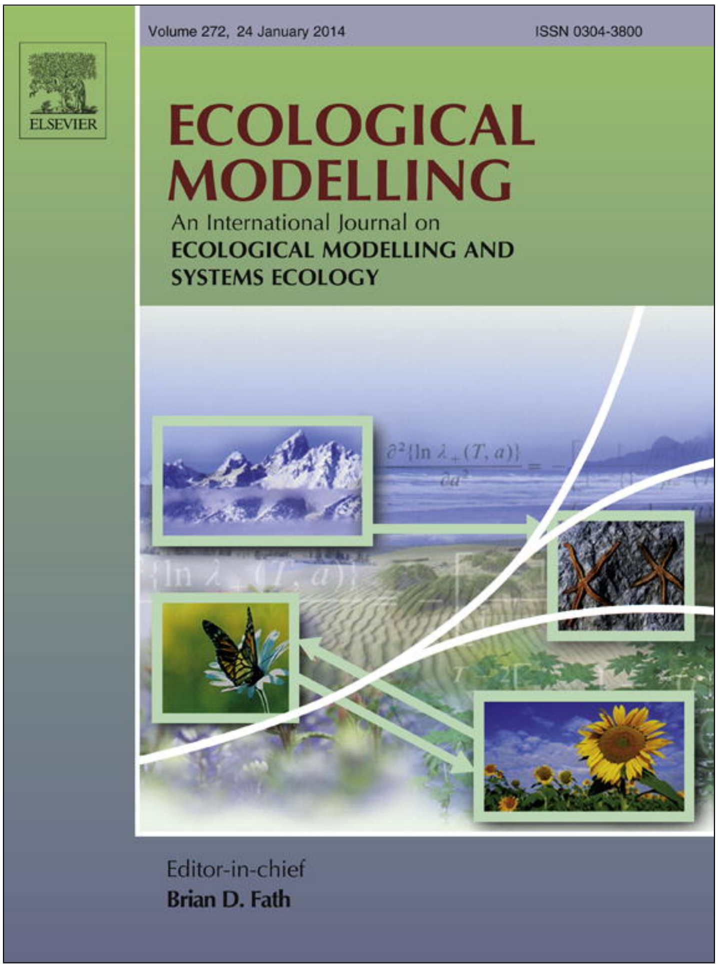
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Evaluation of simulated estimates of forest ecosystem carbon stocks using ground plot data from Canada's National Forest Inventory[☆]

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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

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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.

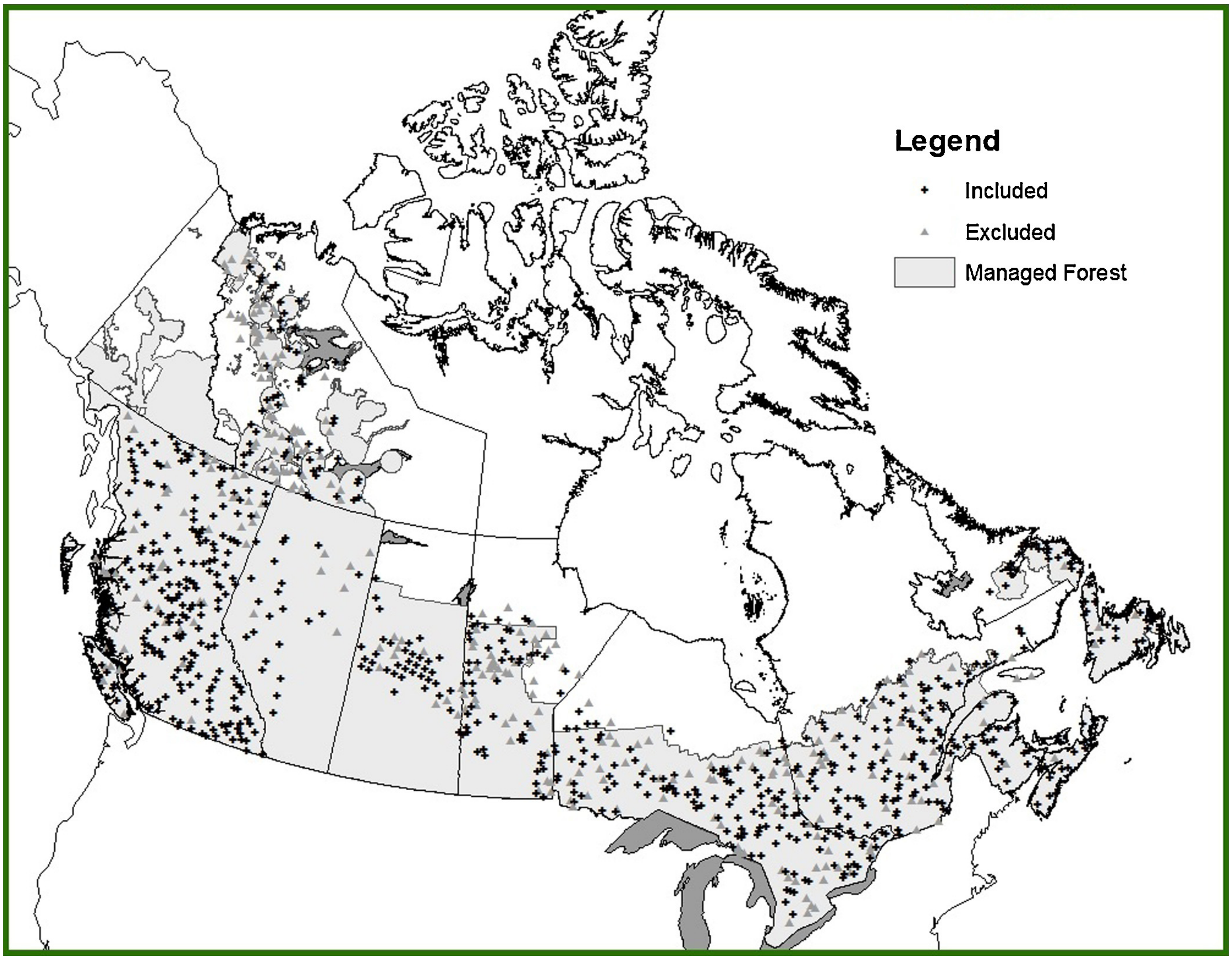

Fig. 1. Distribution of the National Forest Inventory ground plots in relation to the area of the managed forest used for NIR2010 reporting. Of 991 plots, 696 were included and 295 were excluded from the analysis for reasons outlined in Section 2.2. The large area in southwest Canada with no ground plots is within prairie ecozones dominated by agricultural land-use where there are few forest stands.

2.1. *Overview of sampling and estimation procedures for the NFI ground plots*

Canada's National Forest Inventory established 991 ground plots in forested areas across all ecozones (ESWG, 1996) south of the Arctic between 2000 and 2007. These were part of a larger set of 1915 forested and non-forested ground plots that were randomly selected from the nearly 20,000 photo plots established on a 20 km grid that spans the entire country. Many of the established ground plots are located near the centre of the 2-km square 'photo plot' while others are permanent sample plots located nearby that were converted to NFI ground plots.

Each ground plot includes a number of sub-plots where small trees (less than 9 cm in diameter at breast height), large trees, shrubs taller than 1.3 m in height, stumps, woody debris, surface substrate depth, species composition, and site and stand characteristics are measured or assessed. Tree cores were also collected. Samples of forest floor organics, soil to a depth of 55 cm, and vegetation less than 1.3 m in height are collected for laboratory analysis and determination of C content (NFI, 2008).

Total and gross merchantable tree volumes for both live and dead trees were calculated using taper coefficients and volume equations provided by each jurisdiction. National and regional biomass functions and coefficients were used to compute the biomass of wood, bark, branches and foliage of each tree (e.g., Lambert et al., 2005; Ung et al., 2008). Other compilation procedures were used to compute the volume and biomass of stumps and woody debris and to scale up all values, including the C content of forest floor organics and soils to per-hectare values (NFI, 2010).

2.2. *Criteria for including plots in the analysis*

To provide a meaningful comparison between the CBM-CFS3 estimates as implemented for NIR2010 reporting and the ground plot measurements, criteria were established to determine which ground plots were eligible for this study. First, plots located on soils of the Organic Order or organic soils in the Cryosolic Order [SCWG, 1998] were excluded ($n = 140$) because the CBM-CFS3 is currently designed for forested upland sites only (Kurz et al., 2009). Second, plots with no merchantable volume (i.e. at least some trees had to be larger than the regional merchantable diameter limit) and for which stand age could not be estimated were excluded ($n = 46$) because it was unknown if the plots were located in young stands that were recently disturbed, or in older stands of low productivity. Mid- to old-aged stands (mean stand age = 72 years) with no

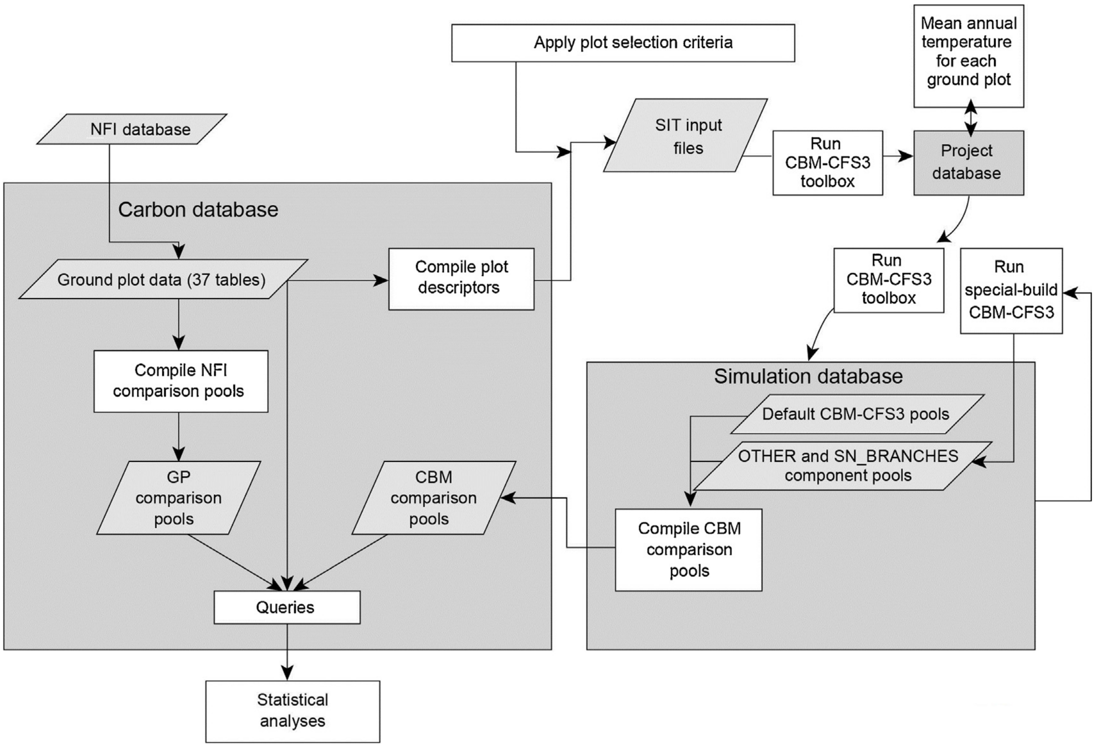

Fig. 2. Overview of major steps in processing ground plot data from the National Forest Inventory (NFI), simulations and output from the Carbon Budget Model of the Canadian Forest Sector 3 (CBM-CFS3), and statistical analyses for the comparison pools. Simulations were conducted first with the CBM-CFS3 toolbox to provide standard output and then with a special-build version of the CBM-CFS3 that used all default parameter values and was modified to report additional estimates for components within the OTHER and SN_BRANCHES pools that are normally not reported separately but were required for comparisons with NFI GP data. CBM: comparison pools derived from the CBM-CFS3; GP: comparison pools derived from ground plot data; SIT: standard import tool for the CBM-CFS3.

merchantable volume were also excluded ($n = 23$) because these low productivity forest types are not included in the inventory used as input for the managed forest area in the NIR2010. Third, plots were excluded ($n = 41$) if all trees were dead, even if they had significant merchantable volume. These plots were excluded because the number, timing, and type of disturbance events leading to complete stand mortality were unknown. After these exclusions, 696 of the remaining 741 plots had sufficient data collected to meet the minimum following requirements to run a simulation for a stand in the NIR2010:

1) the plot contains live trees of a merchantable size and has sufficient data to estimate merchantable volume by tree species to determine the leading species (Appendix A);
2) the plot has sufficient data to define an NFI-based classifier set for the yield curve selection process (classifier sets are used in the NIR2010 to describe stands and to link them to appropriate yield curves; they vary by jurisdiction and include information such as national or regional ecological classification, leading species or forest type, management units, management history, and productivity class); and
3) an estimate is available of the time (years) since the last major disturbance (i.e., stand age, in the case of a stand-replacing disturbance).

2.3. CBM-CFS3 simulations

Model simulations were run using the CBM-CFS3 toolbox (version 1.2.4569.176) (Kull et al., 2011). We emphasize that in this evaluation only CBM-CFS3 default parameters were used which had been derived from the literature or from independent data sets. No parameter adjustments were made. Simulations run for the 696 plots used only the input information that would be available to the CBM-CFS3 in the NFCMARS for the NIR2010. Standard import tool files were created for the 696 plots (Fig. 2), in which each plot was represented as a separate inventory record to be as consistent as possible with implementation of the CBM-CFS3 for NIR2010 simulations.

An estimate of the time (years) since the last major disturbance was required for selection of yield curves and determination of the time-step at which model results would be compared with the ground plot estimates. For most plots, this period was equal to the estimated stand age based on NFI data from cored trees, excluding veteran trees (defined as single trees much older than the average age of other cored trees). For plots where trees were not large enough to be cored but the date of the last harvest or wildfire was available, this date was used to estimate the time since the last major disturbance and was also taken as an estimate of stand age.

The CBM-CFS3 uses empirical yield curves to simulate growth, and these yield curves must be provided as input to the model. For the NIR2010, the curves were obtained from resource management agencies (Stinson et al., 2011). Each curve is characterized by a set of classifiers (e.g., national or regional ecological classification, lead species or forest type, management units, management history, productivity class) that differ among jurisdictions and that are used to link inventory records to yield curves. For selection of yield curves for the CBM-CFS3 simulations, we used the NFI ground plot data (sometimes in combination with additional information from individual jurisdictions) to define a classifier set for each ground plot. Each ground plot classifier set was then used to select a group of potential yield curves for each plot from the yield curves available for the NIR2010. From this group, we selected the yield curve that most closely matched the total merchantable volume of the plot for the leading species at the plot's stand age. Individual tree merchantable volumes (section 15 in the compilation document; NFI, 2010) were summed to generate a total for each species on every

Table 1
Comparison pools used in evaluation of the Carbon Budget Model of the Canadian Forest Sector 3.[a]

Comparison pools			Description
Total	Subtotal	Component	
ECOTOTAL ($n = 284$)	ABOVEGROUND BIOMASS POOLS ($n = 564$)	MSTEM ($n = 696$)	Stem bark and wood of merchantable bole for live merchantable trees
		MTS ($n = 696$)	Stem bark and wood in top and stump portion for live merchantable trees
		NMERCH ($n = 629$)	Stem bark and wood in live nonmerchantable trees and saplings
		BRANCHES ($n = 629$)	Branch biomass of all live trees (bark and wood)
		FOLIAGE ($n = 631$)	Foliage biomass of all live trees
	DEADWOOD POOLS ($n = 538$)	SN_MSTEM ($n = 696$)	Stem bark and wood of merchantable bole for dead merchantable trees
		SN_MTS ($n = 696$)	Stem bark and wood in top and stump portion for dead merchantable trees
		SN_NMERCH ($n = 629$)	Stem bark and wood in dead nonmerchantable trees and saplings
		SN_BRANCHES ($n = 629$)	Branch biomass of all dead trees (bark and wood)
		AGFAST ($n = 538$)	Fine and small woody debris
		MEDIUM ($n = 629$)	Coarse woody debris
	SOIL POOLS ($n = 302$)	ORGSOIL ($n = 536$)	LFH and O soil horizons[b]
		MINSOIL ($n = 313$)	Organic carbon in mineral soil horizons

[a] The n value in parentheses is the numbers of plots for which ground plot data were complete.
[b] See The Canadian System of Soil Classification (SCWG, 1998) for description of horizons.

plot, taking into account the merchantability criteria (Boudewyn et al., 2007).

