Ecological Modelling 222 (2011) 1080–1091

Contents lists available at ScienceDirect

Ecological Modelling

journal homepage: www.elsevier.com/locate/ecolmodel

Including the effects of water stress on decomposition in the Carbon Budget Model of the Canadian Forest Sector CBM-CFS3

C.E. Smyth*, W.A. Kurz, J.A. Trofymow, CIDET Working Group

Natural Resources Canada, Canadian Forest Service, 506 West Burnside Road, Victoria, BC V8Z 1M5, Canada

ARTICLE INFO

Article history:
Received 14 June 2010
Received in revised form 3 December 2010
Accepted 8 December 2010
Available online 14 January 2011

Keywords:
Litter decomposition
Decay rates
Water stress
Moisture deficit
Carbon modeling
CIDET

ABSTRACT

Decomposition of plant detritus and humified organic matter in terrestrial ecosystems is a primary source of atmospheric carbon dioxide (CO_2), yet the dynamics of decomposition are not well understood, particularly their response to climate change. The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) presently includes a sub-model to simulate the decomposition of dead organic matter carbon pools using base decay rates modified by temperature quotients. In this study, representation of litter decomposition was improved in the CBM-CFS3 by reducing decay rates under limited moisture conditions. Water stress effects were determined from comparisons of model predictions with data from a 12-year national litterbag decomposition study—the Canadian Intersite Decomposition Experiment (CIDET). Several simple water-stress modifiers based on precipitation and potential evapotranspiration were tested, and parameters were simultaneously fit by minimizing the least-squared error. The best-fitting formulation used the annual average of the ratio of monthly precipitation to monthly potential evapotranspiration, and increased the explained variance by 8%. Water-stress modifiers were applied to decay rates to predict carbon stocks at 516 ground plots from a national soil plot database. The addition of the water-stress modifier modestly increased litter and humified organic matter carbon stocks at dry locations and decreased these carbon stocks at non-water-stressed locations. The new ability to lower decay rates of certain dead organic matter pools under limited moisture conditions in the CBM-CFS3 has the potential to reduce bias in carbon flux predictions for those regions and for future climate change scenarios where moisture limits decomposition processes.

1. Introduction

At present, the residual portion of fossil fuel emissions that remains in the atmosphere is influenced by the carbon (C) sink in forests, other terrestrial systems and oceans. Whether these systems remain C sinks will influence the level of mitigation effort needed to reach atmospheric CO_2 stabilization targets. Plant detritus and soil organic matter are the largest C pool in terrestrial ecosystems (2344 PgC; Jobbágy and Jackson, 2000; over half in northern permafrost ecosystems; Tarnocai et al., 2009), and natural fluxes of C in and out of terrestrial and ocean reservoirs are an order of magnitude larger annually than the emissions from fossil fuels and land-use change (Schuur et al., 2008). Thus, understanding the dynamics of plant detritus and humified organic matter decomposition is of critical policy and scientific importance for understanding the global C cycle, and the future greenhouse gas (GHG) balance of terrestrial ecosystems. Temperature, precipitation, and litter chemistry all impact the rate of decomposition (e.g., Swift et al., 1979; Gholz et al., 2000). However, most experimental decomposition studies have been regional or local studies of short duration (e.g., Walse et al., 1998; Giardina and Ryan, 2000), and do not include many cold sites that have very low decomposition rates. As a result, there are large uncertainties in C emissions estimates where short-term experimental results have been incorporated into national or global models of ecosystem C balance over long timescales.

A study of six soil C decomposition models by Bauer et al. (2008) found that the moisture modifier reduced decay rates for soil-water contents below optimum moisture contents, but the six models had a wide range of moisture responses. There are many complicated decomposition models available in the literature that include hydrological properties of the soil as well as runoff. The Century model includes a simplified water-budget model with monthly evaporation and transpiration loss, water content of the soil layers, snow water content, and saturated flow of water between soil layers (Parton et al., 1993). Vertical distribution of water in soil layers depends on field capacity, soil texture and organic matter content (Gupta and Larson, 1979). Other models also include soil texture, for example the water-stress modifier in the RothC agricultural model (Coleman and Jenkinson, 2005) estimates the maximum moisture

* Corresponding author. Tel.: +1 250 363 0796; fax: +1 250 363 0775.
E-mail address: carolyn.smyth@nrcan.gc.ca (C.E. Smyth).

0304-3800/$ – see front matter.
doi:10.1016/j.ecolmodel.2010.12.005

deficit based on the clay content of the soil. These models would be very difficult to apply over the 230 Mha of managed forest in Canada because there is very limited data on the spatial distribution of clay content or the vertical distribution of soil texture. Instead, simplified water stress modifiers based on precipitation and PET were selected, in anticipation of the national-scale application of the model.

Our objective in this study was to improve the modeling of litter decomposition by adding the effect of water-stress modifiers to the decomposition sub-model of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3). The CBM-CFS3 is an inventory-based model of forest C dynamics that consists of a linked set of sub-models for live biomass, dead organic matter (defined as all plant detritus and humified organic matter pools including soil C), forest management, land-use change, and disturbance (Kurz et al., 2009). This model is used to estimate GHG emissions and removals from Canada's managed forests and it is an integral part of Canada's National Forest Carbon Monitoring, Accounting and Reporting System (Kurz and Apps, 2006). The dead organic matter decomposition sub-model of CBM-CFS3 is presently sensitive to detritus type and mean annual temperature, but not precipitation. Higher temperatures typically enhance decomposition (e.g., Rustad et al., 2001), but this effect can be reduced in dry soils (Luo et al., 2001; Trofymow et al., 2002). Presently, precipitation is larger than potential evapotranspiration (PET) across much of Canada's managed forest (Hogg and Bernier, 2005), suggesting that the effect of water stress on decomposition may currently be small. However, water stress can be regionally important (Kurz-Besson et al., 2006) and may become important in future climate scenarios where the predicted increase in precipitation is insufficient to offset the increases in PET from a predicted increase in temperature (Hogg and Hurdle, 1995). Incorporating the effects of water stress on decay rates of dead organic matter will likely increase the ability of CBM-CFS3 to accurately predict the future C balance of forests in Canada.

