Ecological Modelling 272 (2014) 323–347

Contents lists available at ScienceDirect

Ecological Modelling

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

Evaluation of simulated estimates of forest ecosystem carbon stocks using ground plot data from Canada's National Forest Inventory☆

C.H. Shaw[a,*], A.B. Hilger[a], J. Metsaranta[a], W.A. Kurz[b], G. Russo[b], F. Eichel[b], G. Stinson[b], C. Smyth[b], M. Filiatrault[a]

[a] Natural Resources Canada, Canadian Forest Service, Northern Forestry Centre, 5320 122 Street, Edmonton, Alberta T6H 3S5, Canada
[b] Natural Resources Canada, Canadian Forest Service, Pacific Forestry Centre, 506 West Burnside Road, Victoria, British Columbia V8Z 1M5, Canada

ARTICLE INFO

Article history:
Received 3 June 2013
Received in revised form
26 September 2013
Accepted 1 October 2013
Available online 9 November 2013

Keywords:
Carbon
CBM-CFS3
Forest
Model evaluation
National Forest Inventory
Standards

ABSTRACT

Assessing the uncertainties in the estimates obtained from forest carbon budget models used for national and international reporting is essential, but model evaluations are rarely conducted mainly because of lack of appropriate, independent ground plot data sets. Ecosystem carbon stock estimates for 696 ground plots from Canada's new National Forest Inventory enabled the assessment of carbon stocks predicted by the Carbon Budget Model of the Canadian Forest Sector 3 (CBM-CFS3). This model uses country-specific parameters, incorporates all five ecosystem carbon pools, and uses a simulation-based approach to predict ecosystem C stocks from forest inventory data to implement a Tier-3 (most complex) approach of the Intergovernmental Panel on Climate Change Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC-GPG). The model is at the core of Canada's National Forest Carbon Monitoring, Accounting, and Reporting System (NFCMARS). The set of ground plots meets the IPCC-GPG standard for model evaluation as it is entirely independent of the model, but similar in type to that required for IPCC Tier-3 inventory-based C stock estimation. Model simulations for each ground plot used only the type of input data available to the NFCMARS for the national inventory report in 2010 and none of the model's default parameters were altered. Ecosystem total C stocks estimated by CBM-CFS3 were unbiased (mean difference = 1.9 Mg ha^{-1}, $p = 0.397$), and significantly correlated ($r = 0.54$, $p = 0.000$) with ground plot-based estimates. Contribution to ecosystem total C stocks error from soil was large, and from deadwood and aboveground biomass small. Results for percent error in the aboveground biomass (7.5%) and IPCC defined deadwood (30.8%) pools compared favourably to the IPCC-GPG standards of 8% and 30%, respectively. Thus, we concluded that the CBM-CFS3 is reliable for reporting of C stocks in Canada's national greenhouse gas inventories. However, available standards for judging model reliability are few, and here we provide recommendations for the development of practical standards. Analyses by leading species ($n = 16$) showed that error could often be attributed to a small subset of species and/or pools, allowing us to identify where improvements of input data and/or the model would most contribute to reducing uncertainties. This C stock comparison is one of the first ever to follow the evaluation process recommended by the IPCC-GPG for a Tier-3 model, and is a first step towards verification of greenhouse gas emission and removal estimates based on C stock changes.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) *Good Practice Guidance for Land Use, Land-Use Change and Forestry* (IPCC-GPG, Penman et al., 2003), Volume 4 of the IPCC *2006 Guidelines for National Greenhouse Gas Inventories* (IPCC-GL, Eggleston et al., 2006), and the *2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol* (IPCC 2013, Tanabe et al., 2013) constitute the international guidelines for the estimation and reporting of greenhouse gas (GHG) emissions and removals in the land use, land-use change, and forestry sector. The guidelines describe three tiers of methods for estimating carbon (C) stocks and stock changes. The highest tier (Tier-3) estimates

* Corresponding author. Tel.: +1 780 430 3821.
E-mail addresses: cshaw@nrcan.gc.ca (C.H. Shaw), ahilger@outlook.com (A.B. Hilger), jmetsara@nrcan.gc.ca (J. Metsaranta), wkurz@nrcan.gc.ca (W.A. Kurz), grusso@nrcan.gc.ca (G. Russo), feichel@nrcan.gc.ca (F. Eichel), gstinson@nrcan.gc.ca (G. Stinson), csmyth@nrcan.gc.ca (C. Smyth), mfiliatr@nrcan.gc.ca (M. Filiatrault).

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http://dx.doi.org/10.1016/j.ecolmodel.2013.10.005

are derived from models or inventory-based measurement systems driven by high-resolution data, with close links among C pools containing biomass, deadwood, litter, and soil. The standard requires that Tier-3 models be capable of producing estimates for all pools defined in the guidelines' reporting structure with a reasonable degree of accuracy and precision, and that the credibility of these models be established through the scientific peer review process, and validation as far as is practicable for the geographic area in which they are applied (Penman et al., 2003).

The Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) (Kurz et al., 2009) (the model, user's guides, tutorials, and links to publications are available through Canada's National Forest Information System at https://carbon.nfis.org/cbm) is a forest C budgeting framework that can be applied to stand-level, regional-, and national-scale analyses that meets Tier-3 standards for international reporting. It is used for national-scale C accounting and reporting in the managed forest area of Canada (Stinson et al., 2011) by Canada's National Forest Carbon Monitoring, Accounting, and Reporting System (NFCMARS, Kurz and Apps, 2006) and contributes to the national GHG inventory report (e.g., Environment Canada, 2010) submitted annually under the requirements of the United Nations Framework Convention on Climate Change (UNFCCC).