The number of yield curves used to represent a stand in the NIR2010 varies by jurisdiction, and multiple curves can be used to represent forest type (hardwood and softwood) or multiple species contained in the plot. Each yield curve used to simulate a plot is associated with a leading species, and each plot is associated with a plot leading species, the latter being defined as the curve leading species with the largest merchantable volume. We then calculated the difference between ground plot total merchantable volume and total merchantable volume from the yield curve at the plot's stand age (YC_DIFF). This value was used in subsequent analyses to assess the effect on C pool estimates from the CBM-CFS3 of using yield curves derived from population-level data to represent a single plot.

Wildfire was the historic disturbance type used to initialize dead organic matter and soil pools in the model initialization procedure (Kurz et al., 2009). The last stand-replacing disturbance simulated before extracting model results at the plot's stand age was wildfire for most plots. Recent disturbances other than wildfire were only simulated if the NFI provided sufficient data to specify the year, type and magnitude of a disturbance (as would be done in the NIR2010). Clear-cut harvests (69 plots) and insect disturbances (1 plot) were simulated as last disturbances where these were the last stand-replacing disturbance. Partial cutting (7 plots) and commercial thinning (6 plots) were simulated as subsequent disturbance events, where these were known to have occurred.

Simulations were run using plot-specific mean annual temperatures estimated by the methods of McKenney et al. (2001) and chosen to be consistent with the mean annual temperatures used in the NIR2010. The CBM-CFS3 provides output for the OTHER and SN_BRANCHES pools but not their component pools (Fig. 3; Table 1). We used a special build of the CBM-CFS3 to also report the C stocks of the component pools summed in the "OTHER" and "SN_BRANCHES" pools (Fig. 3). After the simulations were complete C pool data (Mg ha^{-1}) for each plot, at its stand age as recorded in the inventory, were extracted from the CBM-CFS3 output for comparison with ground-plot based estimates.

2.4. Compilation of comparison pools and determination of sample sizes

Forest C stocks estimated for model pools (e.g., output from the CBM-CFS3) and estimated from measured field data (e.g., NFI ground plot data) are usually not directly comparable, so we defined "comparison pools" (Table 1) and reported them as C density (Mg ha^{-1}). These pools were compiled from the CBM-CFS3 output database tables and the NFI ground plot data tables using two separate processes (Fig. 2). The NFI measurements do not include coarse and fine root biomass or dead coarse roots in mineral soil, so those pools were not assessed (Fig. 3). For clarity in this paper, the term CBM-CFS3 is used to refer to the model, and the term CBM is used in reference to comparison pools estimated from CBM-CFS3 output; the words "ground plot" refer to the NFI ground plots, and the term GP is used in reference to comparison pools estimated from the NFI ground plot data. The definitions of comparison pools were driven mainly by model pool definitions to facilitate identification of model pools that require improvement to reduce overall bias in modelled ecosystem C stocks.

Compilation of CBM comparison pools from model output was relatively straightforward. Carbon pool data for each plot at the plot's stand age were extracted from the CBM-CFS3 output database and compiled into the CBM comparison pools in the C database (Fig. 2). The CBM aboveground fast pool (AGFAST; Fig. 3, Table 1) was made comparable to the GP comparison pool by subtracting the amount of C in the CBM-CFS3 AGFAST pool that the model attributes to originating from dead coarse roots, which are not measured in the NFI.

Compilation of the GP comparison pools was more complex and required processing of individual tree and woody debris data rather than plot-level summaries supplied by the NFI. We used C stock and other data from NFI ground plot data (version 1.1, described in the NFI data dictionary [NFI, 2011] and the NFI compilation standards [NFI, 2010]). An important consideration for compilation of GP comparison pools was ensuring that the protocols used to distinguish nonmerchantable from merchantable trees and the merchantable bole, top, and stump limits (Boudewyn et al., 2007), as implemented in the CBM-CFS3, were also applied to the ground plot data, since NFI tree data are not organized in relation to merchantability limits but rather in terms of "large" trees (dbh ≥ 9 cm) and "small" trees (dbh < 9 cm). The merchantability limits are used in the CBM-CFS3 to determine the split of biomass among the merchantable stemwood (MSTEM), merchantable tops and stumps (MTS), and nonmerchantable (NMERCH) components, as well as the split for their snag pool analogues (snags from merchantable stemwood [SN_MSTEM], snags from merchantable tops and stumps [SN_MTS], and snags from nonmerchantable [SN_NMERCH]) and downed deadwood pools (Fig. 3, Table 1). Therefore, we processed individual tree data for each plot to create GP comparison pools consistent with the merchantability limits of Boudewyn et al. (2007). Also, the estimates of AGFAST and MEDIUM woody debris pools (Fig. 3, Table 1) were compiled to reflect the fact that dimensions of roundwood material entering these pools in the model

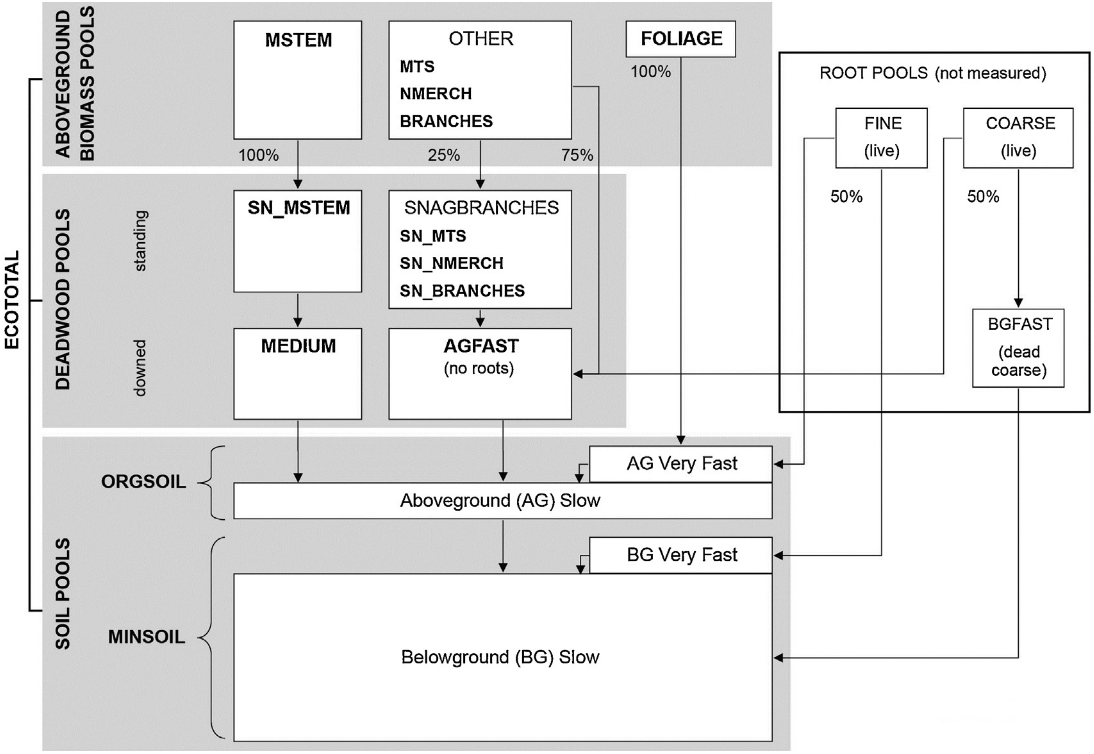

Fig. 3. Carbon pools defined within the Carbon Budget Model of the Canadian Forest Sector 3 (CBM-CFS3), showing simplification into the comparison pools used in this analysis (in bold type) and how the model transfers carbon between pools. See Table 1 for descriptions of comparison pools. The component comparison pools within the OTHER and SN_BRANCHES CBM-CFS3 pools, along with the aboveground fast pool (AGFAST, excluding dead coarse roots), were additional outputs calculated for this analysis with a special build version of the model (see Fig. 2). Root pools inside the bold-outlined box were not measured in the National Forest Inventory ground plots.

(Fig. 3) would also vary by jurisdiction. The MEDIUM pool contains material that could only come from merchantable trees, whereas the AGFAST pool contains any other woody debris under the size limits for merchantable top diameter, from both merchantable-sized and nonmerchantable-sized trees.

Output from the CBM-CFS3 allows for complete estimation of all CBM comparison pools, but the NFI data needed to estimate C stocks for GP comparison pools were not complete for every plot. To avoid underestimation of C stocks for GP comparison pools, pools were estimated only if all data contributing to the pool estimate were complete. For example, data from four NFI fields were summed to estimate AGFAST C stocks. If data had not been collected for any one of these four fields for a given plot, the estimate of the AGFAST C stock for that plot was excluded from the analysis. Because AGFAST is one of six components contributing to the DEADWOOD subtotal (Table 1), that plot would also be excluded from the DEADWOOD total C stock comparison and from the ECOTOTAL comparison. Therefore, the maximum numbers of plots with complete data for estimation of C stocks varied by component, subtotal, and ecosystem total comparison pool (Table 1) and for grouping by leading species. In Section 3, we indicate either the maximum sample size (for grouping by leading species, or comparison pools) or the actual sample size (for individual comparisons). A detailed reporting of all statistics and sample sizes is available in Appendix B. This approach provides the largest sample size possible for each comparison, which in turn results in the most representative sample possible and maximizes power for statistical testing. Sample size was limited mainly by the availability of complete estimates for soil carbon, and consequently for the ECOTOTAL pool, which includes soil carbon. ECOTOTAL was estimated for only 284 plots mainly because MINSOIL could be estimated for only 313 of the 696 plots included in this analysis. Reasons that MINSOIL could not be estimated included no or insufficient data ($n = 203$), potential but unknown contribution of inorganic C to the total C data value available for the mineral soil ($n = 178$), and occurrence of plots on rock ($n = 2$). To assess the magnitude of the impact of missing ground plot data, we recalculated statistics for ECOTOTAL and subtotal (AGBIOMASS, DEADWOOD, SOIL) pools for all 696 plots by assuming a value of zero for any missing data in the component pools. For detailed analysis by leading species, the sample was restricted to cases where at least 10 plots were available for a leading species.

2.5. Data analysis

Classic descriptive statistics were calculated for all pools (n values, means, and standard error or standard deviation, p values for t-statistics, as appropriate) using SYSTAT®12 (2007), and the fit of modelled estimates to field data was evaluated using appropriate goodness-of-fit statistics (Smith and Smith, 2007). We used the coefficient of determination (R^2) to estimate the proportion of variance in the error of the biomass pool estimates explained by YC_DIFF to assess the contribution of the error in predicting plot volume from a yield curve to the error in estimating biomass. First we calculated the difference (error) between the GP and CBM estimates (as GP–CBM) for every biomass pool in every plot. Then, we calculated R^2 for the relationship between YC_DIFF and each biomass pool error. All relationships were plotted, examined, and analyzed for influential outliers. Because the data set was comprehensive for all modelled pools (except dead coarse roots and root biomass), we had a unique opportunity to partition the total variance of the error (calculated as GP–CBM) and the total variance of the CBM and GP pool estimates. Variance partitioning would be impossible with data sets in which estimates were available for only a few of the many pools contributing to the ecosystem totals.

2.5.1. Model goodness-of-fit

We used the goodness-of-fit statistics described by Smith and Smith (2007), which have been used in many (cited 337 times on 10 March 2011) previous model comparisons (Smith et al., 2012). Because the ground plot data do not include any replicated measurements, we used mean difference (MD) to test for bias. Note that negative values for MD indicate overestimation of pool size by the model, because differences are calculated as measured minus modelled as defined by Smith and Smith (2007). In addition, we used the sample correlation coefficient (r) to evaluate the model for the degree of association. The statistical significance of bias was determined by calculating Student's t value for the MD and the significance of r by calculating the square root of F and then comparing each with the appropriate critical $t_{(p \leq 0.05)}$. We chose $t_{(p \leq 0.05)}$ to provide a statistical standard for comparison (all statistics are found in the results tables and Appendix B). A significant MD value indicates that the model has significant bias, and a significant positive r value indicates a good match between trends in the GP and CBM estimates. These statistics were calculated for all comparison pools (where $n \geq 5$) and for all plots combined.

2.5.2. Variance partitioning

We estimated the contribution of subtotal and component pools to the total variances of the ECOTOTAL and subtotal pools, respectively, to understand the relative importance of each pool in explaining the overall variance of CBM and GP pool estimates, and error (bias) estimates (i.e., GP–CBM). We used Crystal Ball® (2009) to estimate total variance, the proportional contribution of subtotal comparison pools to total ecosystem variance, and the proportional contribution of component pools to the total variance of each subtotal comparison pool (Table 1). Weibull distributions were fit to data for each pool contributing to a total variance. Correlation between contributing pools can significantly affect the contribution to variance results, so any correlations ≥0.50 between contributing pools were accounted for in the computations. Using 1000 Monte Carlo runs, Crystal Ball® computes the rank correlation coefficients between pairs of contributing pools and their sum. It then calculates contribution to variance by squaring the rank correlation coefficients and normalizing them to 100% (Crystal Ball®, 2009). This is an approximate, not exact, variance decomposition (Crystal Ball®, 2009).

3. Results

We first describe results for total ecosystem C stocks (ECOTOTAL) based on an analysis of all plots for which simulations could be run ($n = 696$), with some reference to subtotal pools (AGBIOMASS, DEADWOOD, SOIL) (Tables 1–2). Following that we describe results for all subtotal pools and component pools for the 16 leading species where at least 10 plots were available for a leading species. A total of 623 plots were included in the leading species analyses. The remaining 73 plots were represented by 21 leading species, including plots concentrated in the southeastern part of Canada (dominated by eastern hardwood and larch species [*Larix* spp.]), in the high elevation mountainous regions of western Canada (predominantly high-elevation larch and pine species [*Pinus* spp.]), and on the west coast (coastal coniferous species and red alder [*Alnus rubra* (Bong.)]).

3.1. Comparison of ecosystem total (ECOTOTAL) C stocks

Estimates of all (13) component pools were complete for 284 of the 696 plots to allow for comparison of ECOTOTAL pool C stocks against model predictions (Table 2A). ECOTOTAL C stocks were also recalculated for all 696 plots, where missing data were assumed to be zero, approximating situations where pools may have been overlooked or not considered for measurement in the field, but ecosystem totals are still reported (Table 2B). If only plots with complete data were considered ($n = 284$) the bias (MD = 1.9 Mg ha^{-1} or 0.9% of the average observed mean ecosystem C density) was not significant ($p = 0.397$) and the correlation ($r = 0.54$) was significant ($p = 0.000$) (Table 2A). Most of the bias in ECOTOTAL could be explained by bias in MINSOIL ($R^2 = 0.89$, $n = 284$, $p = 0.000$). Substituting zeros for missing data resulted in a large and significant bias (MD = −48.2 Mg ha^{-1}, $p = 0.000$; or −31.8% of the average observed mean ecosystem C density) primarily because an incomplete accounting of mineral soil C (MINSOIL) underestimated the GP mean for this pool, resulting in an apparent overestimation by the model (Table 2B). Substituting zeros for missing data had little impact on the magnitude of the MD or correlation for the AGBIOMASS and DEADWOOD pools. This is because there were few missing data for AGBIOMASS pools and even though there were more missing data for DEADWOOD pools, their influence were small because DEADWOOD C stocks are small relative to the other subtotal (AGBIOMASS and SOIL) pools. However, MINSOIL was a large pool and had a large number of missing data. Thus, incomplete ground plot soil data can lead to erroneous conclusions regarding model accuracy for ECOTOTAL and MINSOIL. Substituting zeros for missing ground plot data also increased the likelihood of declaring a significant MD because MDs were estimated to be larger and because of the effect of a larger sample size ($n = 696$ compared with 284) on reducing the standard error of the MD. With large sample sizes the likelihood of declaring a small MD significant, increases, as well as declaring a small correlation (r value) significant. For example, a correlation as low as 0.15 for MINSOIL was significant at $p = 0.005$ but ecologically not very useful (Table 2C).

The only published standards we found to assess the importance of bias for forest C accounting are the IPCC-GPG standards for national-scale reporting in industrialized nations, of 8% (see Section 4.2.1.5 in Eggleston et al., 2006) and 30% (see Section 3.2.1.2.1.4 in Penman et al., 2003) for IPCC AGBIOMASS and DEADWOOD, respectively. There were no IPCC-GPG standards provided for IPCC ECOTOTAL, LITTER or SOIL pools. We calculated percent errors for the AGBIOMASS and DEADWOOD pools to meet IPCC pool definitions. CBM-CFS3 estimates of the bias for IPCC AGBIOMASS and DEADWOOD pools were 7.5% and 30.8% respectively, which compared favourably to the IPCC-GPG standards (Table 2C). Results were also affected by definitions of subtotal pools. When converting from comparison pools used in this study to IPCC pools, the bias was redistributed. Percent error results for our comparison pools suggested that DEADWOOD was overestimated and ORGSOIL underestimated by the model, while percent error results for the IPCC DEADWOOD pool was smaller because the errors from our DEADWOOD and ORGSOIL pools were redistributed in the IPCC DEADWOOD pool (Table 2).