The first objective of this study was to test five water-stress modifiers based on precipitation and PET by comparing CBM-CFS3 decomposition sub-model predictions to C-remaining time series data. Data were from the Canadian Intersite Decomposition Experiment (CIDET), a national litterbag decomposition study (Trofymow and CIDET Working Group, 1998). CIDET was an unusually long (12-year) and spatially extensive (21 sites located across Canada) decomposition study that included ten foliar litter types. A variety of PET estimates has been used for moisture studies (e.g. Parton et al., 1993; Adair et al., 2008; Ise and Moorcroft, 2006) and there does not appear to be a consensus on which method of estimating PET is the most appropriate. To remove any potential bias from the PET estimates, six methods were used to estimate PET for two of the water-stress modifiers.

Our second objective was to determine the best-fitting water-stress modifier and recalibrate CBM-CFS3 decay parameters after including the water-stress modifiers in the model. The third objective was to examine residual errors between predictions and measurements, and to determine which CIDET sites had improved predictions due to the inclusion of the water-stress modifier. The final objective was to estimate the effect of water stress on forest floor and mineral soil C stocks in a simulation of stands from 516 sample ground plots across Canada. These ground plot data have been used in previous model calibration, and it was of interest to assess the impact of the water-stress modifier on the C-stock predictions.

2. Materials and methods

The best-fitting water stress modifier was selected by comparing the predicted C-remaining time series to the CIDET litterbag C remaining data. Section 2.1 describes the measured C-remaining time series, and Section 2.2 describes how the CBM-CFS3 predicts C-remaining time series. Section 2.3 describes the five water-stress modifiers, and Section 2.4 describes the six PET formulae. Five water-stress modifiers were estimated using P and PET, and two of the water-stress modifier used six estimates of PET. Finally, Section 2.5 describes the methods to optimize the water-stress modifier coefficients and decay parameter, and selects the best-fitting water-stress modifier.

2.1. Litter decomposition measurements

Foliar-litter decay measurements from a national litterbag experiment were used to determine the best-fitting water-stress modifier and to calibrate parameters in the CBM-CFS3 decomposition sub-model. Data were from the Canadian Intersite Decomposition Experiment (CIDET), a national litterbag experiment that measured litter C remaining of 10 standard foliar litter materials over 12 years (Trofymow and CIDET Working Group, 1998; Trofymow et al., 2002; http://cfs.nrcan.gc.ca/subsite/cidet). These data have been used extensively, including quantitative assessment of model parameters in three C dynamics models (Smyth et al., 2010; Zhang et al., 2007; Palosuo et al., 2005) and testing of several combined C and nitrogen models (Zhang et al., 2008; Manzoni et al., 2008); and have also contributed to the understanding of the effects of climate and litter quality on decomposition processes (Trofymow et al., 2002; Preston and Trofymow, 2000; Moore et al., 2006).

Approximately 11,000 litterbags were all laid out in 1992 at 18 upland sites and 3 wetland sites across Canada on 4 replicate plots per site. Litterbags of each of the 10 foliar litters and two wood blocks were strung on nylon line, with 10 strings of litterbags placed in each of four replicate plots at each of the 21 sites. Foliar litters and one wood block were placed on the forest floor surface; the second wood block was buried at about 20 cm depth. One tenth of the litterbags were collected annually in the first 8 years, and biennially for the 9th and 10th collections. After each collection, samples were dried at 70 °C and masses were recorded. Samples were then ground, and C concentration was determined on a LECO CR-12 carbon system (Leco Corporation, St. Joseph, MI).

A subset of the data was used in these analyses- eight foliar tree litters (five coniferous, three deciduous) at 18 upland sites. Except for data from the first year, this subset of data was used to test the alternative models of water stress on decomposition rates. Data from the first year were not included in the statistical analyses. Carbon loss in the first year has been linked to winter precipitation (Trofymow et al., 2002; Smyth et al., 2010), possibly due to its direct role in leaching C from the litters or leaching of soluble phenolic compounds (Trofymow et al., 2002). Wetland sites, herbaceous litters and wood blocks were not considered. Two sites had shorter time series but were included for some of the analysis: PET (Petawawa) had data for 6 years; and PAL (Prince Albert) had data for 8 years. In total there were 174 observations of C remaining, after averaging over all litter types.

Climate data were from nearby Meteorological Services Canada (MSC) climate stations (http://www.msc-smc.ec.gc.ca) and ANUCLIM interpolated climate data (McKenney et al., 2001) and were averaged from 1992 to 2004, the period of the CIDET litterbag experiment (Table 2, Smyth et al., 2010). Some data were replaced or missing because ANUCLIM data for 2004 were unavailable: TOP and SHL temperature data were replaced with 2004 MSC data, and HID precipitation data for 2004 were not used.

2.2. Decomposition sub-model and predictions

A brief description of the CBM-CFS3 dead organic matter sub-model is given here, and interested readers are referred to Kurz