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The importance of tree species and soil taxonomy to modeling forest soil carbon stocks in Canada

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A B S T R A C T

Accurate initialization of soil and dead organic matter carbon (C) stocks in forest ecosystem models is challenging but critical to forest C estimation, assessing current and future responses to climate change, and evaluation of management options for climate change mitigation strategies. We identified opportunities to improve the accuracy of soil C estimates from the Carbon Budget of the Canadian Forest Sector (CBM-CFS3) — a model of forest C dynamics used to support greenhouse gas emission reporting. Accuracy of soil C stocks estimated by models is very dependent on the initialization process. Here, we used redundancy analysis (RDA) and ordinations in an exploratory analysis to compare the variance structures of soil C estimates determined by model variables used in the initialization process, in two different soil C datasets; one derived from the model, the other obtained from 2391 ground plots. We also used the ground plot data to determine if soil taxonomy (information currently not used in the CBM-CFS3) could be used to explain variation in addition to that already accounted for by variables in the model. Total variance of the plot C dataset was about twice as large as the variance of the model C dataset confirming that currently the model does not represent all factors that control variation in soil C stocks. Soil C stocks in the mineral soil were highly correlated with C stocks in soil organic horizons in the model dataset but not in the plot dataset, suggesting that the variables included in our assessment controlling C stocks in the mineral soil horizons are different than in the organic soil horizons. Tree productivity (maximum yield curve volume per hectare) explained a much larger proportion of the total variation in the model dataset than in the plot dataset, whereas the leading tree species explained more variation in the plot dataset than in the model, suggesting that accuracy of initialization of soil C stocks could be improved by including leading tree species to stratify soil C modeling parameters. Leading species that are in greatest need of improved representation were identified by ordination. The results from the RDA showed that soil taxonomy explained 4 (order) to 13% (subgroup) of plot soil C variance, in addition to that explained by variables currently used in the model that determine initial soil C stocks. Soil taxonomy and leading species can compensate for one another to explain variance in soil C stocks. Our results suggest the potential of using the combination of leading tree species and soil taxonomy to improve soil C stocks initialized by forest C models, but this remains to be tested.

1. Introduction

Soil carbon (C) is indisputably important as a C stock and as a contributor to the global C budget (Schlesinger and Andrews, 2000; Gottschalk et al., 2012). Forest ecosystems cover approximately 3.8 billion ha globally (Pan et al., 2011) and their soil represents a significant component of forest C budgets (Lal, 2005). The contribution of soil to forest C budgets is particularly high for boreal forest ecosystems (Lal, 2005; Kurz et al., 2013) — the dominant forest biome in Canada (Brandt, 2009). Soil C models in various forms (Peltoniemi et al., 2007) are integrated into forest ecosystem models like the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3; Kurz and Apps, 1999; Kurz et al., 2009), FORCARB (Harmon and Marks, 2002), BIOME-BGC (Running and Hunt, 1993), CO2FIX (Schelhaas et al., 2004) and EFIMOD 2 (Komarov et al., 2003), and these models have been designed or adapted to estimate forest C budgets or to contribute to the understanding of forest C dynamics. Important applications of these models include meeting national and international reporting requirements (Stinson et al., 2011), assessing current and predicting future responses to climate change (Boisvenue and Running, 2010;

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Shanin et al., 2010), and/or evaluating forest management activities and their contributions to climate change mitigation objectives (Smyth et al., 2014). However, the uncertainty of soil C stock and stock change estimation by these models is often high (Palosuo et al., 2012; Todd-Brown et al., 2013; Shaw et al., 2014). This study compares the relative importance of factors influencing soil C stock estimation from plot data and a forest ecosystem C budget model (CBM-CFS3) with the goal of improving the accuracy of initial estimates of soil C stocks derived from the model spin-up procedures (Kurz et al., 2009).

Soil C models vary in structure, number and type of pools, and the approach used to initialize the pools (McGill, 1996; Peltoniemi et al., 2007). Here we focus on variables that affect soil C stocks in the initialization process that is used to estimate stocks in modeled pools prior to running simulations or scenario analyses. Initialization of soil pools as part of the modeling process, rather than using inventory-based estimates, is necessary because the data required to estimate initial soil C stocks are typically not measured in forest inventories, soil data that is collected is often insufficient to represent areas that are large or that have diverse soils, and because model pools are often defined in such a way that their measurement in field samples is difficult or time consuming (Zimmerman et al., 2007). Most approaches to initialization depend on the validity of the steady-state assumption; that soil C inputs (primarily from plants) are equivalent to soil C outputs (primarily from heterotrophic respiration). One of the most common approaches to initialization is to run the model to a steady state in which the slower pools cease to change (Hashimoto et al., 2011). The approach to initialization of soil C in models is important because it affects the outcome of contemporary and predictive simulations. It influences soil C stock and stock change estimation (Foereid et al., 2012; Xu et al., 2011; Palosuo et al., 2012), calibration of model pools with slow turnover rates (Peltoniemi et al., 2007; Wutzler and Reichstein, 2007), and the range in soil C stocks or sequestration rates (Foereid et al., 2012; Wutzler and Reichstein, 2007).