We plotted the cumulative percentage of plots against the absolute value of their percent error as an aid to identifying a reasonable, practical standard for ECOTOTAL error (Fig. 4). We calculated that 72% of all plots had ≤50% error, 16% had between 50 and 75% error, and 5% had 76 to 100% error. The percentages of plots associated with each error limit were similar (73%, 15% and 6%, respectively) even if mineral soil C (MINSOIL) was excluded from the ECOTOTAL, suggesting these proportions were robust to inclusion or exclusion of the pool contributing the most uncertainty to ECOTOTAL estimation (see variance partitioning in Section 3.2).

3.2. Variance partitioning of ecosystem total (ECOTOTAL) C stocks

We examined the variance structure of the error (GP–CBM) in CBM C stock estimates to identify the component pools that were most influential on the error of modelled ECOTOTAL C stocks. We also examined the variance structure of GP and CBM stocks to

Table 2
Comparison of C stocks, bias and correlation for ecosystem total and subtotal pools calculated (A) with complete ground plot (GP) data, (B) without complete GP data and substituting zeros for missing data and (C) with pools recalculated to meet the definitions of the Intergovernmental Panel on Climate Change-Good Practice Guidance (IPCC-GPG) reporting pools. GP: C stock estimates based on ground plots; CBM: C stock estimates based on the CBM-CFS3; MD: mean difference (GP – CBM). See Table 1 for comparison pool descriptions.

	n	GP (Mg ha^{-1})		CBM (Mg ha^{-1})		MD (Mg ha^{-1})			% Bias	Correlation	
		Mean	(se)	Mean	(se)	Mean	(se)	*p*		*r*	*p*
(A) Complete GP data											
ECOTOTAL	284	223.0	(7.54)	221.1	(7.61)	1.9	(7.28)	0.397	0.9	0.54	0.000
AGBIOMASS	629	57.1	(1.95)	52.8	(1.64)	4.3	(0.93)	0.000	7.5	0.88	0.000
DEADWOOD	538	17.9	(1.10)	27.1	(0.89)	−9.2	(1.20)	0.000	−51.6	0.28	0.000
SOIL	302	139.1	(5.48)	128.5	(4.76)	10.6	(6.40)	0.050	7.6	0.23	0.000
ORGSOIL	536	47.4	(1.86)	37.5	(0.92)	9.9	(2.03)	0.000	20.9	0.06	0.072
MINSOIL	313	96.6	(4.74)	88.4	(3.42)	8.1	(5.43)	0.067	8.4	0.15	0.005
(B) Incomplete GP data											
ECOTOTAL	696	151.4	(4.50)	199.6	(4.31)	−48.2	(4.37)	0.000	−31.8	0.51	0.000
AGBIOMASS	696	55.3	(1.79)	52.0	(1.50)	3.3	(0.85)	0.000	6.0	0.88	0.000
DEADWOOD	696	16.1	(0.92)	27.7	(0.80)	−11.6	(1.05)	0.000	−71.8	0.26	0.000
SOIL	696	79.9	(3.39)	119.9	(2.63)	−40.0	(3.95)	0.000	−50.0	0.16	0.000
ORGSOIL	696	36.5	(1.62)	37.7	(0.80)	−1.2	(1.78)	0.248	−3.3	0.04	0.143
MINSOIL	696	43.4	(2.80)	82.2	(1.89)	−38.7	(3.11)	0.000	−89.2	0.16	0.000
(C) IPPC–GPG pools											
ECOTOTAL[a]	284	223.0	(7.54)	221.1	(7.61)	1.9	(7.28)	0.397	0.9	0.54	0.000
AGBIOMASS[a]	629	57.1	(1.95)	52.8	(1.64)	4.3	(0.93)	0.000	7.5	0.88	0.000
DEADWOOD	538	14.6	(1.02)	19.2	(0.82)	−4.5	(1.18)	0.015	−30.8	0.19	0.000
LITTER	504	50.6	(1.98)	45.6	(1.09)	5.0	(2.18)	0.025	9.9	0.08	0.065
MINSOIL[a]	313	96.6	(4.74)	88.4	(3.42)	8.1	(5.43)	0.067	8.4	0.15	0.005

[a] IPCC and CBM comparison pools are the same.

understand which estimates (GP or CBM) were most influential on the error (GP–CBM). Ideally, total variance of each CBM component pool should approximate that of the corresponding GP component pool, and the variance of the error should be small relative to the variance of the pools. We used percent contribution to identify the subtotal or component pools with the most influence on variance totals. This approach allowed us to assess the combined influence of pool size and pool error. A pool with large C stocks and relatively small error variance, and a pool with small C stocks and a relatively large error variance, may contribute equivalent proportions to the total variance of the error.

The total variance for ECOTOTAL error (GP–CBM) was as high as the total variance for the GP and CBM pools because the patterns for subtotal pool contributions to variance differed between the GP and CBM stocks (Fig. 5a). Almost 90% of the variation in the ECOTOTAL error was contributed by the SOIL subtotal pool, with minor contributions from the DEADWOOD and AGBIOMASS subtotal pools.

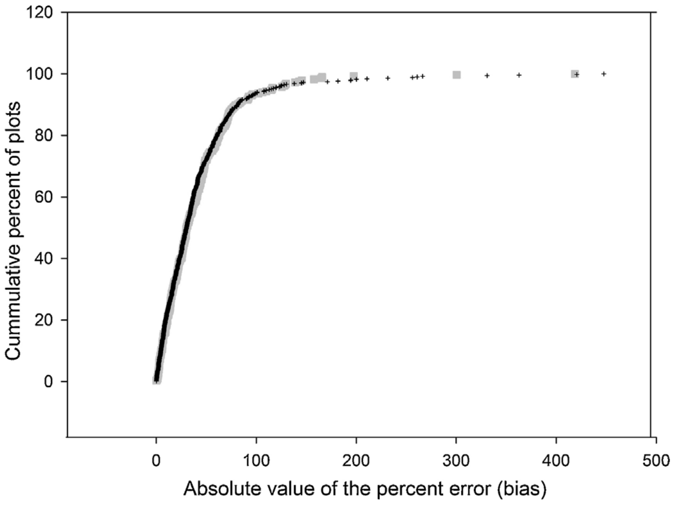

Fig. 4. Relationship between the cumulative percent of plots (total *n* = 284) and their percent error for the ecosystem total (ECOTOTAL) (grey squares) and ecosystem total without mineral soil (MINSOIL) (black crosses). Three of the four extreme outliers for ECOTOTAL are interior Douglas-fir plots.

The total variance of the error (GP–CBM) of the AGBIOMASS subtotal pool was the lowest (<500 [Mg ha^{-1}]^2; Fig. 5b) of the three subtotal pools (Fig. 5a) and was low relative to the total variance for the AGBIOMASS GP and CBM pools (Fig. 5b). The total variance of the CBM AGBIOMASS pool was about 35% lower than that of the GP AGBIOMASS pool. The patterns for contributions to variance by component pools were similar for the GP and CBM data (Fig. 5b). The largest contributor to variance in the AGBIOMASS GP and CBM pools and error was the MSTEM component. The NMERCH pool also contributed a high proportion to the AGBIOMASS error but only a small proportion to the GP and CBM pool variances. Conversely, the MTS pool contributed a high proportion to the GP and CBM pool variances but little to the AGBIOMASS error.

The total variance of the error of the DEADWOOD subtotal pool was high relative to the total variance of the GP and CBM pools (Fig. 5c), a pattern opposite to that for the AGBIOMASS subtotal pool described in the previous paragraph (Fig. 5b). Four of the six DEADWOOD component pools contributed a similar proportion (approximately 20% each) to the total variance of the GP data, but the corresponding contributions to the CBM total variance ranged widely, from about 5% (SN_BRANCHES pool) to 60% (MEDIUM pool) (Fig. 5c). The high contribution of the CBM MEDIUM pool to the DEADWOOD subtotal variance influenced the high contribution of the MEDIUM pool to the DEADWOOD error. For three (SN_MSTEM, SN_MTS, SN_BRANCHES) of the remaining five component pools, the contribution to variance for GP estimates was greater than for CBM estimates, so it was GP variation that largely determined the variance of the error for these pools (Fig. 5c). The contribution of the AGFAST pool to total DEADWOOD error was small, and the SN_NMERCH contributions to all variances were also small (Fig. 5c).

Within the SOIL subtotal pool, total variances of the error and of the GP data were similar, and they were approximately four times greater than the variance of the CBM SOIL pool (Fig. 5d). The CBM MINSOIL and ORGSOIL pools contributed similar proportions to the

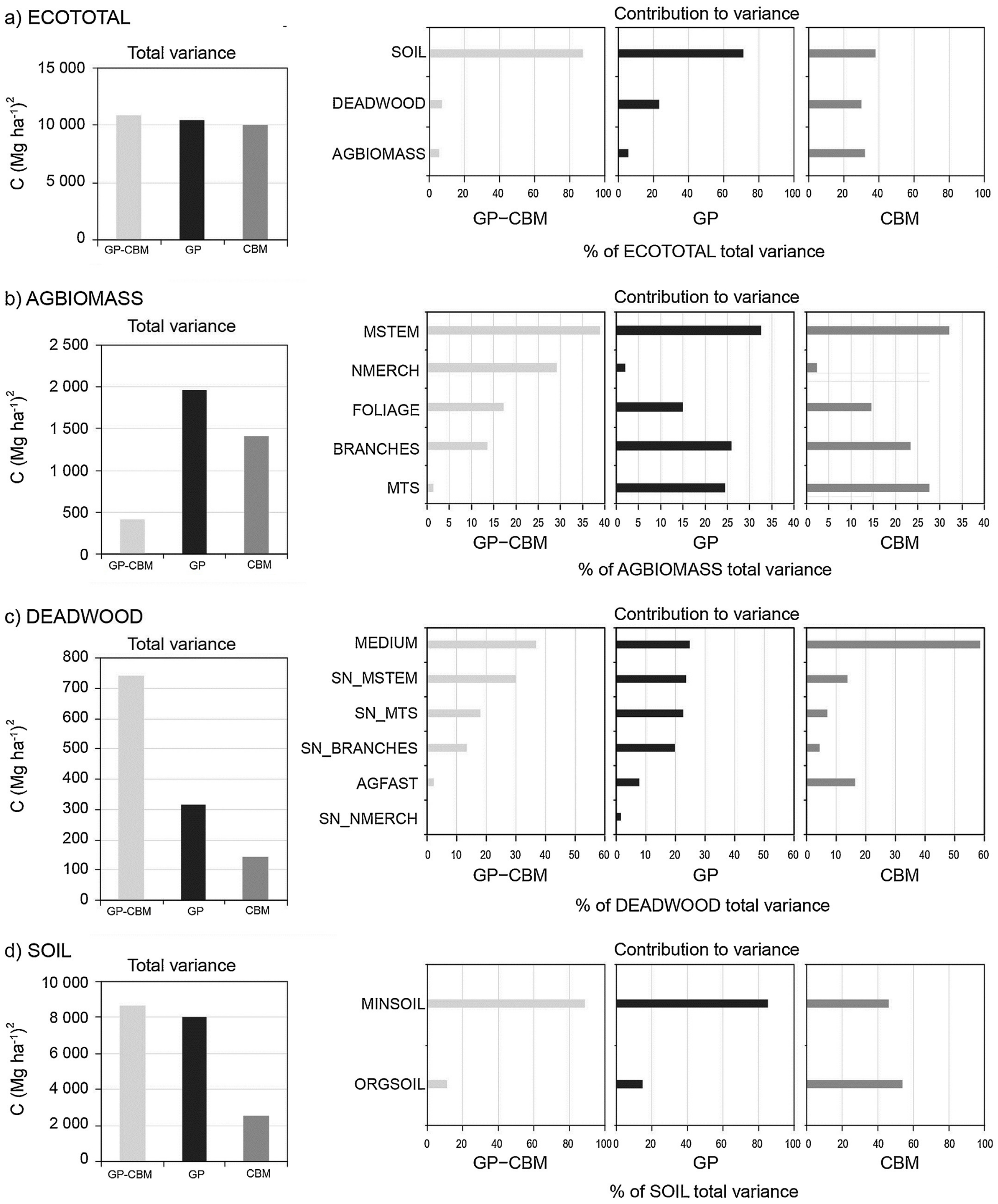

Fig. 5. Variance structure of carbon (C) pool values estimated using the National Forest Inventory ground plot (GP) data and using output from the Carbon Budget Model of the Canadian Forest Sector 3 (CBM) and the difference between measured and modelled values (GP–CBM) for ECOTOTAL and subtotal pools. Total variances are shown on the left and proportional contributions of subtotal or component pools to total variance on the right. See Table 1 for descriptions of comparison pools.

Table 3
Comparison of C stocks, model bias, and correlation between modelled and ground plot estimates for ecosystem total (ECOTOTAL) with and without soil (SOIL = ORGSOIL + MINSOIL) for 13 leading species. GP: C stock estimates based on ground plots; CBM: C stock estimates based on the CBM-CFS3; MD: mean difference (GP – CBM). Negative values for MD represent overestimation by the model. See Table 1 for comparison pool descriptions.

Leading species[a]	n	ECOTOTAL with SOIL										ECOTOTAL without SOIL			
		GP (Mg ha^{-1})		CBM (Mg ha^{-1})		MD (Mg ha^{-1})			% Bias	Correlation		MD (Mg ha^{-1})		Correlation	
		Mean	(se)	Mean	(se)	Mean	(se)	p		r	p	MD	p	r	p
Balsam fir	19	138.5	(−12.2)	169.4	(11.2)	−30.9	(16.3)	0.033	−22.3	0.03	0.445	−12.1	0.000	0.69	0.000
Subalpine fir	27	253.2	(21.7)	187.8	(14.5)	65.4	(18.7)	0.000	25.8	0.53	0.002	10.6	0.011	0.90	0.000
Red maple	5	170.1	(19.4)	210.2	(13.3)	−40.2	(25.3)	0.078	−23.6	−0.16	0.391	21.3	0.019	0.16	0.350
Sugar maple	8	253.1	(24.8)	291.7	(26.8)	−38.6	(24.7)	0.071	−15.3	0.54	0.069	21.4	0.003	0.75	0.000
Paper birch	7	181.0	(20.4)	169.2	(26.6)	11.8	(19.6)	0.280	6.5	0.68	0.031	4.7	0.289	0.39	0.108
Engelmann spruce	10	260.6	(34)	181.1	(18.6)	79.5	(39.9)	0.031	30.5	−0.07	0.421	7.2	0.285	0.65	0.005
White spruce	16	254.6	(24.7)	170.1	(17.4)	84.5	(33.6)	0.009	33.2	−0.26	0.164	−7.7	0.036	0.65	0.000
Black spruce	53	206.1	(12.1)	157.5	(8.0)	48.6	(14.4)	0.001	23.6	0.01	0.475	−9.9	0.000	0.62	0.000
Jack pine	46	78.2	(9.0)	83.3	(11.3)	−5.1	(5.5)	0.000	−6.5	0.74	0.000	−11.3	0.000	0.84	0.000
Lodgepole pine	54	147.0	(15.9)	206.7	(20.8)	−59.7	(6.8)	0.268	−40.6	0.51	0.000	−14.8	0.000	0.84	0.000
Trembling aspen	24	181.8	(11.7)	251.3	(15.1)	−69.6	(16.4)	0.000	−38.3	0.27	0.100	−8.4	0.019	0.60	0.000
Douglas-fir	13	203.0	(28.6)	318.7	(18.8)	−115.6	(17.4)	0.000	−56.9	0.81	0.000	−39.0	0.000	0.88	0.000
Western hemlock	9	503.4	(84.1)	489.1	(34.8)	14.3	(62.6)	0.411	2.8	0.74	0.005	48.8	0.054	0.74	0.006

[a] See Appendix A for scientific names.

CBM total SOIL variance (Fig. 5d), but for the GP SOIL variance, the proportion contributed by the MINSOIL pool was approximately four times that of the ORGSOIL pool (Fig. 5d). These results indicate that the model structure and/or parameters need to be improved to express more variation in soil C stocks, and in particular to express more variation in MINSOIL C.