The evaluation of forest C accounting (Prisley and Mortimer, 2004) and biophysical process models (Bellocchi et al., 2010) includes, but is not limited to, comparison of model output with field measurements and publication of the results. The CBM-CFS3 already meets many recommendations for evaluating forest C accounting models (Prisley and Mortimer, 2004) by making the model easily accessible and available in multiple languages (specifically, English, French, Spanish, and Russian), providing user's guides (already available in English and French and under production in Spanish and Russian, Kull et al., 2011), and through peer reviewed scientific papers that describe the model's scope, structure, and calibration (e.g., Kurz et al., 2009). The CBM-CFS3 model has been evaluated using sensitivity analyses (White et al., 2008), model inter-comparison projects (Hayes et al., 2012; Wang et al., 2011, 2013), comparison against field measurements for parts of the model (Banfield et al., 2002; Bernier et al., 2010; Bhatti et al., 2002; Smyth et al., 2010; Trofymow et al., 2008), and against comprehensive data sets collected in regional studies (Hagemann et al., 2010; Moroni et al., 2010b; Taylor et al., 2008). However, the model has not yet been evaluated against comprehensive plot-level field measurements at sites representative of the forest types found across the entire managed forest of Canada.

The IPCC-GL (Eggleston et al., 2006) specify that C accounting models be evaluated against an independent data set based on measurements from a monitoring network similar to what would be used for a national-scale measurement-based inventory, with the difference that a network of plots for evaluating model results can have a lower sampling density because it is being used only to check model results (Eggleston et al., 2006). However, as Prisley and Mortimer (2004) pointed out, one reason that evaluations with field data are rarely done is the lack of adequate independent data sets. Most forest ecosystem C model evaluations are comprehensive for model pools, but involve a relatively small number of intensely measured research sites (Chen et al., 2003; Friend et al., 2007; Sun et al., 2008; Turner et al., 2005; Zhang et al., 2002), or use a large number of plots but make comparisons for only one or two ecosystem components, such as soil (Homann et al., 2000; Mol Dijkstra et al., 2009; Smith et al., 1997), biomass and litter (Beets et al., 1999; Domke et al., 2012), standing dead trees (Woodall et al., 2012) or downed deadwood (Domke et al., 2013).

To establish and maintain a forest monitoring network representative of a forest land base is especially challenging for countries like Canada with a very large and often difficult-to-access forest area. Despite these challenges, Canada's National Forest Inventory (NFI) has succeeded in establishing a set of forest ground plots meeting the IPCC definition of an optimal network for model evaluation (Eggleston et al., 2006). The NFI ground plot sampling intensity is lower than needed for national-scale C stock estimation for Tier-3 reporting based on inventory, but adequate for evaluation of model results because sufficient data are collected to estimate C stocks for most CBM-CFS3 pools. In this study we do not compare the national-scale estimates of the CBM-CFS3 to national-scale estimates based on the NFI ground plots. Rather we compare plot-level predictions of the CBM-CFS3 to plot-level estimates based on ground plot data, as a check on the ability of the model's structure and parameters to predict ecosystem total C stocks, consistent with the intent of the IPCC recommendations. The NFI, a collaborative effort involving federal, provincial, and territorial governments has been measuring ground plots across Canada according to a uniform set of guidelines since 2000 (https://nfi.nfis.org/documentation/ground_plot/Gp_guidelines_v5.0.pdf). At each ground plot, detailed data are collected to provide a range of forest inventory information, including estimates of total aboveground biomass components, deadwood (including standing and downed trees), and information on the C content of the forest floor and soil. Collection of the first set of measurements was completed in 2006, and after completion of quality control and compilation the data were made available in 2010, providing this first opportunity to evaluate the performance of the CBM-CFS3 against a standardized national data set representative of the range of forest types used in national GHG inventory reporting (e.g., NIR2010, Environment Canada, 2010).

This study provides a direct assessment of C stock estimation by the CBM-CFS3 consistent with the spatial extent of Canada's managed forest as reported in national GHG inventories. The objective of this study is to evaluate the plot-level performance of the CBM-CFS3 by comparing model-estimated C stocks with estimates derived from the NFI ground plot data. We primarily examined estimates for total ecosystem C stocks, but also examined results for subtotal pools (aboveground biomass, deadwood, and soil) and component pools contributing to each subtotal to identify pools that were most influential on ground plot estimates, CBM-CFS3 estimates, and model bias. We further examined the error (bias) and trends (correlation) for all pools by tree species to isolate the major sources of error and provide recommendations for combinations of species and pools that require further research to improve overall model accuracy.

2. Methods

The NFI has multiple objectives so the plot network covers a geographic domain larger than necessary for this study's area of interest; the design of the NFI is intended to sample the entire forested area of Canada, whereas the NIR reports emissions and removals only for the managed forest area (Fig. 1). For this reason, and because data were incomplete for some plots, we had to establish criteria for inclusion of plots and data in the analysis. We designed a system (Fig. 2) to process the NFI ground plot data and to generate the necessary inputs for model simulations, to compile estimates of C stocks from the NFI ground plot data and the CBM-CFS3 model output for pools that could be compared, and to compile plot characteristics useful for interpretation of results. The remainder of this section provides an overview of these processes, along with a description of the statistical and analytical procedures used to describe and compare the CBM-CFS3 and NFI ground-plot based estimates.