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Forest soil decomposition and its contribution to heterotrophic respiration: A case study based on Canada

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ABSTRACT

Soil carbon (C) stocks are large C reservoirs that are characterized by turnover times of decades to centuries. The ability to predict how long C remains in soils requires an understanding of soil decomposition and the influence of climate change on destabilization processes. This study examined forest soil decomposition and quantified the influence of the choice of decomposition parameters on national-scale heterotrophic respiration (R_h) estimates for the managed forest of Canada.

Soil carbon (C) stock estimates from 597 ground plots were used to optimize five decomposition-related parameters of the two slowly decaying C pools of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). An exhaustive grid search method found multiple optimal solutions, i.e. combinations of base decay rates and temperature quotients for the slowly decaying C pools. Impacts on the R_h for the 2.3×10^6 km^2 of Canada's managed forest were estimated using national inventory and disturbance data for ten optimal combinations of base decay rates and temperature quotients. The R_h was estimated in contemporary (1990) and potential future (2099) temperature conditions for which an increase of 4 °C in mean annual air temperature was assumed. The selection of optimal parameter combination had little impact on the resultant estimates of R_h, with a maximum difference of 1.7 g C m^{-2} yr^{-1} or 4.0 Tg C yr^{-1} (0.54% of total R_h) in 1990 and a maximum difference of 8.2 g C m^{-2} yr^{-1} or 18.8 Tg C yr^{-1} (2.3% of total R_h) in 2099.

The slow pool within the mineral soil accounted for 54% of the total dead organic matter C stock. It had a disproportionately small contribution of 8.7% to the total contemporary national-scale R_h estimate and was relatively insensitive to temperature changes. If we accept the space-for-time substitution of temperature sensitivities used in the model parameterization, then these results suggest that the mineral soil decomposition modeled by the CBM-CFS3 will result in a weaker positive feedback in response to an increase in global temperatures than is currently anticipated in other models. However, the majority of the R_h comes from relatively small, but quickly decaying pools. The overall temperature quotient was estimated to be 2.15, which would result in an increase in R_h in response to an increase in global temperatures.

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1. Introduction

Forests, other terrestrial ecosystems, and oceans take up over 50% of the annual anthropogenic CO_2 emissions (Le Quéré et al., 2009; Pan et al., 2011; Le Quéré et al., 2012), and future strength of these sinks will influence the level of mitigation effort needed to reach atmospheric CO_2 stabilization targets (IPCC, 2007). The biosphere holds large carbon pools, which could lead to emissions if destabilized through changes in climate or land use (Schuur et al, 2008). The majority of total soil C stocks has turnover times of decades to centuries, and understanding the response of these C pools to climate change is of critical importance to predict soil C fluxes (Trumbore, 2000; Conant et al., 2011).

Despite our understanding of the specific mechanisms leading to soil C formation (Six et al., 2002), there is incomplete knowledge on the response of soil C stocks to climate change (Fissore et al., 2009). Decomposition involves nutrients and C, a variety of decomposers and stabilization mechanisms and is a complicated system to represent (Walse et al., 1998; Kleber et al., 2011). Many complicated soil organic matter models exist, but these tend to be used on relatively small spatial scales (Manzoni and Porporato, 2009). There is a tendency to incorporate more processes into models to improve fitness between simulated and observed data, but complicated models also increase the number of parameters to

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estimate. This can lead to equifinality in data assimilation when different parameter values of the same model may fit data equally well, limiting the ability to distinguish which models or parameter values are better than others (Luo et al., 2009).

Large-scale modeling of decomposition tends to use a much simpler representation of the complexities, offering a pragmatic approach to provide national assessments of Greenhouse Gas (GHG) inventories (Smith and Heath, 2001; Stinson et al., 2011). Decomposition is typically described by multi-pool C stocks with different decomposition rate constants that describe the heterogenous character of detritus and soil, and the short-term and long-term response of C (Schimel et al., 1994; Trumbore, 2000; Bauer et al., 2008). Often the rate constants are specified for optimal environmental conditions and decay rates are reduced if there are temperature and/or moisture conditions which limit decomposition (Bauer et al., 2008). Model calibrations tend to focus on rate constants, humification parameters (Paul et al., 2003), and apparent temperature sensitivities (Karhu et al., 2010).

Here we examine national-scale estimates of forest soil heterotrophic respiration using an ecosystem model, the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) (Kurz et al., 2009). The CBM-CFS3 is an integral part of Canada's National Forest C Monitoring, Accounting and Reporting System (NFCMARS) (Kurz and Apps, 2006), which estimates GHG emissions and removals from managed forests in Canada (Stinson et al., 2011) for international reporting (Environment Canada, 2012). CBM-CFS3 uses a multi-pool stock model with decay rates for various detritus types that are affected by temperature. Unlike many other ecosystem models, soil stocks are initialized using a spin-up procedure which includes disturbances (Kurz and Apps, 1999; Kurz et al., 2009) resulting in non-equilibrium soil conditions, consistent with the observation that soils may not be in equilibrium due to disturbances and very long turnover times of stable compounds (Wutzler and Reichstein, 2008).