3.3. *Comparison of C pools by leading tree species*

The ECOTOTAL pool could be calculated for 13 leading species with at least five plots from the 284 plots with complete GP data (Table 3). Bias (MD) spanned a wide range in values from −115.6 Mg ha^{-1} (57% overprediction by CBM) for Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) to 84.5 Mg ha^{-1} (33% underprediction by CBM) for white spruce (*Picea glauca* (Moench) Voss) (Table 3). Overestimation for Douglas-fir was influenced by three outliers with very high bias (Fig. 4). Values for MD by leading species were often significant and correlations often low and not significant (Table 3). If SOIL (ORGSOIL + MINSOIL) was excluded from the ECOTOTAL so that comparison pools and statistics were based on the sum of AGBIOMASS and DEADWOOD pools, the magnitude of the bias was substantially reduced and correlations were substantially improved. Without soil, ECOTOTAL correlations (r) for 11 of 13 leading species were $\geq$0.62 and $p \leq 0.006$. With soil, ECOTOTAL correlations (r) for only five of 13 leading species were $\geq$0.51 with $p \leq 0.002$ (Table 3). These results confirm that for most of the leading species analyzed (excepting red maple [*Acer rubrum* L.] and paper birch [*Betula papyrifera* Marsh.]), the correlations between GP and CBM for the ECOTOTAL without SOIL are good, but CBM estimates are often biased. Therefore we focused our in-depth analysis of leading species on identifying sources of bias in the subtotal pools. Another reason for focusing on bias is that accounting or correcting for bias in one pool can substantially improve correlations in one or more downstream pools (i.e., pools that receive input from the biomass pools). For example, we found that correcting for YC_DIFF in balsam poplar (*Populus balsamifera* L.) increased the correlation for the MSTEM pool from 0.49 to 0.96, in the SN_MSTEM pool from −0.08 to 0.89, and in the MEDIUM pool from −0.50 to 0.80. Thus, it is problematic to give too much credence to poor correlations, especially for soil pools, that receive input from of a

Table 4
Mean difference (GP – CBM) in estimated carbon stocks between National Forest Inventory ground plots (GP) and Carbon Budget Model of the Canadian Forest Sector 3 (CBM) for the AGBIOMASS subtotal pool and its component pools, by leading species.[a,b] See Table 1 for comparison pool descriptions.

Leading species[c]	n[d]	AGBIOMASS (Mg ha^{-1})	MSTEM (Mg ha^{-1})	MTS (Mg ha^{-1})	NMERCH (Mg ha^{-1})	BRANCHES (Mg ha^{-1})	FOLIAGE (Mg ha^{-1})
Mean difference (Mg ha^{-1})							
Balsam fir	41	−4.7 *	−3.0 *	2.4 *	−2.4 *	−0.1 ns	−0.2 ns
Subalpine fir	37	3.6 ns	6.4 *	1.7 *	−7.7 *	2.2 *	1.0 ns
Red maple	10	21.7 *	9.5 *	4.7 *	−0.8 ns	5.5 *	1.7 *
Sugar maple	19	34.8 *	20.2 *	4.1 *	−3.1 *	7.1 *	2.9 *
Paper birch	20	5.3 ns	3.1 *	3.2 *	−3.0 ns	2.5 *	0.4 ns
Engelmann spruce	18	6.8 ns	8.1 *	1.7 *	−8.4 *	4.1 *	1.3 *
White spruce	58	−2.0 ns	4.2 ns	0.4 ns	−5.9 *	0.1 ns	−0.8 *
Black spruce	165	−2.0 ns	−0.6 *	2.4 *	−3.0 *	−0.4 *	0.2 ns
Jack pine	46	3.1 ns	1.9 ns	1.8 *	−1.1 ns	0.3 *	0.7 *
Lodgepole pine	54	2.4 ns	7.5 *	3.1 *	−5.8 *	−1.2 *	−1.3 *
Eastern white pine	12	18.9 *	14.1 *	2.1 *	−0.2 ns	1.1 ns	1.7 *
Balsam poplar	10	−6.0 ns	1.6 ns	−0.4 ns	−8.9 *	1.8 *	0.0 ns
Trembling aspen	84	6.6 *	7.1 *	1.6 *	−4.2 *	1.7 *	0.3 *
Douglas-fir	19	−12.7 *	11.6 *	1.6 *	−23.2 *	−2.7 *	0.1 ns
Eastern white cedar	13	21.1 *	12.1 *	1.8 *	0.2 ns	3.3 *	1.6 *
Western hemlock	17	22.2 *	30.7 *	−0.7 ns	−13.9 *	4.3 *	1.7 ns

[a] Asterisks indicate significant results at $p \leq 0.05$ (ns: not significant).
[b] See Appendix B for complete listing of means, standard errors, correlations, n and p values.
[c] See Appendix A for scientific names of leading species.
[d] For each leading species, n is the largest sample size available from among pools for that leading species.

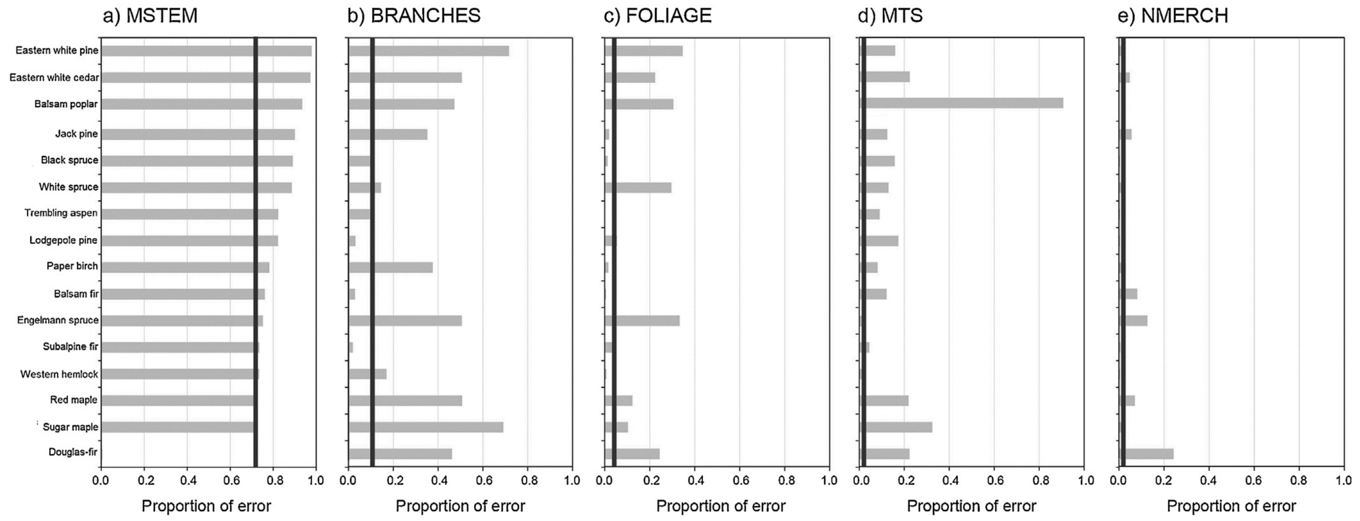

Fig. 6. Proportion of error in the aboveground biomass (AGBIOMASS) component pools that is explained by the difference between the ground plot and yield curve total merchantable volume (YC_DIFF) for 16 leading species. See Appendix A for scientific names of leading species and Table 1 for descriptions of comparison pools. Leading species are ordered from largest to smallest proportion of error in MSTEM (largest biomass pool) explained by YC_DIFF. Black bars indicate the mean value across all 16 species.

series of upstream biomass and deadwood pools (Fig. 3). Efforts to reduce uncertainty in the model's prediction of soil C stocks should therefore first focus on reducing bias in the estimates of upstream pools.

3.3.1. *Sources of bias in the AGBIOMASS pool by leading species*

Carbon stock estimates for the AGBIOMASS pool were unbiased for eight of 16 leading species (Table 4). For the remaining eight leading species, bias was mostly manifest as underestimation by the CBM-CFS3, which accounted for the significant but small bias (MD = 4.3 Mg ha^{-1}) for all plots combined (Table 2). For leading species where AGBIOMASS underestimation occurred, it was mainly attributable to the merchantable stemwood (MSTEM) component pool (Table 4). A large percentage (72–98%) of the error in the MSTEM pool for 15 of 16 leading species could be explained by the difference in volume estimates from the ground plots and the input yield curves (YC_DIFF; Fig. 6a). Some error in the remaining component pools was related to YC_DIFF, especially for the BRANCHES pool (various leading species; Fig. 6b) and for the MTS pool (balsam poplar only; Fig. 6d); however, the bias for the latter combination of leading species and component pool (MD = −0.4 Mg ha^{-1}) was neither significant, nor large (Table 4).

For the most part, the errors in the FOLIAGE, MTS, and NMERCH component pools were explained not by YC_DIFF (Fig. 6c–e) but more likely by the biomass equations used to estimate component pools from stemwood biomass and how they are implemented in the CBM-CFS3, or by the individual-tree models used to estimate components by the NFI and subsequently used by us for estimation of GP pools (or both of these factors). AGBIOMASS in the CBM-CFS3 is estimated from volume per hectare using stand-level parameters whereas NFI ground plot biomass is estimated by summing individual tree biomass estimates. For the most part, the individual tree biomass equations used for NFI estimation are the same as those used in developing the stand-level volume-to-biomass parameters in Boudewyn et al. (2007) which are implemented for volume-to-biomass conversions in the CBM-CFS3. Thus, error observed in biomass estimates between GP and CBM (when YC_DIFF = 0) can be attributed to implementation of the stand-level volume-to-biomass conversion equations (Boudewyn et al., 2007). The ability of the CBM-CFS3 to represent within-stand variation in species composition for biomass expansion equations is limited to the dominant hardwood or softwood leading species (or both) for which yield curves are provided. Therefore, some additional error in estimation of the AGBIOMASS pool may occur in stands with multiple hardwood or softwood species, even where YC_DIFF is zero.

To illustrate this point, we compared MSTEM C values calculated using three different approaches: (1) for the ground plot based on individual tree data and individual tree (IT) biomass equations taken from the NFI (IT approach), (2) by the CBM-CFS3 using the Boudewyn et al. (2007) stand-level equations that are assigned on the basis of leading hardwood or softwood species associated with one or more yield curves (the CBM-CFS3 approach), and (3) using the stand-level equations in Boudewyn et al. (2007) to calculate a weighted (by basal area) mean, accounting for the contribution of each species to the total (the STAND approach). These different approaches to calculating MSTEM were implemented for two example plots, in both of which there was no difference between the yield curve volume and the ground plot volume (i.e., YC_DIFF = 0). The first example plot, simulated with one yield curve, was composed of five softwood and one hardwood leading species; the second example plot was simulated with three yield curves to represent two softwood and one hardwood leading species. In the first case, the estimates of the MSTEM C generated by the IT, CBM-CFS3, and STAND methods were 21, 32, and 26 Mg ha^{-1}, respectively. The CBM-CFS3 estimate was 52% greater than the IT estimate, whereas the STAND estimate was only 24% greater than the IT estimate. The CBM-CFS3 estimate was high because only one of the species (the leading species for the plot) was used to select the biomass equation applied to the whole plot, and its factor for conversion to biomass from volume was high relative to all other species in the stand. In the second example, the species composition of the plot was simpler and the basal area was evenly divided between hardwood and softwood species. The estimates generated by the IT, CBM-CFS3, and STAND approaches were similar, at 24, 26, and 27 Mg ha^{-1}, respectively.

The bias of the NMERCH component was significant for 11 of 16 leading species, for which there was always an overestimation by the CBM-CFS3 (Table 4). Generally the error was not correlated with YC_DIFF (Fig. 6e). The biomass expansion equations from Boudewyn et al. (2007) that are used in the CBM-CFS3 to estimate the biomass

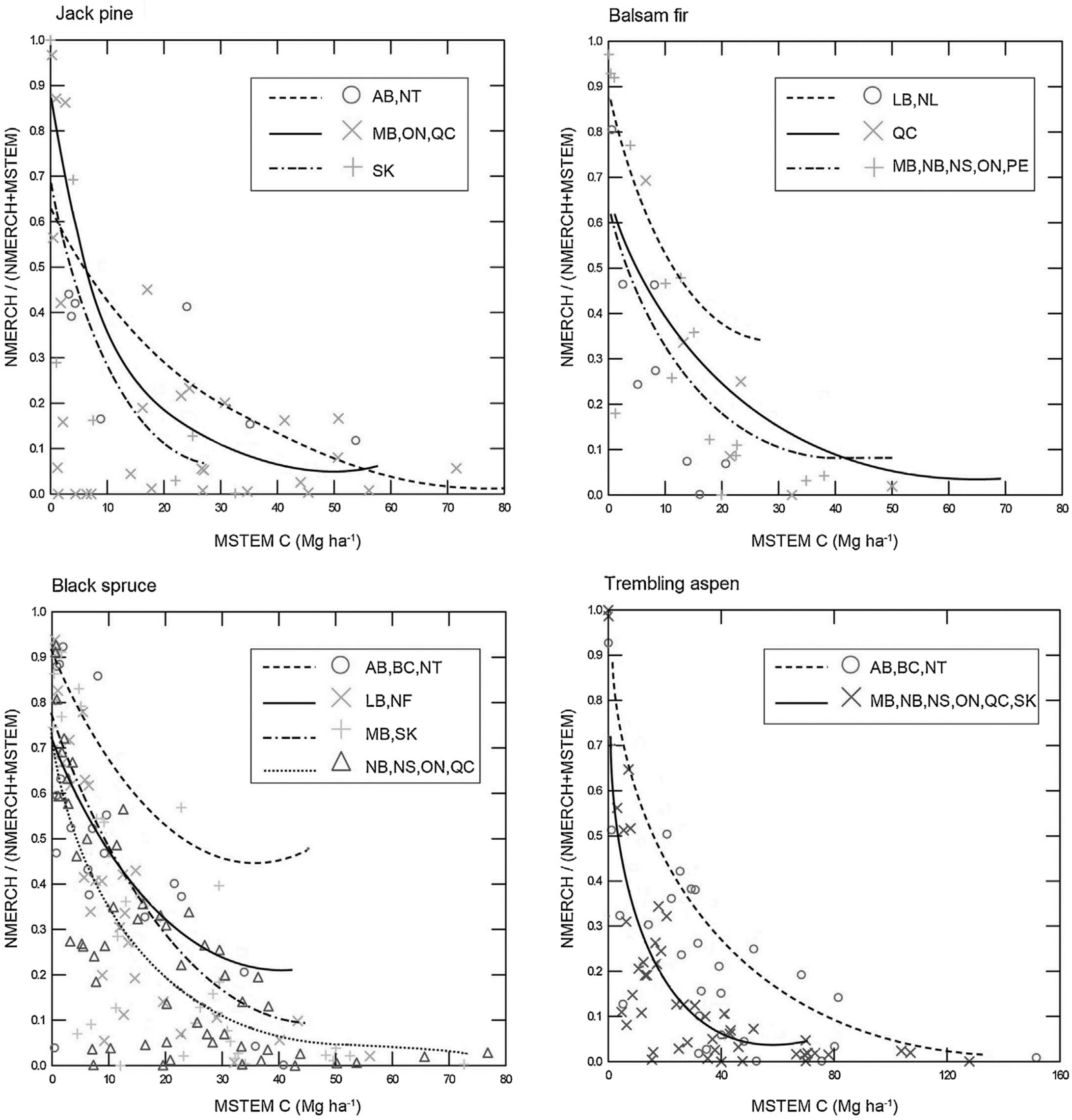

Fig. 7. Carbon (C) in the NMERCH pool as a proportion of NMERCH + MSTEM in the Carbon Budget Model of the Canadian Forest Sector 3 (represented by the "best fit" lines) and the National Forest Inventory ground plot data (points), in relation to C in the MSTEM pool, for the leading species black spruce (*Picea mariana* (Mill.) BSP), jack pine (*Pinus banksiana* Lamb.), balsam fir (*Abies balsamea* (L.) Mill.), and trembling aspen (*Populus tremuloides* Michx.), for groups of Canadian jurisdictions with similar biomass expansion factors. Jurisdiction codes: AB: Alberta; BC: British Columbia; LB: Labrador; MB: Manitoba; NB: New Brunswick; NL: Newfoundland; NS: Nova Scotia; NT: Northwest Territories; ON: Ontario; PE: Prince Edward Island; QC: Quebec; SK: Saskatchewan. See Table 1 for descriptions of comparison pools.

components included in NMERCH are assigned on the basis of leading species, jurisdiction, and terrestrial ecozone. For four leading species (jack pine [*Pinus banksiana* Lamb.], balsam fir [*Abies balsamea* (L.) Mill.], black spruce [*Picea mariana* (Mill.) BSP], and trembling aspen [*Populus tremuloides* Michx.]), we had sufficient data to examine the relationship between NMERCH and MSTEM from the CBM-CFS3, and the NFI ground plot data (Fig. 7). The NMERCH pool was overestimated by the CBM-CFS3 for trembling aspen regardless of jurisdiction, but overestimation for balsam fir occurred only for Newfoundland and Labrador and not for any other jurisdiction. NMERCH for black spruce was overestimated in three of the four jurisdictional groups that we examined but not for the group including Quebec, Ontario, Nova Scotia, and New Brunswick, where estimation of NMERCH was unbiased but the uncertainty was high (as indicated by the wide scatter of NFI GP estimates around the CBM-CFS3 curve). NMERCH overestimation by the CBM-CFS3 for jack pine was more pronounced for the group consisting of Manitoba, Ontario, and Quebec, than for the other jurisdictions.