The CBM-CFS3 differs from many other models in that it includes pools for soil organic horizon C as well as soil mineral horizon C and it simulates natural (e.g., fire, insects) and anthropogenic (e.g., harvest) disturbance effects on biomass, dead organic matter (DOM: standing and downed dead wood) pools, and soil organic horizon C; in turn these can affect mineral soil C. Including disturbance effects has been an important and unique feature of the CBM-CFS3 since its inception (Kurz et al., 1992) because they are important for estimating greenhouse gas (GHG) emissions from Canada's forested area. In the CBM-CFS3 all DOM and soil pools are initialized (starting at zero) through a spin-up process in which cycles of stand development, initiated by stand-replacing wildfire (or another user-defined stand-replacing disturbance such as insects or harvesting), are repeated for as many times as required to reach a quasi-steady state defined as the point where the sum of the slow pools at the end of two successive cycles differs by less than 0.1% (Fig. 1). Thereafter, the model simulates the last stand-replacing disturbance and grows the stand to the age in the inventory. Thus, depending on the time since last disturbance, the pools can be far from an equilibrium state (e.g., recently disturbed stands) or close to an equilibrium state (e.g., in very old stands which are rare in boreal forest ecosystems). Estimates of initial soil C stocks by the CBM-CFS3 are typically lower than estimates from the most common equilibrium approach, because it accounts for losses of soil C due to disturbances (Fig. 1). Despite these differences, the CBM-CFS3 sometimes over- or underestimates initial soil C stocks, and estimates a much narrower range (lower total variance) in soil C stocks compared with ground plot data (higher total variance) (Shaw et al., 2014).

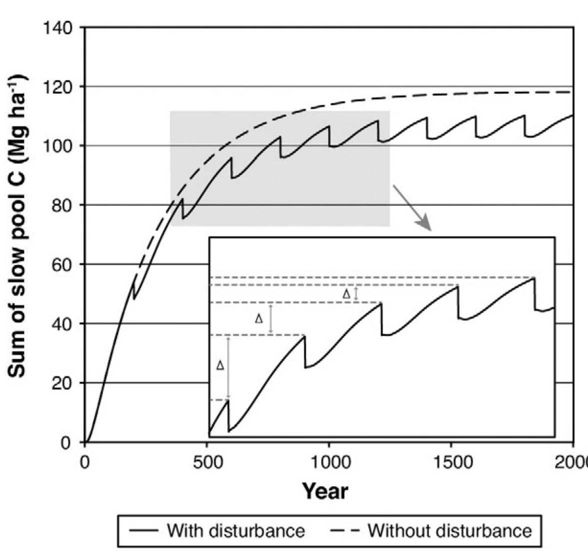

Fig. 1. Comparison of the accumulated sum of slow soil C pools during initialization of the CBM-CFS3 with disturbance from a stand-replacing fire using a 200-year historical fire return interval (solid line) and with no disturbances (dashed line).

Thus, the main objectives of this exploratory study are to determine if the CBM-CFS3 makes full and appropriate use of variables used in the initialization process to express variation in soil C stocks, and if soil taxonomy can account for additional variation in predicted soil C stocks. We included soil taxonomy because currently it is not used in the model, but may be useful for improving modeled soil C estimates because it has been linked to differences in forest soil C stocks (Shaw et al., 2008) and pedological factors and processes important to soil C stabilization and accumulation (Shaw et al., 2008; Schaetzl and Anderson, 2005; Jandl et al., 2007).

2. Methods

We compared the variance structure of soil C stocks estimated from 2391 plots located across Canada to the variance structure of soil C estimated by the CBM-CFS3 in national-scale simulations, as explained by variables used in the model that determine initial soil C stocks. In the CBM-CFS3 variables that influence initial soil C stock estimates (e.g., decomposition, disturbance impacts, and biomass estimation) are defined at different spatial scales (Table 1; Kurz et al., 2009). We used redundancy analysis (RDA) (ter Braak, 1987; ter Braak and Prentice, 1988) to partition total variance of the model-based and the plot-based estimates of mineral and organic horizon soil C as explained by the model's spatial structure and associated variables. Here we describe the two datasets (plot- and model-derived) and the RDA methods used for their analysis.

2.1. Model-derived dataset for the RDA

Canada's National Forest Carbon Monitoring, Accounting and Reporting System (NFCMARS; Stinson et al., 2011) combines national scale forest inventory, growth and yield curve, disturbance and land-use change activity data with the CBM-CFS3 to estimate C stocks and fluxes for Canada's managed forest area. In this application forest stands (ranging in size from 1 to 370,000 ha) are represented by aspatial inventory data located within polygons of varying sizes depending on the source of the inventory data (Kurz et al., 2009). Nearly three million records representing stands in the managed forest area (Fig. 2) are used as input to the CBM-CFS3 when it is used in the NFCMARS. The model generates, among other information, estimates of soil C stocks. Output from the CBM-CFS3 model runs for 1990 from the 2010 National Inventory Report (2010NIR; Environment Canada, 2010) was compressed to a manageable 21,994 records by averaging results for stands with similar classifier set values. Classifier sets vary by jurisdiction and include information such as national or regional ecological classification, leading species or forest type, management units, management history, or productivity class. Classifier sets are used in the CBM-CFS3 to describe stands and to assign the appropriate yield curves. Estimates for organic