmosphere as CO2. In the event of a disturbance (e.g., fire, harvest) pool sizes are adjusted by a disturbance matrix that specifies the proportion of C in one pool that transfers to another pool, to the atmosphere, or to the forest products sector. More details about the model structure and algorithms are given in Kurz et al. (2009).

The CBM-CFS3 is run in two stages; the initialization, or spin-up, run followed by the simulation run. During the spin-up run the model repeatedly cycles through the yield curve(s) of each stand in the inventory using the defined historical stand-replacing disturbance type and return interval, to build up biomass, deadwood and soil pools. The spin-up run continues until the aboveground slow (in the soil organic layer) and belowground slow (mineral soil) pools reach a quasi-equilibrium state when the difference between the sum of the pools' C stocks at the end of two successive rotations is $\leq$0.1%. Once this state has been reached, one last simulation of the spin-up completes the initialization. In the last simulation the most recent stand-replacing disturbance, as defined by the inventory record, is applied to the stand, and the model grows the forest stand to the current age, also defined in the inventory record. All biomass and dead organic matter pool estimates are then used at the start of the simulation run. We used the plot-level temperatures from the McKenney et al.'s (2001) dataset to run the CBM-CFS3.

2.2. NFI data and the calibration procedure

The CBM-CFS3 was calibrated using C pool estimates derived from ground plot data collected for the Canadian National Forest Inventory (NFI, 2008, 2010, 2011). The NFI ground plot sampling design consists of four concentric circular plots for measurement of large and small trees; two 30 m long line transects perpendicular to each other for measurement of woody debris and surface substrate depth; four circular micro-plots with a radius 0.56 m for measuring biomass of small trees, shrubs, herbs, mosses, fine woody debris, forest floor and soil bulk density; a soil pit for measuring soil attributes [see Fig. 3.1 in (NFI, 2008)]. The diameter of each snag stem is measured, and its biomass and the biomass of the snag's branches are estimated using allometric equations (Ung et al., 2008). The quantity, diameter, and decay class of woody debris are measured every 5 m along the two 30 m transects, and are then converted to C mass using methods described in (Marshall et al., 2000). The substrate (organic soil layer) depth is measured every 2 m along the perpendicular transects and multiplied by the organic layer bulk density (collected from the four micro-plots) and the C concentration to obtain the C stock of the soil organic C layer. Mineral soil samples are taken from three depths down to 55 cm in the first micro-plot, two depths down to 35 cm in the second micro-plot and one depth down to 15 cm in the third and fourth micro-plots, and the mineral soil C stock is determined from bulk density and C concentration data for the above samples.

We calibrated the model using the NFI-derived estimates of C stocks in deadwood and soil pools only, as it was demonstrated that the CBM-CFS3 performed well in simulating live biomass components; the model explained over 77% of spatial variation in the total aboveground biomass when compared to estimates based on NFI data, whereas the explained variation in the total deadwood or soil pools did not exceed 8% (Shaw et al., 2014). In addition, focusing on the poorly performing parts of the model allowed us to reduce the dimensionality of the parameter space and thus promote faster convergence of parameters to their optimum values. We recognize that calibrating against C stock change data rather than one-time C stock pool data would be ideal for arriving at parameters best suited to prediction in time but the NFI re-measurement data for the dead organic matter pools were not available at the time of this analysis. Once these data are available a separate analyses will be conducted with the C stock change data. However, using the NFI C pool data now affords us the opportunity to calibrate parameters that capture the large spatial variation of Canada's forested area and some temporal variation by assuming that spatial relationships between the C cycle and mean annual temperature (MAT) would resemble temporal relationships between these two variables. Such space for time substitution allowed us to estimate the parameters associated with C cycle changes in response to temperature.

Data collected by the NFI were not always directly comparable to the modelled deadwood and soil C pools, therefore we used the "comparison pools" defined in Shaw et al. (2014) and described in Fig. 1 to match modelled and observed data. We used the 635 upland plots out of the 696 NFI plots in Shaw et al. (2014) that