3.3.2. *Sources of bias in the DEADWOOD pool by leading species*

On average, the DEADWOOD subtotal pool was overestimated by the CBM-CFS3 (MD = −9.2 Mg ha^{-1}; Table 2). The bias was significant for 11 of 16 leading species, primarily because of overestimation in the downed deadwood component pools (i.e., AGFAST and MEDIUM pools) (Table 5) and to a lesser degree the SN_MSTEM estimates. The remaining snag component pools had more leading species with statistically significant bias, although the bias values were generally small (Table 5).

3.3.3. *Sources of bias in SOIL pool by leading species*

On average, total soil C (SOIL pool) and its component pools (ORGSOIL and MINSOIL pool) were underestimated by the CBM-CFS3 (MD = 10.6 Mg ha^{-1}; Table 2). SOIL subtotal estimates were unbiased for seven of the 14 leading species for which MD was calculated (Table 6). For three of the remaining seven leading species (jack pine, trembling aspen, and Douglas-fir), the SOIL pool was overestimated by the CBM-CFS3. Both component pools were

Table 5
Mean difference (GP – CBM) in estimated carbon stocks between National Forest Inventory ground plots (GP) and the Carbon Budget Model of the Canadian Forest Sector 3 (CBM) for the DEADWOOD subtotal pool and its component pools, by leading species.[a,b] See Table 1 for comparison pool descriptions.

Leading species[c]	n[d]	DEADWOOD (Mg ha^{-1})	SN_MSTEM (Mg ha^{-1})	SN_MTS (Mg ha^{-1})	SN_NMERCH (Mg ha^{-1})	SN_BRANCHES (Mg ha^{-1})	AGFAST (Mg ha^{-1})	MEDIUM (Mg ha^{-1})
Mean difference (Mg ha^{-1})								
Balsam fir	41	−8.0 *	−1.5 *	0.3 *	−0.1 ns	1.1 *	−2.7 *	−5.4 *
Subalpine fir	37	5.3 *	5.8 *	0.8 *	−0.5 *	3.4 *	−8.8 *	1.2 ns
Red maple	10	−0.4 ns	−1.9 ns	0.2 ns	−0.1 *	0.2 ns	−1.1 ns	1.7 ns
Sugar maple	19	−13.4 *	−3.6 *	0.3 *	−0.1 ns	0.3 ns	−4.7 *	−6.1 *
Paper birch	20	0.5 ns	0.0 ns	0.7 *	−0.4 *	1.3 *	−1.2 ns	−1.8 ns
Engelmann spruce	18	−0.4 ns	1.6 ns	0.4 *	−0.4 *	1.2 *	−6.5 *	5.7 ns
White spruce	58	−6.6 *	−0.4 ns	0.3 *	−0.1 ns	0.3 *	−4.4 *	−2.6 *
Black spruce	165	−9.6 *	−1.2 *	0.3 *	0.2 ns	0.3 *	−4.5 *	−4.5 *
Jack pine	46	−14.7 *	−2.6 *	0.2 *	0.3 ns	0.4 *	−2.9 *	−10.5 *
Lodgepole pine	54	−17.0 *	−2.2 *	0.4 *	0.7 *	0.1 ns	−6.2 *	−7.7 *
Eastern white pine	12	−10.7 *	−2.8 *	0.3 *	0.2 ns	0.1 ns	−1.3 *	−7.1 *
Balsam poplar	10	−22.0 *	−3.3 *	0.1 ns	−0.6 *	0.6 ns	−2.5 *	−17.3 *
Trembling aspen	84	−15.4 *	−1.2 ns	0.5 *	0.1 ns	0.8 *	−3.7 *	−12.0 *
Douglas-fir	19	−21.6 *	−4.8 *	0.3 *	−1.4 *	−0.1 ns	−13.1 *	−10.7 *
Eastern white cedar	13	−0.2 ns	−0.2 ns	0.3 *	0.0 ns	0.7 *	−1.0 *	−1.0 ns
Western hemlock	17	21.2 ns	−4.2 ns	0.4 ns	0.4 ns	1.7 ns	−8.6 *	16.1 ns

[a] Asterisks indicate significant results at $p \leq 0.05$ (ns: not significant).
[b] See Appendix B for complete listing of means, standard errors, correlations, n and p values.
[c] See Appendix A for scientific names of leading species.
[d] For each leading species, n is the largest sample size available from among pools for that leading species.

Table 6
Mean difference (GP – CBM) in estimated carbon stocks between National Forest Inventory ground plots (GP) and the Carbon Budget Model of the Canadian Forest Sector 3 (CBM) for the SOIL subtotal pool and its component pools, by leading species.[a,b] See Table 1 for comparison pool descriptions.

Leading species[c]	n[d]	SOIL (Mg ha^{-1})	ORGSOIL (Mg ha^{-1})	MINSOIL (Mg ha^{-1})
Mean difference (Mg ha^{-1})				
Balsam fir	29	−16.1 ns	29.2 *	−20.9 *
Subalpine fir	29	55.1 *	−11.3 *	65.6 *
Red maple	7	−43.6 ns	−6.8 ns	−36.4 *
Sugar maple	15	−42.4 ns	−23.9 *	−15.0 ns
Paper birch	11	0.9 ns	0.3 ns	1.2 ns
Engelmann spruce	13	78.9 *	13.8 ns	70.0 *
White spruce	51	88.8 *	40.6 *	77.8 *
Black spruce	125	62.6 *	31.8 *	39.4 *
Jack pine	38	−31.9 *	2.1 ns	−25.4 *
Lodgepole pine	44	3.2 ns	−1.9 ns	4.4 ns
Eastern white pine	10	64.6 ns	3.9 ns	59.5 ns
Balsam poplar	7	NA NA	9.4 ns	NA NA
Trembling aspen	70	−59.0 *	−18.2 *	−31.3 *
Douglas-fir	15	−75.9 *	−28.0 *	−50.2 *
Eastern white cedar	7	NA NA	25.6 ns	NA NA
Western hemlock	12	−50.9 ns	−14.2 ns	−52.2 *

[a] Asterisks indicate significant results at $p \leq 0.05$ (ns: not significant; NA: not applicable).
[b] See Appendix B for complete listing of means, standard errors, correlations, n and p values.
[c] See Appendix A for scientific names of leading species.
[d] For each leading species, n is the largest sample size available from among pools for that leading species.

overestimated for Douglas-fir and trembling aspen, but only the MINSOIL pool for jack pine (Table 6). For the final four leading species (black spruce, Engelmann spruce [*Picea engelmannii* Parry ex Engelm.], subalpine fir [*Abies lasiocarpa* (Hook.) Nutt.], and white spruce), the CBM-CFS3 underestimated the SOIL subtotal pool. For white spruce and black spruce, both the ORGSOIL and MINSOIL component pools were underestimated, but for subalpine fir and Engelmann spruce, SOIL underestimation was because of underestimation of the MINSOIL component pool (Table 6).

4. Discussion

Although it is generally accepted that model evaluations should include a comparison with field data, such comparisons are rarely done, due to lack of adequate independent data sets for validation, difficulties with selection of meaningful statistical tests or approaches, and difficulties with specification of what constitutes acceptable performance (Prisley and Mortimer, 2004). Our evaluation overcame the first of these limitations by using the NFI's national-scale set of independent ground plot data. However, the challenges of selecting appropriate test statistics and defining criteria for acceptable model performance remained. Other challenges that we encountered during the project, also discussed by Bellocchi et al. (2010), included ensuring the quality and representativeness of measured data for model inputs and evaluation of model outputs, ensuring that modelled and measured pools had the same definitions, and evaluation of system-level and submodel outputs to ensure detection of counter-interactions (e.g., overestimation in one component pool cancels out underestimation in another). In our case it was particularly important to ensure that ground plot data were compiled to be consistent with merchantability diameter limits used in the CBM-CFS3, and to ensure that we only compared estimates where complete ground plot data were available. The latter was critical as portions of ground plot data are often missing because of the difficulties associated with measuring deadwood and soil in particular. Our results clearly demonstrate that comparing model estimates to incomplete ground plot estimates can lead to erroneous conclusions regarding model bias. In our analysis, this was of particular significance to mineral soil C, and therefore ecosystem total C stocks, because of the large contribution of mineral soil to the ecosystem total and because of the large proportion of NFI ground plots for which mineral soil C estimates were not available. When total ecosystem C stock predictions were compared to incomplete (i.e., mineral soil C stock estimates missing) ground plot data, it led to the erroneous conclusion that the model overestimated mineral soil and ecosystem total C stocks.

Specification of a standard for acceptable model performance was a major challenge. For forest C accounting models, there is no accepted approach to statistical testing or acceptance criteria (Prisley and Mortimer, 2004) and the IPCC-GPG (Eggleston et al., 2006; Penman et al., 2003) also provides only minimal guidance. Because there are no published standards for ecosystem total estimates, we relied on classical comparison statistics (bias and correlation) to conclude that the CBM-CFS3 is reliable for estimation of ecosystem total C stocks with a 0.9% bias. We used classical comparison statistics as well as IPCC-GPG standards to assess model performance for the AGBIOMASS and DEADWOOD subtotal pools. The IPCC standards are preferred for the subtotal pools, not because one would conclude the model performed better using that metric, but rather because it is a standard meaningful to forest C accounting. When the classical statistics were used with our large sample size (maximum $n = 696$), which is necessary for assessment of large forest areas such as Canada's, very small MDs and very low correlations were often statistically significant, but neither ecologically meaningful nor useful for ecosystem-level forest C accounting. Therefore, meaningful standards are still required for judging model success. Classical comparison statistics were most useful for identifying those pools and/or leading species for which further work is required to improve model accuracy.

On average the CBM-CFS3 was unbiased for ecosystem total C stock estimation ($\mathrm{MD} = 1.9\,\mathrm{Mg\,ha^{-1}}$, $p = 0.397$), but this resulted from compensating over- and underestimation of various components of total ecosystem C stocks. We suggest an alternate approach to judging success for ecosystem total C stocks based on the proportion of plots meeting an acceptable standard for error. Based on our analysis, we suggest that a result might be judged good if 90% of all plots compared have 75% error or less. A 75% rate of error for the ecosystem total seems reasonable because the ecosystem total included DEADWOOD error (IPCC standard of 30%), but also error from LITTER and SOIL. SOIL alone could account for much of the additional acceptable error because the variance of SOIL in the GP data was over 25 times that of DEADWOOD, soil C stocks are difficult to measure in the field (Shaw et al., 2008; Yanai et al., 2003), and difficult to model (Conant et al., 2011; Schmidt et al., 2011). This proposed metric for judging success of modelled estimates for ecosystem total C stocks may need to be altered for ecosystems that differ substantially from those in the managed forest area of Canada.

Our analysis showed that by far, the SOIL pool (mainly MINSOIL) contributed the largest proportion to variance in ECOTOTAL error. This result is partially explained by the fact that the model expressed a relatively small proportion (25%) of the variation estimated from the GP data, which indicates that accuracy in estimation of ecosystem total C stocks by the CBM-CFS3 will be improved mainly by accurately expressing more variation in soil C stocks and the factors or processes influencing C accumulation in soil. In the CBM-CFS3 and other soil or forest ecosystem models, C stocks in mineral soil are often determined by the model initialization process used to estimate initial C stocks of deadwood and soil pools before any simulations are performed. Therefore, improving the representation of variation in mineral soil C stocks will likely require improvements in the initialization process, which presents a substantial challenge to the soil modelling community and is currently a focus of research (Foereid et al., 2012; Xu et al., 2011; Yeluripati et al., 2009) and debate over approaches to modelling soil C (Conant et al., 2011; Schmidt et al., 2011).

On average, the CBM-CFS3 underestimated the ORGSOIL and MINSOIL pools. However, the estimates were unbiased for over half of the leading species and thus the national-scale underestimation was being driven by a few leading species, mainly balsam fir, white and black spruce. These three leading species are often associated with substantial moss contributions to ecosystem net primary productivity (Lavoie et al., 2005; Turetsky et al., 2010), which is currently not represented in the CBM-CFS3. NFI data also showed that, of the plots characterized by the 16 leading species, those with black spruce as the leading species had the highest mean moss biomass (3%), the highest percent cover of *Sphagnum* and *Pleurzium* moss species (34%), and the highest frequency moss-derived O soil horizons (76%), all of which indicate that mosses play an important role in the C budget of these ecosystems. Previous studies have also concluded that estimates of black spruce C budgets by the CBM-CFS3 could be improved by including moss C dynamics (Bona et al., 2013; Hagemann et al., 2010; Moroni et al., 2010b) and that the contribution of mosses may also be important to the C budgets of forests with leading species of white spruce (Bona et al., 2013) or balsam fir (Moroni et al., 2010b).

Fire plays an important role in the ecology of all three leading species where soil C was overestimated. It may be possible that the model default value for the proportion of organic horizon and downed deadwood C lost to combustion during fire should be increased for these leading species. For Douglas-fir, soil C overestimation may be tracked back to overestimation of the nonmerchantable component, which was large compared to all other leading species. Carbon from this pool is eventually transferred to soil pools and may account for their overestimation. Other research has shown that trembling aspen litter and downed wood (that eventually transfer C to soil) decays at rates faster than for other leading species common in Canada (Alban and Pastor, 1993; Prescott and Vesterdal, 2005; Angers et al., 2012; Braise and Drouin, 2012). It may be possible that trembling aspen default decay rates in the CBM-CFS3 need to be increased, or the proportion of decaying material that enters the slow pool decreased, both of which would reduce overestimation of soil C by the model. However, at present the CBM-CFS3 does not accommodate species-specific decay rates of dead organic matter pools.

The DEADWOOD subtotal pool made the second-largest contribution to ECOTOTAL error, but that contribution was substantially less than the contribution of the SOIL pool. Within the DEADWOOD pool, total variance for the CBM pool was lower than that for the GP pool, and the total variance of the error was substantially larger than the variance for either the CBM or the GP pool individually. These results indicate that agreement between model and GP estimates for the DEADWOOD pool may be poor, but the effect of the DEADWOOD error on ECOTOTAL error is small. The contributions of the six component pools to total variations in the DEADWOOD pool show that accuracy of the DEADWOOD pool in the CBM-CFS3 would be improved if the model expressed greater variation in standing-deadwood pools (i.e., SN_MSTEM, SN_MTS, SN_NMERCH, SN_BRANCHES) and relatively less variation in downed-deadwood pools (i.e., AGFAST and MEDIUM) to approximate the variance structure of the GP pools. The largest component pools (MEDIUM and SN_MSTEM) contributed the most error within the DEADWOOD subtotal pool. The standing-deadwood pools reflect recent stand dynamics and the impacts of disturbances that did not result in stand replacement. Observed higher variance in standing-deadwood pools in the GP data than in CBM-CFS3 estimates may reflect incomplete information about minor non-stand-replacing disturbances in the simulation input data. Although the size of the MD varied by leading species the downed deadwood (AGFAST and

MEDIUM) pools were overestimated, or the MD was not statistically significant. This was also true for the SN_MSTEM pool, excepting subalpine fir. The consistent overestimation of DEADWOOD pools suggests a need to improve overall modelling of deadwood dynamics keeping in mind that the contribution of this subtotal pool to overall ecosystem total error was small.

In the US, Woodall et al. (2012) compared field estimates for standing-deadwood C stocks (equivalent to our combined snag pools) with those based on the US approach to estimation of C stock, which differs substantially from the CBM-CFS3. They concluded that the error associated with estimation of standing deadwood C stocks was high, but the contribution of standing deadwood C stocks to ecosystem total C stocks was a small overestimation (4.2%). The same contribution calculated from our data (4.8%) was similar in absolute magnitude, but the value was an underestimation and was not statistically significant. In the US study, mean C stocks for 14 forest types ranged from 0.62 to 6.76 Mg ha^{-1} when estimated from their field data and from 1.52 to 17.01 Mg ha^{-1} when estimated from their model. When grouped by leading species, our GP estimates (i.e., field data) ranged from 2.6 to 19.4 Mg ha^{-1}, which was higher than the US estimates; the range in our modelled estimates (3.7–19.2 Mg ha^{-1}) was similar to that for our GP data. Woodall et al. (2012) noted that their field measurements did not include trees with dbh < 12.7 cm, that mortality of small-diameter trees may be an important driver of deadwood accumulation, and that this size class deserves further investigation. The NFI field data and the CBM-CFS3 included trees down to 1.3 m in height, which may account for the higher estimates of snag C from our GP data compared with the US field data and the unbiased estimation by the CBM-CFS3.