In this study, we used a global optimization method to examine the decay rate constants and temperature quotients of the CBM-CFS3 soil pools through comparisons to soil C stocks from ground plots. The difficulties associated with directly measuring changes in the sizes of soil C stocks has led to a focus on C fluxes (Valentini et al., 2000), but measurements of R_h, although also highly variable (Keenan et al., 2012), are scarce for the managed forest of Canada. Here we use ground plot data and a systems-based approach that emphasizes the consistency between observed stock sizes, C input rates and decay rates as a means to examine a range of plausible soil C decomposition parameters.

We pose two questions here (1) what is the range of five parameter values of soil decomposition processes that are consistent with observed soil C stocks, and (2) how does the choice of parameters affect national-scale estimates of R_h under contemporary and projected future climate conditions?

We present estimates of R_h for Canada's 2.3×10^6 km^2 of managed forest using the same national inventory and disturbance data that are used for international reporting of Canada's GHG emissions and removals (Stinson et al., 2011). The R_h estimates, including the contribution of the soil pools, are presented for contemporary conditions, and future projections in the year 2099 for two climate scenarios.

2. Materials and methods

2.1. The carbon Budget Model of the Canadian Forest Sector

The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) is an inventory-based model of upland forest C dynamics consisting of a linked set of submodels for live biomass, dead organic matter, forest management, land-use change, and disturbances (Kurz et al., 2009). The model and its development are described in previous publications (Kurz et al., 1992; Kurz and Apps, 1999; Kull et al., 2006; Kurz et al., 2009), with ongoing calibration and development work described in Li et al. (2003), Smyth et al. (2011) and Hilger et al. (2012).

Table 1
Default decomposition rate parameters for the 11 CBM-CFS3 dead organic matter pools, where k_{bi} is the base decay rate, Q_i is the temperature quotient, and τ_i is the transfer rate.

Pool no.	Pool	k_{bi} (% yr^{-1})	Q_i	τ_i (%)
1	Slow (mineral soil)	0.330	1.00	–
2	Slow (soil organic horizon)	1.500	2.65	0.6
3	Stem snags softwood	1.870	2.00	17.0
4	Stem snags hardwood	1.870	2.00	17.0
5	Medium	3.740	2.00	17.0
6	Branch snags softwood	7.175	2.00	17.0
7	Branch snags hardwood	7.175	2.00	17.0
8	Fast (soil organic horizon)	14.350	2.00	17.0
9	Fast (mineral soil)	14.350	2.00	17.0
10	Very fast (soil organic horizon)	35.500	2.65	18.5
11	Very fast (mineral soil)	50.000	2.00	17.0

The dead organic matter submodel in CBM-CFS3 has 11 C pools (Table 1) designated according to their speed of decay (slow, medium, fast and very-fast), including four standing dead snag pools. The model has two variants of the very fast, fast and slow pools, one within the soil organic horizon, and the other within the mineral soil. Having two variants of the pools allows us to separate inputs from roots and aboveground litter, and to differentiate impacts on C pools from disturbances, such as fire, and to align pool definitions with attributes that can be measured in the field.

Carbon is transferred annually from live biomass C pools to dead organic matter pools through litterfall, mortality and disturbances,

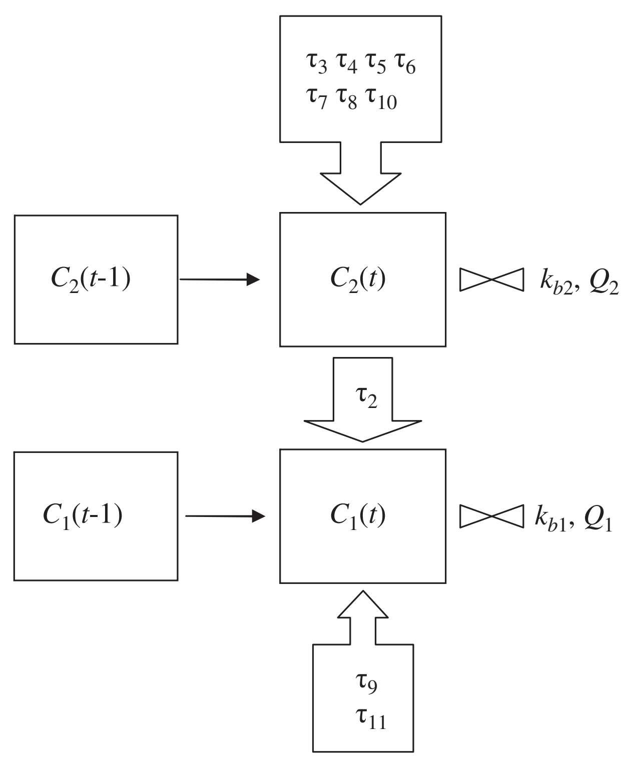

Fig. 1. Schematic of the transfers (τ_i) and decay of C, with base decay rate k_{bi}, and temperature quotient Q_i, for the slow pool within the mineral soil (C_1) and the slow pool within the soil organic horizon (C_2) at timestep t.

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