The large (relative to DEADWOOD GP and CBM pools) error variance for the DEADWOOD pool in our evaluation was attributable to low correlations for the downed-deadwood component pools (i.e., AGFAST, MEDIUM) rather than the standing-deadwood component pools. The MEDIUM and AGFAST pools were overestimated for forest types with balsam fir and black spruce as leading species, i.e., forest types where mosses are often important. Moroni et al. (2010a) and Hagemann et al. (2010) have shown that high-productivity mosses can rapidly bury small-diameter wood characteristic of balsam fir and black spruce stands. If downed wood was buried by mosses in the balsam fir and black spruce NFI ground plots, it would not have been included in the woody debris inventory, such that the GP data may have underestimated downed woody debris, rather than the CBM-CFS3 overestimating this component pool. Other factors that may contribute to poor correlations for the DEADWOOD pool include the possibility that ground plots experienced undocumented historic disturbances affecting mortality and deadwood dynamics that were therefore not accounted for in CBM-CFS3 simulations. CBM-CFS3 parameters for deadwood decomposition and transfer of C between deadwood pools express little variation related to the ecology and decomposition traits that do vary with tree species (Harmon et al., 2011), because of limitations imposed on the model by computational capacity and incomplete scientific understanding. Once these limitations are addressed, parameters developed to reflect the effects of forest type (hardwood or softwood) or tree species (e.g., Hilger et al., 2012; Smyth et al., 2010) can be tested for implementation in the model. Bias in estimation of deadwood C stocks may also result, in part, from biases in methodologies and compilation, such as ascribing density factors (Harmon et al., 2011) for conversion of deadwood volume to deadwood mass.

We observed that the magnitude of the overestimation of the DEADWOOD subtotal pool (−9.2 Mg ha^{-1}) was similar to that for the underestimation of the SOIL subtotal pool (10.6 Mg ha^{-1}). When the data for these two subtotal pools were combined, the MD was −2.3 Mg ha^{-1} and not significant ($p \leq 0.05$). We considered the possibility that because dead organic matter collectively was unbiased that balancing the decay and transfer dynamics between deadwood and soil pools may resolve the bias. However, this is not likely the case because for leading species where the SOIL pools had a large and significant underestimate (e.g., black spruce, Engelmann spruce, white spruce), the DEADWOOD pool bias was not significant, or if significant was very small relative to the bias for SOIL. Also, where SOIL had a large significant overestimate (e.g., Douglas-fir, jack pine, trembling aspen), the DEADWOOD pool also had a large and significant overestimate.

The AGBIOMASS pool is the subtotal pool that was modelled most accurately by the CBM-CFS3. Although the accuracy of estimation for some component pools contributing to the AGBIOMASS pool could be improved, thereby reducing error variances, the contribution of the AGBIOMASS pool to ECOTOTAL error, which is already small, would simply become even smaller.

Error in the MSTEM pool, and sometimes in other biomass components, originates mainly from the application of yield curves meant to represent growth dynamics of a population of plots to model a single plot. This error, which we defined as YC_DIFF, can be propagated to other biomass and ecosystem C stock components. Observed error in biomass pools also arises from differences in the regression models used to estimate stand-level biomass in the CBM-CFS3 (stand-level, Boudewyn et al., 2007) and the tree-level estimates in the NFI (tree-level, e.g., Lambert et al., 2005; Ung et al., 2008). Improved simulation of historical growth dynamics at each plot and reconciliation of differences between biomass estimation methods in the model and in the plot data should result in improved estimation of biomass pools, and reduce the effect of this error on other ecosystem C pools in the CBM-CFS3. Better representation of the mix of species in a stand, especially if the species differ noticeably in terms of their stand-level volume-to-biomass conversion equations, is one example of the steps that could be undertaken. In its current version, the CBM-CFS3 summarizes multiple species-specific yield curves into softwood and hardwood components, and the dominant species in each component is used to select parameters for biomass estimation. The volume-to-biomass conversion could be made more accurate if parameters were applied individually to each species and curve provided as input. In addition, as plot re-measurements begin to accrue, yield curves could be based on repeated measurements of stem increment, or these curves could be generated by regionally parameterized growth models that are already available in some jurisdictions (e.g., Bokalo et al., 2012; British Columbia Ministry of Forests, 2009; Huang et al., 2009). Subsets of plots could also be intensively sampled to obtain dendrochronological estimates of past growth rates (e.g., Metsaranta and Kurz, 2012). Essentially, any steps taken to improve the simulation of past growth, mortality, and disturbances will improve the accuracy of biomass pool estimates.

Even though the NMERCH pool was smaller than the MSTEM pool, its contribution to error in the AGBIOMASS pool was similar in magnitude. Our results showed that in general the CBM-CFS3 overestimates NMERCH and that this overestimation could not be explained by YC_DIFF. However, analysis for leading species showed that estimation of NMERCH was unbiased for some jurisdictions and some leading species; therefore improvement of the equations will be a priority only for some combinations of jurisdiction and leading species. The ability to improve estimation of NMERCH is highly dependent on the availability of adequate data sets upon which to base the regression equations. Limited data were available to Boudewyn et al. (2007) for fitting the non-merchantable and sapling factors, and those authors emphasized the positive bias (overestimation) of these factors, especially in stands with fewer or smaller trees. It would also help if improved individual-tree biomass equations could be developed and applied to both the NFI ground plots and the volume-to-biomass model development, especially for very small (Bjarnadottir et al., 2007; Boudewyn et al., 2007) and very large trees (Boudewyn et al., 2007; Lutz et al., 2012; Matsuzaki et al., 2013). As more data become available, these factors can be improved, tested, and integrated into the CBM-CFS3 and the NFI.

The primary purpose of the CBM-CFS3 is for reporting of GHG emissions and removals and for the analysis of the impacts on C budgets of alternative management or policy scenarios. In both cases, results rely on the comparison of stock changes over time or stock differences among scenarios. Some of the apparent biases in estimating stock sizes may in fact be of lesser importance for the estimation of stock changes or the comparison of alternative scenarios.

5. Conclusions

Comprehensive comparison of model output with field measurements is a key component of evaluating forest C budget models. Nonetheless, such comparisons are rarely conducted. Over the course of this comparison exercise, we were able to resolve major challenges that have been discussed (but not necessarily executed) in previous reviews of model evaluation protocols. However, we conclude that there is a need to continue to develop practical and meaningful standards for judging success of forest C budget models, beyond what is provided by the IPCC-GPG, but based on a similar metric of percent error, or possibly pool-specific bias in units of C ($\mathrm{Mg\,ha^{-1}}$). We provide an example of one such metric for ecosystem total C stocks: it requires that a percentage of the independent comparison plots meet a minimal standard for error (e.g., 75%). Percent error for total ecosystem C stocks predicted by the CBM-CFS3 was 0.9%; 88% of plots for which ecosystem total C stocks were estimated ($n = 284$) had $\leq$75% error. Percent error of CBM-CFS3 predictions for IPCC-GPG defined aboveground biomass (7.5% error) and deadwood (30.8% error) pools compared favourably to the IPCC-GPG standards for these pools of 8% and 30%, respectively. Classical model evaluation statistics were useful for identifying model components in need of refinement to improve model accuracy, but they were not necessarily the best metric for judging model success for the application of national-scale C accounting.

The contributions of aboveground biomass and deadwood subtotal pools to ecosystem total C stock error were small relative to the soil subtotal pool. Thus, improving estimation of ecosystem total C stocks requires improving estimation of soil C stocks. Our analysis showed that aboveground biomass estimation by the CBM-CFS3 could be further improved by revising nonmerchantable biomass coefficients, and improving the ability of regional yield curves to represent growth at fine scales and growth of stands where the species mix is highly diverse. Opportunities exist for improvement of deadwood C stock estimation as the CBM-CFS3 consistently overestimated downed deadwood pools (AGFAST and MEDIUM pools) and to a lesser degree, the snag merchantable stemwood pool (SN_MERCH). For some leading species, soil C stock estimation might be improved if explicit modelling of moss C pools were included. Adequate modelling of soil C will require expression of more variation in stocks and consideration of processes creating that variation (e.g., causation of C stabilization, permafrost, saturation of soil by water).

Many of the model pools estimated with the least certainty were those for which collection of field data is typically difficult (e.g., soil, downed deadwood, biomass of tree components) or those that are commercially unimportant (e.g., nonmerchantable trees). However, it is clear that improving data sets, sampling procedures, and the biomass and deadwood models used to estimate forest C stocks from field data for these pools will help to reduce the uncertainty in both model (indirectly) and inventory (directly)-based ecosystem-scale estimates of C stocks for Tier-3 reporting.

Finally, the purpose of national forest C accounting and reporting systems is to estimate GHG emissions and removals that cannot be measured directly at a national scale and are thus often estimated from C stock changes. By evaluating the ability of the CBM-CFS3 to estimate ecosystem C stocks, our analysis is an important first step towards verification of estimates of GHG emissions and removals. However, verification of national-scale estimates of C stock changes remains a future challenge that can be addressed once repeated measurements of all relevant C stocks in NFI ground plots become available.

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Appendix A. Common and scientific and names for leading tree species in the National Forest Inventory plots, and names used in the Carbon Budget Model of the Canadian Forest Sector 3 (CBM-CFS3)

Common name	Scientific name	CBM-CFS3
Balsam fir	*Abies balsamea* (L.) Mill.	Balsam fir
Subalpine fir	*Abies lasiocarpa* (Hook.) Nutt.	Subalpine fir (or alpine fir)
Red maple	*Acer rubrum* L.	Red maple
Sugar maple	*Acer saccharum* Marsh.	Sugar maple
White birch	*Betula papyrifera* Marsh.	White birch
Engelmann spruce	*Picea engelmannii* Parry ex Engelm.	Engelmann spruce
White spruce	*Picea glauca* (Moench) Voss	White spruce
Black spruce	*Picea mariana* (Mill.) BSP	Black spruce
Spruce	*Picea* spp.	Spruce
Jack pine	*Pinus banksiana* Lamb.	Jack pine
Lodgepole pine	*Pinus contorta* Dougl. ex Loud.	Lodgepole pine
Eastern white pine	*Pinus strobus* L.	Eastern white pine
Balsam poplar	*Populus balsamifera* L.	Balsam poplar
Trembling aspen	*Populus tremuloides* Michx.	Trembling aspen
Douglas-fir	*Pseudotsuga menziesii* (Mirb.) Franco	Douglas-fir and Rocky Mountain Douglas-fir
Eastern white cedar	*Thuja occidentalis* L.	Eastern white-cedar

Appendix A (*Continued*)

Common name	Scientific name	CBM-CFS3
Western hemlock	*Tsuga heterophylla* (Raf.) Sarg.	Western hemlock
Amabilis fir	*Abies amabilis* (Dougl. ex Loud.) Dougl. ex J. Forbes	Amabilis fir
Silver maple	*Acer saccharinum* L.	Silver maple
Maple	*Acer* spp.	Other maple
Red alder	*Alnus rubra* Bong.	Red alder
Yellow birch	*Betula alleghaniensis* Britt.	Yellow birch
Bitternut hickory	*Carya cordiformis* (Wangenh.) K. Koch	Bitternut hickory
Yellow cedar	*Chamaecyparis nootkatensis* (D. Don) Spach	Yellow-cypress
White ash	*Fraxinus americana* L.	Other hardwoods
Black ash	*Fraxinus nigra* Marsh.	Other hardwoods
Red ash	*Fraxinus pennsylvanica* Marsh.	Other hardwoods
Tamarack	*Larix laricina* (Du Roi) K. Koch	Tamarack/larch
Western larch	*Larix occidentalis* Nutt.	Western larch
Red spruce	*Picea rubens* Sarg.	Red spruce
Whitebark pine	*Pinus albicaulis* Engelm.	Whitebark pine
Ponderosa pine	*Pinus ponderosa* P. Laws. ex C. Laws.	Ponderosa pine
Red pine	*Pinus resinosa* Ait.	Red pine
Western redcedar	*Thuja plicata* Donn ex D. Don	Western redcedar
Basswood	*Tilia americana* L.	Other hardwoods
Eastern hemlock	*Tsuga canadensis* (L.) Carrière	Eastern hemlock
Mountain hemlock	*Tsuga mertensiana* (Bong.) Carrière	Mountain hemlock
White elm	*Ulmus americana* L.	Other hardwoods

Appendix B. Statistics for all comparison pools by leading species

See Tables B.1–B.19

Table B.1
Definition of comparison pools.

Ecosystem total	Subtotal pools	Component pool	Description
ECOTOTAL (sum of all pools)	AGBIOMASS (sum of MSTEM, MTS, NMERCH, BRANCHES, FOLIAGE)	MSTEM	Stem bark and wood of merchantable bole for live merchantable trees
		MTS	Stem bark and wood in top and stump portion for live merchantable trees
		NMERCH	Stem bark and wood in live nonmerchantable trees and saplings
		BRANCHES	Branch biomass of all live trees (bark and wood)
		FOLIAGE	Foliage biomass of all live trees
	DEADWOOD (sum of SN_MSTEM, SN_MTS, SN_NMERCH, SN_BRANCHES, AGFAST, MEDIUM)	SN_MSTEM	Stem bark and wood of merchantable bole for dead merchantable trees
		SN_MTS	Stem bark and wood in top and stump portion for dead merchantable trees
		SN_NMERCH	Stem bark and wood in dead nonmerchantable trees and saplings
		SN_BRANCHES	Branch biomass of all dead trees (bark and wood)
		AGFAST	Fine and small woody debris
		MEDIUM	Coarse woody debris
	SOIL (sum of ORGSOIL, MINSOIL)	ORGSOIL	LFH and O soil horizons
		MINSOIL	Organic carbon in mineral soil horizons

Table B.2
Definition of Statistics.

Statistic	Statistic_definition
n	Sample size
GP_mean	Mean C stock (Mg ha^{-1}) based on National Forest Inventory ground plot data
CBM_mean	Mean C stock (Mg ha^{-1}) based on output from the Carbon Budget Model of the Canadian Forest Sector 3
MD	Mean difference of GP – CBM
GP_se	Standard error of the GP_mean
CBM_se	Standard error of the CBM_mean
MD_se	Standard error of the MD
MD_*p*	*p*-Value from *t*-distribution testing for the significant of MD
r	Correlation
*r*_*p*	*p*-Value from *t*-distribution testing for the significant of the correlation

Table B.3
Statistics for the AGBIOMASS pool. See Table B.1 for definitions of pools. See Table B.2 for definitions of statistics. See Appendix A for scientific names of leading species.

Leading species	*n*	GP_mean	CBM_mean	MD	GP_se	CBM_se	MD_se	MD_*p*	*r*	*r*_*p*
Balsam fir	29	32.8	37.5	−4.7	3.2	3.4	2.6	0.033	0.70	0.000
Subalpine fir	37	66.3	62.7	3.6	6.2	5.2	2.7	0.092	0.90	0.000
Red maple	8	52.2	30.5	21.7	7.2	6.9	6.7	0.003	0.54	0.068
Sugar maple	16	89.0	54.2	34.8	10.3	7.5	6.3	0.000	0.80	0.000
Paper birch	12	33.9	28.7	5.3	6.1	5.1	5.5	0.173	0.53	0.029
Engelmann spruce	18	67.6	60.8	6.8	10.9	7.9	4.2	0.057	0.95	0.000
White spruce	56	35.5	37.5	−2.0	4.2	2.7	3.2	0.272	0.64	0.000
Black spruce	138	37.0	38.9	−2.0	1.8	1.5	1.5	0.090	0.63	0.000
Jack pine	44	32.8	29.6	3.1	3.7	2.6	2.2	0.084	0.81	0.000
Lodgepole pine	54	70.7	68.3	2.4	5.3	4.9	2.6	0.180	0.88	0.000
Eastern white pine	12	63.4	44.5	18.9	6.9	6.5	6.3	0.004	0.56	0.023
Balsam poplar	10	33.7	39.7	−6.0	7.9	2.7	7.8	0.224	0.20	0.286
Trembling aspen	77	54.3	47.7	6.6	4.1	3.3	2.4	0.004	0.81	0.000
Douglas-fir	19	83.6	96.3	−12.7	13.1	10.2	7.0	0.039	0.85	0.000
Eastern white cedar	11	50.4	29.3	21.1	7.1	4.2	5.7	0.001	0.59	0.020
Western hemlock	17	206.9	184.7	22.2	16.2	12.6	7.4	0.003	0.90	0.000

Table B.4
Statistics for the MSTEM pool. See Table B.1 for definitions of pools. See Table B.2 for definitions of statistics. See Appendix A for scientific names of leading species.

Leading species	*n*	GP_mean	CBM_mean	MD	GP_se	CBM_se	MD_se	MD_*p*	*r*	*r*_*p*
Balsam fir	41	18.4	21.4	−3.0	2.2	2.1	0.7	0.000	0.95	0.000
Subalpine fir	37	36.0	29.6	6.4	4.3	3.5	1.3	0.000	0.96	0.000
Red maple	10	30.7	21.2	9.5	3.8	4.6	4.0	0.014	0.57	0.034
Sugar maple	19	55.7	35.5	20.2	6.9	5.1	4.0	0.000	0.81	0.000
Paper birch	20	24.5	21.4	3.1	3.4	2.9	1.6	0.028	0.89	0.000
Engelmann spruce	18	41.3	33.2	8.1	8.4	6.8	2.3	0.001	0.98	0.000
White spruce	58	23.2	19.0	4.2	3.3	1.7	2.4	0.043	0.70	0.000
Black spruce	165	18.7	19.3	−0.6	1.3	1.0	0.6	0.171	0.87	0.000
Jack pine	46	20.7	18.8	1.9	2.8	2.1	1.3	0.077	0.90	0.000
Lodgepole pine	54	47.6	40.1	7.5	4.7	4.0	1.4	0.000	0.96	0.000
Eastern white pine	12	42.5	28.4	14.1	5.6	4.9	5.0	0.005	0.56	0.021
Balsam poplar	10	22.2	20.6	1.6	5.2	2.8	4.6	0.368	0.49	0.063
Trembling aspen	84	36.6	29.5	7.1	3.3	2.5	1.8	0.000	0.85	0.000
Douglas-fir	19	52.2	40.6	11.6	9.9	9.7	2.4	0.000	0.97	0.000
Eastern white cedar	13	31.1	19.0	12.1	5.0	3.3	3.8	0.002	0.64	0.006
Western hemlock	17	147.2	116.4	30.7	15.5	12.5	5.9	0.000	0.93	0.000

Table B.5
Statistics for the MTS pool. See Table B.1 for definitions of pools. See Table B.2 for definitions of statistics. See Appendix A for scientific names of leading species.

Leading species	*n*	GP_mean	CBM_mean	MD	GP_se	CBM_se	MD_se	MD_*p*	*r*	*r*_*p*
Balsam fir	41	3.8	1.4	2.4	0.5	0.2	0.4	0.000	0.68	0.000
Subalpine fir	37	3.7	2.0	1.7	0.3	0.2	0.3	0.000	0.61	0.000
Red maple	10	6.4	1.7	4.7	1.0	0.5	0.7	0.000	0.83	0.000
Sugar maple	19	7.3	3.2	4.1	0.8	0.6	0.5	0.000	0.80	0.000
Paper birch	20	5.0	1.8	3.2	0.8	0.3	0.6	0.000	0.83	0.000
Engelmann spruce	18	4.0	2.2	1.7	0.6	0.5	0.4	0.000	0.71	0.000
White spruce	58	2.3	1.9	0.4	0.3	0.2	0.2	0.060	0.41	0.000
Black spruce	165	3.8	1.4	2.4	0.2	0.1	0.2	0.000	0.55	0.000
Jack pine	46	3.2	1.5	1.8	0.4	0.2	0.4	0.000	0.51	0.000
Lodgepole pine	54	5.8	2.7	3.1	0.5	0.3	0.4	0.000	0.63	0.000
Eastern white pine	12	4.0	2.0	2.1	0.5	0.4	0.4	0.000	0.54	0.029
Balsam poplar	10	1.7	2.1	−0.4	0.3	0.3	0.5	0.191	−0.24	0.249
Trembling aspen	84	4.0	2.4	1.6	0.3	0.2	0.3	0.000	0.45	0.000
Douglas-fir	19	4.2	2.6	1.6	0.5	0.7	0.4	0.000	0.84	0.000
Eastern white cedar	13	3.3	1.5	1.8	0.4	0.3	0.3	0.000	0.58	0.014
Western hemlock	17	7.2	7.8	−0.7	0.5	0.9	0.6	0.141	0.72	0.000

Table B.6
Statistics for the NMERCH pool. See Table B.1 for definitions of pools. See Table B.2 for definitions of statistics. See Appendix A for scientific names of leading species.

Leading species	*n*	GP_mean	CBM_mean	MD	GP_se	CBM_se	MD_se	MD_*p*	*r*	*r*_*p*
Balsam fir	29	4.5	6.9	−2.4	0.8	0.7	1.2	0.020	−0.21	0.131
Subalpine fir	37	3.1	10.8	−7.7	0.5	0.5	0.7	0.000	0.09	0.295
Red maple	8	4.4	5.2	−0.8	1.6	0.5	1.6	0.307	0.26	0.259
Sugar maple	16	2.1	5.2	−3.1	0.6	0.3	0.6	0.000	0.19	0.238
Paper birch	12	3.4	6.4	−3.0	1.0	1.8	2.2	0.100	−0.28	0.187
Engelmann spruce	18	2.9	11.3	−8.4	0.6	1.0	1.0	0.000	0.25	0.155
White spruce	56	3.0	8.9	−5.9	3.2	0.9	0.8	0.000	0.30	0.010
Black spruce	138	5.6	8.5	−3.0	0.6	0.5	0.7	0.000	0.21	0.007
Jack pine	44	3.8	5.0	−1.1	0.7	0.3	0.7	0.064	0.06	0.341
Lodgepole pine	54	7.5	13.3	−5.8	1.3	0.5	1.3	0.000	0.24	0.040
Eastern white pine	12	3.1	3.3	−0.2	0.7	0.4	0.6	0.401	0.37	0.109
Balsam poplar	10	1.4	10.3	−8.9	1.0	2.2	2.4	0.001	0.05	0.440
Trembling aspen	77	4.7	8.9	−4.2	0.6	0.8	0.7	0.000	0.54	0.000
Douglas-fir	19	5.8	29.0	−23.2	2.7	2.2	3.5	0.000	−0.06	0.399
Eastern white cedar	11	4.2	4.1	0.2	1.5	0.4	1.7	0.457	−0.44	0.081
Western hemlock	17	12.2	26.1	−13.9	3.2	1.8	3.0	0.000	0.40	0.049

Table B.7
Statistics for the BRANCHES pool. See Table B.1 for definitions of pools. See Table B.2 for definitions of statistics. See Appendix A for scientific names of leading species.

Leading species	*n*	GP_mean	CBM_mean	MD	GP_se	CBM_se	MD_se	MD_*p*	*r*	*r*_*p*
Balsam fir	29	5.6	5.7	−0.1	0.5	0.5	0.5	0.470	0.63	0.000
Subalpine fir	37	15.0	12.8	2.2	1.4	1.1	1.1	0.025	0.65	0.000
Red maple	8	10.3	4.7	5.5	1.4	1.3	1.2	0.000	0.60	0.045
Sugar maple	16	17.5	10.3	7.1	1.8	1.4	1.2	0.000	0.75	0.000
Paper birch	12	6.0	3.5	2.5	1.1	0.7	1.0	0.009	0.47	0.055
Engelmann spruce	18	12.4	8.3	4.1	1.6	0.8	1.3	0.001	0.63	0.001
White spruce	56	4.0	3.9	0.1	0.5	0.4	0.3	0.397	0.75	0.000
Black spruce	138	4.5	4.9	−0.4	0.2	0.2	0.2	0.033	0.54	0.000
Jack pine	44	3.2	2.9	0.3	0.3	0.2	0.2	0.050	0.79	0.000
Lodgepole pine	54	5.5	6.6	−1.2	0.4	0.5	0.5	0.008	0.47	0.000
Eastern white pine	12	8.8	7.6	1.1	0.9	1.1	1.1	0.148	0.45	0.063
Balsam poplar	10	6.8	5.0	1.8	2.0	0.5	2.1	0.201	−0.05	0.446
Trembling aspen	77	6.5	4.9	1.7	0.5	0.4	0.4	0.000	0.71	0.000
Douglas-fir	19	12.8	15.5	−2.7	1.8	1.5	1.5	0.038	0.60	0.002
Eastern white cedar	11	7.8	4.5	3.3	0.9	0.6	0.8	0.000	0.53	0.038
Western hemlock	17	26.7	22.4	4.3	2.1	0.7	1.8	0.010	0.59	0.004

Table B.8
Statistics for the FOLIAGE pool. See Table B.1 for definitions of pools. See Table B.2 for definitions of statistics. See Appendix A for scientific names of leading species.

Leading species	*n*	GP_mean	CBM_mean	MD	GP_se	CBM_se	MD_se	MD_*p*	*r*	*r*_*p*
Balsam fir	29	4.7	4.9	−0.2	0.6	0.7	0.5	0.316	0.64	0.000
Subalpine fir	37	8.5	7.5	1.0	0.7	0.5	0.6	0.053	0.48	0.001
Red maple	8	3.3	1.7	1.7	0.8	0.4	0.8	0.026	0.37	0.175
Sugar maple	16	5.0	2.1	2.9	1.0	0.2	1.1	0.006	−0.28	0.139
Paper birch	12	2.9	2.5	0.4	0.4	0.3	0.4	0.140	0.22	0.240
Engelmann spruce	18	7.1	5.8	1.3	0.8	0.4	0.7	0.026	0.54	0.007
White spruce	56	3.3	4.1	−0.8	0.3	0.2	0.4	0.016	0.14	0.151
Black spruce	138	5.7	5.6	0.2	0.3	0.3	0.3	0.281	0.55	0.000
Jack pine	44	3.0	2.4	0.7	0.3	0.1	0.3	0.018	0.39	0.003
Lodgepole pine	54	4.2	5.6	−1.3	0.3	0.4	0.4	0.000	0.38	0.002
Eastern white pine	12	5.0	3.3	1.7	0.4	0.3	0.4	0.000	0.38	0.104
Balsam poplar	10	1.6	1.6	0.0	0.5	0.1	0.5	0.479	−0.09	0.397
Trembling aspen	77	2.6	2.3	0.3	0.2	0.1	0.1	0.011	0.60	0.000
Douglas-fir	19	8.7	8.6	0.1	1.3	0.5	1.5	0.468	−0.15	0.269
Eastern white cedar	11	5.7	4.1	1.6	0.6	0.4	0.5	0.001	0.58	0.024
Western hemlock	17	13.7	11.9	1.7	1.2	0.3	1.3	0.094	−0.11	0.333

Table B.9
Statistics for the DEADWOOD pool. See Table B.1 for definitions of pools. See Table B.2 for definitions of statistics. See Appendix A for scientific names of leading species.

Leading Species	*n*	GP_mean	CBM_mean	MD	GP_se	CBM_se	MD_se	MD_*p*	*r*	*r*_*p*
Balsam fir	28	12.4	20.4	−8.0	1.8	2.1	2.8	0.003	−0.03	0.445
Subalpine fir	30	29.0	23.7	5.3	3.9	1.9	3.2	0.049	0.59	0.000
Red maple	8	17.8	18.2	−0.4	4.3	2.5	4.8	0.471	0.04	0.460
Sugar maple	16	10.7	24.1	−13.4	2.1	3.9	4.4	0.002	0.00	0.498
Paper birch	1	18.2	17.7	0.5	2.8	3.2	4.6	0.456	−0.15	0.331
Engelmann spruce	13	34.7	35.1	−0.4	9.2	7.0	13.5	0.488	−0.37	0.100
White spruce	50	12.9	19.5	−6.6	1.8	2.0	2.2	0.002	0.32	0.012
Black spruce	114	10.0	19.6	−9.6	1.0	0.9	1.2	0.000	0.21	0.011
Jack pine	39	6.8	21.5	−14.7	0.8	1.4	1.5	0.000	0.14	0.191
Lodgepole pine	45	20.8	37.8	−17.0	2.5	2.7	3.2	0.000	0.25	0.045
Eastern white pine	12	9.6	20.4	−10.7	1.8	2.2	3.2	0.001	−0.26	0.203
Balsam poplar	5	9.6	31.6	−22.0	3.2	6.2	7.6	0.012	−0.21	0.360
Trembling aspen	68	15.6	31.0	−15.4	1.6	1.7	2.5	0.000	−0.14	0.127
Douglas-fir	15	21.4	43.0	−21.6	3.4	3.7	5.0	0.000	0.01	0.482
Eastern white cedar	10	10.5	10.7	−0.2	2.0	2.5	1.7	0.453	0.74	0.003
Western hemlock	13	84.0	62.7	21.2	23.2	5.1	23.5	0.187	0.07	0.413

Table B.10
Statistics for the SN_MSTEM pool. See Table B.1 for definitions of pools. See Table B.2 for definitions of statistics. See Appendix A for scientific names of leading species.

Leading species	*n*	GP_mean	CBM_mean	MD	GP_se	CBM_se	MD_se	MD_*p*	*r*	*r*_*p*
Balsam fir	41	2.5	4.0	−1.5	0.5	0.6	0.8	0.039	−0.15	0.171
Subalpine fir	37	9.4	3.6	5.8	1.7	0.6	1.6	0.000	0.32	0.026
Red maple	10	1.4	3.4	−1.9	0.8	0.6	1.2	0.059	−0.49	0.065
Sugar maple	19	1.5	5.1	−3.6	0.5	0.8	1.0	0.001	−0.15	0.273
Paper birch	20	3.8	3.8	0.0	1.1	0.7	1.3	0.488	0.02	0.466
Engelmann spruce	18	7.4	5.8	1.6	3.0	1.9	3.9	0.344	−0.19	0.220
White spruce	58	2.5	2.9	−0.4	0.5	0.4	0.5	0.236	0.20	0.069
Black spruce	165	2.2	3.3	−1.2	0.3	0.3	0.3	0.000	0.08	0.145
Jack pine	46	1.6	4.2	−2.6	0.4	0.6	0.6	0.000	0.14	0.175
Lodgepole pine	54	4.2	6.4	−2.2	0.7	0.8	1.1	0.026	−0.04	0.376
Eastern white pine	12	2.5	5.3	−2.8	0.8	1.0	1.4	0.030	−0.32	0.147
Balsam poplar	10	2.7	6.0	−3.3	1.2	1.3	1.8	0.044	−0.08	0.414
Trembling aspen	84	4.4	5.6	−1.2	0.7	0.5	0.8	0.070	0.15	0.089
Douglas-fir	19	4.0	8.8	−4.8	1.3	2.5	2.8	0.047	0.05	0.414
Eastern white cedar	13	2.7	2.9	−0.2	0.9	0.7	1.0	0.418	0.32	0.134
Western hemlock	17	11.5	15.6	−4.2	4.5	2.1	4.8	0.194	0.09	0.362

Table B.11
Statistics for the SN_MTS pool. See Table B.1 for definitions of pools. See Table B.2 for definitions of statistics. See Appendix A for scientific names of leading species.

Leading species	*n*	GP_mean	CBM_mean	MD	GP_se	CBM_se	MD_se	MD_*p*	*r*	*r*_*p*
Balsam fir	41	0.4	0.1	0.3	0.1	0.0	0.1	0.000	0.12	0.227
Subalpine fir	37	0.9	0.1	0.8	0.1	0.0	0.1	0.000	0.59	0.000
Red maple	10	0.4	0.1	0.2	0.2	0.0	0.2	0.162	−0.31	0.182
Sugar maple	19	0.5	0.2	0.3	0.2	0.0	0.2	0.050	−0.29	0.112
Paper birch	20	0.8	0.1	0.7	0.3	0.0	0.3	0.006	−0.27	0.118
Engelmann spruce	18	0.6	0.2	0.4	0.1	0.0	0.1	0.002	−0.01	0.488
White spruce	58	0.4	0.1	0.3	0.1	0.0	0.1	0.000	0.20	0.060
Black spruce	165	0.4	0.1	0.3	0.0	0.0	0.0	0.000	0.31	0.000
Jack pine	46	0.3	0.1	0.2	0.1	0.0	0.1	0.004	0.48	0.000
Lodgepole pine	54	0.6	0.2	0.4	0.1	0.0	0.1	0.000	0.43	0.000
Eastern white pine	12	0.4	0.1	0.3	0.1	0.0	0.1	0.002	0.47	0.053
Balsam poplar	10	0.3	0.1	0.1	0.1	0.0	0.1	0.131	−0.22	0.269
Trembling aspen	84	0.7	0.2	0.5	0.1	0.0	0.1	0.000	0.38	0.000
Douglas-fir	19	0.5	0.2	0.3	0.1	0.0	0.1	0.003	0.52	0.008
Eastern white cedar	13	0.4	0.1	0.3	0.1	0.0	0.1	0.007	0.12	0.344
Western hemlock	17	0.9	0.5	0.4	0.3	0.1	0.3	0.090	0.23	0.181

Table B.12
Statistics for the SN_NMERCH pool. See Table B.1 for definitions of pools. See Table B.2 for definitions of statistics. See Appendix A for scientific names of leading species.

Leading species	*n*	GP_mean	CBM_mean	MD	GP_se	CBM_se	MD_se	MD_*p*	*r*	*r*_*p*
Balsam fir	29	0.4	0.5	−0.1	0.1	0.1	0.1	0.310	0.10	0.304
Subalpine fir	37	0.3	0.8	−0.5	0.1	0.0	0.1	0.000	0.21	0.109
Red maple	8	0.2	0.3	−0.1	0.1	0.0	0.1	0.040	0.22	0.295
Sugar maple	16	0.2	0.3	−0.1	0.1	0.0	0.1	0.129	0.09	0.362
Paper birch	12	0.1	0.4	−0.4	0.0	0.1	0.1	0.000	0.61	0.013
Engelmann spruce	18	0.4	0.8	−0.4	0.1	0.1	0.1	0.009	−0.27	0.137
White spruce	56	0.5	0.6	−0.1	0.1	0.1	0.1	0.140	0.11	0.204
Black spruce	138	0.8	0.6	0.2	0.1	0.0	0.1	0.099	0.49	0.000
Jack pine	44	0.7	0.4	0.3	0.2	0.0	0.2	0.051	0.09	0.281
Lodgepole pine	54	1.6	0.9	0.7	0.4	0.0	0.4	0.031	0.08	0.290
Eastern white pine	12	0.4	0.2	0.2	0.2	0.0	0.2	0.140	0.40	0.089
Balsam poplar	10	0.1	0.6	−0.6	0.0	0.1	0.1	0.000	0.45	0.085
Trembling aspen	77	0.8	0.7	0.1	0.2	0.1	0.2	0.212	0.23	0.021
Douglas-fir	19	0.5	2.0	−1.4	0.2	0.2	0.3	0.000	−0.34	0.076
Eastern white cedar	11	0.3	0.3	0.0	0.1	0.0	0.1	0.472	−0.51	0.045
Western hemlock	17	2.1	1.7	0.4	0.9	0.1	1.0	0.358	−0.29	0.124

Table B.13
Statistics for the SN_BRANCHES pool. See Table B.1 for definitions of pools. See Table B.2 for definitions of statistics. See Appendix A for scientific names of leading species.

Leading species	*n*	GP_mean	CBM_mean	MD	GP_se	CBM_se	MD_se	MD_*p*	*r*	*r*_*p*
Balsam fir	29	1.5	0.4	1.1	0.4	0.1	0.4	0.006	0.06	0.372
Subalpine fir	37	4.3	0.9	3.4	0.8	0.1	0.8	0.000	0.33	0.020
Red maple	8	0.5	0.3	0.2	0.3	0.1	0.3	0.280	−0.40	0.149
Sugar maple	16	1.0	0.7	0.3	0.3	0.1	0.3	0.163	−0.26	0.159
Paper birch	12	1.6	0.3	1.3	0.5	0.1	0.5	0.012	−0.19	0.269
Engelmann spruce	18	1.8	0.6	1.2	0.7	0.1	0.7	0.048	−0.05	0.423
White spruce	56	0.6	0.3	0.3	0.1	0.0	0.1	0.001	0.47	0.000
Black spruce	138	0.7	0.4	0.3	0.1	0.0	0.1	0.000	0.29	0.000
Jack pine	44	0.6	0.2	0.4	0.2	0.0	0.2	0.012	0.39	0.004
Lodgepole pine	54	0.5	0.4	0.1	0.1	0.0	0.1	0.165	0.12	0.188
Eastern white pine	12	0.6	0.5	0.1	0.2	0.1	0.2	0.360	0.13	0.342
Balsam poplar	10	0.9	0.3	0.6	0.4	0.0	0.4	0.058	0.15	0.335
Trembling aspen	77	1.1	0.4	0.8	0.2	0.0	0.2	0.000	0.21	0.034
Douglas-fir	19	0.9	1.0	−0.1	0.3	0.1	0.3	0.322	0.15	0.261
Eastern white cedar	11	1.0	0.3	0.7	0.2	0.0	0.2	0.002	0.53	0.038
Western hemlock	17	3.1	1.4	1.7	1.2	0.0	1.2	0.084	0.11	0.342

Table B.14
Statistics for the AGFAST pool. See Table B.1 for definitions of pools. See Table B.2 for definitions of statistics. See Appendix A for scientific names of leading species.

Leading species	*n*	GP_mean	CBM_mean	MD	GP_se	CBM_se	MD_se	MD_*p*	*r*	*r*_*p*
Balsam fir	28	2.6	5.3	−2.7	0.4	0.5	0.7	0.000	−0.15	0.227
Subalpine fir	30	3.0	11.8	−8.8	0.4	0.7	0.7	0.000	0.27	0.073
Red maple	8	4.8	5.9	−1.1	1.1	1.2	1.0	0.152	0.61	0.041
Sugar maple	16	2.2	6.9	−4.7	0.3	0.9	0.9	0.000	0.19	0.237
Paper birch	11	4.0	5.3	−1.2	1.5	1.0	1.8	0.250	0.01	0.494
Engelmann spruce	13	3.5	10.1	−6.5	0.5	1.1	1.0	0.000	0.39	0.090
White spruce	50	2.7	7.1	−4.4	0.4	0.7	0.8	0.000	−0.05	0.362
Black spruce	114	2.3	6.8	−4.5	0.2	0.3	0.4	0.000	0.19	0.020
Jack pine	39	1.9	4.9	−2.9	0.3	0.4	0.5	0.000	−0.05	0.383
Lodgepole pine	45	3.2	9.4	−6.2	0.3	0.4	0.4	0.000	0.31	0.018
Eastern white pine	12	2.8	4.1	−1.3	0.5	0.5	0.6	0.021	0.34	0.136
Balsam poplar	5	3.0	5.5	−2.5	0.8	0.8	1.0	0.022	0.21	0.361
Trembling aspen	68	3.7	7.3	−3.7	0.4	0.5	0.5	0.000	0.14	0.119
Douglas-fir	15	5.5	18.7	−13.1	0.6	1.0	1.4	0.000	−0.59	0.007
Eastern white cedar	10	2.3	3.3	−1.0	0.3	0.6	0.4	0.011	0.76	0.002
Western hemlock	13	10.3	18.9	−8.6	3.2	0.7	3.8	0.017	−0.73	0.001

Table B.15
Statistics for the MEDIUM pool. See Table B.1 for definitions of pools. See Table B.2 for definitions of statistics. See Appendix A for scientific names of leading species.

Leading species	*n*	GP_mean	CBM_mean	MD	GP_se	CBM_se	MD_se	MD_*p*	*r*	*r*_*p*
Balsam fir	29	4.4	9.8	−5.4	0.8	1.3	1.6	0.001	−0.12	0.262
Subalpine fir	37	9.3	8.1	1.2	1.5	1.4	2.0	0.266	0.12	0.246
Red maple	8	10.4	8.6	1.7	3.2	1.3	3.2	0.297	0.16	0.350
Sugar maple	16	4.8	11.0	−6.1	1.3	2.1	2.4	0.009	0.07	0.402
Paper birch	12	6.1	7.9	−1.8	1.0	1.9	1.8	0.156	0.37	0.112
Engelmann spruce	18	19.8	14.0	5.7	4.4	4.0	6.8	0.202	−0.33	0.089
White spruce	56	6.3	8.9	−2.6	1.3	1.2	1.5	0.036	0.33	0.005
Black spruce	138	3.5	8.0	−4.5	0.5	0.5	0.7	0.000	0.09	0.156
Jack pine	44	1.7	12.3	−10.5	0.3	1.0	1.0	0.000	0.09	0.271
Lodgepole pine	54	10.9	18.6	−7.7	1.8	1.8	2.2	0.000	0.28	0.020
Eastern white pine	12	2.9	10.1	−7.1	0.9	1.5	1.9	0.001	−0.24	0.222
Balsam poplar	10	3.1	20.4	−17.3	0.7	3.0	3.4	0.000	−0.50	0.059
Trembling aspen	77	5.4	17.4	−12.0	0.8	1.1	1.4	0.000	−0.14	0.119
Douglas-fir	19	9.9	20.5	−10.7	1.9	5.8	6.0	0.042	0.06	0.404
Eastern white cedar	11	2.8	3.8	−1.0	0.8	1.0	0.7	0.092	0.70	0.004
Western hemlock	17	45.3	29.1	16.1	16.0	5.1	17.0	0.175	−0.05	0.426

Table B.16
Statistics for the SOIL pool. See Table B.1 for definitions of pools. See Table B.2 for definitions of statistics. See Appendix A for scientific names of leading species.

Leading species	*n*	GP_mean	CBM_mean	MD	GP_se	CBM_se	MD_se	MD_*p*	*r*	*r*_*p*
Balsam fir	20	93.8	109.9	−16.1	11.7	5.7	14.6	0.138	−0.31	0.085
Subalpine fir	27	150.4	95.3	55.1	17.9	7.4	17.9	0.002	0.20	0.154
Red maple	5	105.8	149.4	−43.6	20.9	8.9	24.1	0.057	−0.17	0.386
Sugar maple	8	145.4	187.8	−42.4	28.3	11.7	28.2	0.079	0.22	0.300
Paper birch	7	125.7	124.9	0.9	19.1	14.7	15.7	0.479	0.60	0.063
Engelmann spruce	10	169.9	90.9	78.9	32.5	9.3	34.5	0.018	−0.07	0.421
White spruce	16	191.6	102.7	88.8	27.1	10.6	32.6	0.005	−0.37	0.075
Black spruce	69	162.1	99.5	62.6	10.9	3.9	11.9	0.000	−0.08	0.244
Jack pine	14	57.0	88.9	−31.9	5.4	6.4	6.9	0.000	0.33	0.119
Lodgepole pine	40	111.2	108.0	3.2	14.4	4.4	14.6	0.412	0.12	0.237
Eastern white pine	3	178.2	113.5	64.6	65.7	6.1	64.0	0.193	0.32	0.378
Balsam poplar	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Trembling aspen	25	101.0	160.0	−59.0	10.7	8.5	13.6	0.000	0.01	0.480
Douglas-fir	13	91.3	167.2	−75.9	14.6	5.8	13.3	0.000	0.42	0.068
Eastern white cedar	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Western hemlock	9	210.6	261.5	−50.9	47.6	20.7	38.1	0.101	0.63	0.024

NA: not available.

Table B.17
Statistics for the ORGSOIL pool. See Table B.1 for definitions of pools. See Table B.2 for definitions of statistics. See Appendix A for scientific names of leading species.

Leading species	*n*	GP_mean	CBM_mean	MD	GP_se	CBM_se	MD_se	MD_*p*	*r*	*r*_*p*
Balsam fir	29	62.1	32.8	29.2	11.8	1.4	11.7	0.008	0.18	0.173
Subalpine fir	29	24.6	36.0	−11.3	2.7	2.7	3.6	0.001	0.08	0.342
Red maple	7	34.2	41.0	−6.8	9.2	5.1	9.4	0.242	0.23	0.301
Sugar maple	15	24.0	47.9	−23.9	6.3	4.6	4.5	0.000	0.70	0.001
Paper birch	11	43.7	43.4	0.3	4.2	4.3	3.8	0.469	0.60	0.019
Engelmann spruce	13	46.4	32.5	13.8	9.5	2.9	8.3	0.054	0.55	0.019
White spruce	51	68.5	27.9	40.6	7.9	1.7	8.3	0.000	−0.12	0.206
Black spruce	125	63.4	31.6	31.8	4.3	1.1	4.5	0.000	−0.11	0.103
Jack pine	38	27.0	24.9	2.1	3.5	1.6	3.7	0.288	0.08	0.312
Lodgepole pine	44	30.4	32.2	−1.9	3.1	1.6	3.2	0.283	0.17	0.138
Eastern white pine	10	29.8	25.8	3.9	8.4	2.6	8.6	0.326	0.08	0.416
Balsam poplar	7	48.9	39.5	9.4	15.6	4.7	18.3	0.309	−0.47	0.127
Trembling aspen	70	30.8	49.1	−18.2	2.1	2.3	2.9	0.000	0.12	0.152
Douglas-fir	13	22.7	50.6	−28.0	5.3	2.2	4.7	0.000	0.46	0.049
Eastern white cedar	7	49.2	23.6	25.6	18.9	4.3	17.9	0.090	0.35	0.214
Western hemlock	12	66.2	80.4	−14.2	16.0	3.8	14.6	0.170	0.49	0.045

Table B.18
Statistics for the MINSOIL pool. See Table B.1 for definitions of pools. See Table B.2 for definitions of statistics. See Appendix A for scientific names of leading species.

Leading species	*n*	GP_mean	CBM_mean	MD	GP_se	CBM_se	MD_se	MD_*p*	*r*	*r*_*p*
Balsam fir	20	56.9	77.8	−20.9	8.9	4.1	11.4	0.037	−0.45	0.021
Subalpine fir	28	123.1	57.5	65.6	17.1	5.0	16.7	0.000	0.22	0.125
Red maple	5	65.3	101.7	−36.4	19.9	6.4	18.5	0.045	0.37	0.257
Sugar maple	8	112.1	127.1	−15.0	28.9	7.3	29.8	0.311	−0.01	0.492
Paper birch	7	81.8	80.6	1.2	14.8	9.2	15.2	0.469	0.27	0.272
Engelmann spruce	10	131.6	61.6	70.0	36.3	8.3	37.9	0.041	−0.08	0.413
White spruce	16	148.5	70.7	77.8	28.2	7.7	32.2	0.011	−0.42	0.047
Black spruce	70	105.2	65.9	39.4	10.4	2.5	10.8	0.000	−0.05	0.341
Jack pine	15	36.8	62.2	−25.4	3.9	4.0	6.3	0.000	−0.30	0.133
Lodgepole pine	41	80.6	76.2	4.4	12.8	3.0	12.9	0.367	0.07	0.327
Eastern white pine	3	141.4	81.8	59.5	60.8	3.9	61.4	0.202	−0.13	0.450
Balsam poplar	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Trembling aspen	27	71.9	103.2	−31.3	10.5	5.1	11.5	0.005	0.02	0.459
Douglas-fir	15	64.8	115.1	−50.2	11.7	4.2	10.9	0.000	0.37	0.083
Eastern white cedar	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Western hemlock	10	139.7	191.9	−52.2	29.0	17.2	25.8	0.029	0.47	0.074

NA: not available.

Table B.19
Statistics for the ECOTOTAL pool. See Table B.1 for definitions of pools. See Table B.2 for definitions of statistics. See Appendix A for scientific names of leading species.

Leading species	*n*	GP_mean	CBM_mean	MD	GP_se	CBM_se	MD_se	MD_*p*	*r*	*r*_*p*
Balsam fir	19	138.5	169.4	−30.9	12.2	11.2	16.3	0.033	0.03	0.445
Subalpine fir	27	253.2	187.8	65.4	21.7	14.5	18.7	0.000	0.53	0.002
Red maple	5	170.1	210.2	−40.2	19.4	13.3	25.3	0.078	−0.16	0.391
Sugar maple	8	253.1	291.7	−38.6	24.8	26.8	24.7	0.071	0.54	0.069
Paper birch	7	181.0	169.2	11.8	20.4	26.6	19.6	0.280	0.68	0.031
Engelmann spruce	10	260.6	181.1	79.5	34.0	18.6	39.9	0.031	−0.07	0.421
White spruce	16	254.6	170.1	84.5	24.7	17.4	33.6	0.009	−0.26	0.164
Black spruce	53	206.1	157.5	48.6	12.1	8.0	14.4	0.001	0.01	0.475
Jack pine	46	78.2	83.3	−5.1	9.0	11.3	5.5	0.000	0.74	0.000
Lodgepole pine	54	147.0	206.7	−59.7	15.9	20.8	6.8	0.268	0.51	0.000
Eastern white pine	3	264.6	203.6	61.0	72.0	48.9	59.2	0.189	NA	0.172
Balsam poplar	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Trembling aspen	24	181.8	251.3	−69.6	11.7	15.1	16.4	0.000	0.27	0.100
Douglas-fir	13	203.0	318.7	−115.6	28.6	18.8	17.4	0.000	0.81	0.000
Eastern white cedar	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Western hemlock	9	503.4	489.1	14.3	84.1	34.8	62.6	0.411	0.74	0.005

NA: not available.

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