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Decreasing uncertainty in CBM-CFS3 estimates of forest soil carbon sources and sinks through use of long-term data from the Canadian Intersite Decomposition Experiment

C.E. Smyth, J.A. Trofymow, W.A. Kurz,
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Canada

The Pacific Forestry Centre, Victoria, British Columbia

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More information on CIDET is available at: http://cfs.nrcan.gc.ca/subsite/cidet

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Abstract

Dead organic matter submodel parameters of the Carbon Budget Model of the Canadian Forest Sector 3 (CBM-CFS3) were verified using litterbag decomposition data from the Canadian Intersite Decomposition Experiment (CIDET). This national experiment provided 12 years of decomposition time series data from 18 sites across Canada for calibration of decay parameters for foliar litter (very fast decay pool) and aboveground fine woody debris (fast decay pool).

Time series of measured carbon remaining were compared to model predictions to improve the model's decomposition algorithm, which includes base decay rates, temperature response coefficients, and the proportion of carbon transferred from quickly decaying dead organic matter pools to the slow humified pool. A statistical approach was developed to optimize several model parameters simultaneously by minimizing residual errors.

For foliar litter, which is contained in the aboveground very fast pool in the CBM-CFS3, the asymptotic form of the decay function used in the model was consistent with the measured time series for both needle and leaf litter. Optimized decay parameters had a smaller base decay rate (0.36 yr^{-1} at a 10° C reference temperature), a larger temperature quotient (Q_{10} = 2.7), and a slightly larger proportion transferred to the slow pool (0.185) compared to the default model decay parameters. The absolute error between predicted and measured carbon remaining was reduced from 14.1% to 7.6% when the optimized parameters were used in place of the default parameters.

Potential model modifications were tested to assess if additional climate variables would further improve model predictions. Adding summer precipitation as a decay modifier and simulating first-year leaching with winter precipitation resulted in modest improvements.

For wood blocks, which are contained in the aboveground fast pool in the CBM-CFS3, the data were not well represented by the model's asymptotic form of decay. Instead, colder sites had a linear decay rate and the remaining sites had a variable decay rate that would be better described by a sigmoidal function. Four potential modifications to the decay algorithm were tested to estimate improvements in model predictions of fast pool decay. These included a temperature-dependent time delay, a sigmoidal function for decay, and the addition of a holding pool that had either a delayed transfer or a decayed transfer. These modifications reduced the errors by about 1.9%, 3.4%, 2.2%, and 2.6%, respectively. Their implementation in the model would, however, require the introduction and simulation of additional pools. This effort would be justifiable only if more long-term decay data were available to improve model parameterization. Such data are expected in the future from ongoing long-term decomposition experiments.

Résumé

Les paramètres du sous-modèle visant les matières organiques mortes du Modèle du bilan du carbone du secteur forestier canadien 3 (MBC-SFC3) ont été vérifiés en utilisant les données sur la décomposition du contenu d'un sac de litière provenant de l'Expérience canadienne sur la décomposition interstationnelle (CIDET). Cette expérience menée à l'échelle nationale fournit des données chronologiques s'étendant sur 12 ans sur la décomposition de litière provenant de 18 sites au Canada aux fins de calibrage des paramètres de décomposition des litières feuillues (réservoir à décomposition très rapide) et des débris ligneux fins au-dessus du sol (réservoir à décomposition rapide).

Les séries chronologiques des restes de carbone mesurés ont été comparées aux prédictions du modèle afin d'en améliorer l'algorithme de décomposition, lequel comprend les taux de décomposition de base, les coefficients de réaction à la température ainsi que la proportion de carbone qui est transféré des réservoirs de matières organiques mortes en décomposition rapide au réservoir à humectage lent. Une méthode statistique a été mise au point pour optimiser simultanément plusieurs paramètres du modèle en réduisant au minimum les erreurs résiduelles.

Dans le cas de la litière feuillue, laquelle se trouve dans un réservoir à décomposition rapide au-dessus du sol dans le MBC-SFC3, la forme asymptotique de la fonction de décomposition qui a été utilisée dans le modèle correspondait aux séries chronologiques mesurées à l'endroit de la litière d'aiguille et de la litière feuillue. Les paramètres optimisés de décomposition affichaient un taux de décomposition plus faible (0,36 an^{-1} à une température de référence de 10° C), un quotient de température supérieur (Q_{10}= 2,7) et une proportion légèrement plus élevée de transfert au réservoir à décomposition lente (0,185), comparativement aux paramètres de décomposition par défaut du modèle. L'erreur absolue entre le taux de carbone prévu et le taux de carbone résiduel mesuré est passée de 14,1 % à 7,6 % lorsque les paramètres optimisés ont été utilisés au lieu des paramètres par défaut.

Les modifications que l'on pourrait apporter au modèle ont été mises à l'essai afin de déterminer si des variables supplémentaires concernant le climat permettraient d'améliorer davantage les prédictions du modèle. L'ajout des précipitations estivales, comme facteur de modification de la décomposition, et la stimulation de la lixiviation la première année avec les précipitations hivernales ont permis de modestes améliorations.

Dans le cas des blocs de bois, lesquels se trouvent dans des réservoirs à décomposition rapide au-dessus du sol dans le MBC-SFC3, les données n'étaient pas bien représentées par la forme asymptotique de décomposition du modèle. En fait, les sites où les températures sont plus fraîches avaient un taux de décomposition linéaire, tandis que les autres sites avaient un taux de décomposition variable qui se prêterait davantage à une description selon la fonction sigmoïdale. Au total, on a mis à l'essai quatre modifications que l'on pourrait apporter à l'algorithme de décomposition pour estimer les améliorations aux prédictions du modèle de décomposition des réservoirs à décomposition rapide, notamment un temporisateur axé sur la température, une fonction sigmoïdale pour la décomposition ainsi que l'ajout d'un réservoir de retenue dont le transfert était retardé ou pourri. Ces modifications ont réduit les erreurs d'environ 1,9 %, 3,4 %, 2,2 % et 2,6 % respectivement. Toutefois, leur application au modèle exigerait l'introduction et la simulation de réservoirs supplémentaires. Cet effort pourrait être justifié uniquement si l'on disposait de données à long terme sur la décomposition qui permettraient d'améliorer l'établissement de paramètres pour le modèle. Les expériences de longue durée sur la décomposition sont censées fournir de telles données.

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Symbols and abbreviations

A	constant
AUR	Acid Unhydrolyzable Residue (mg/g)
B	constant
C_r	carbon remaining (%)
$\hat{C}_r$	predicted carbon remaining (%)
C_c	carbon concentration (%)
E_{12}	error at t = 12 years (%)
E_a	absolute error (%)
$\bar{E}_a$	time-averaged absolute error (%)
g	litter type
i	pool identifier: 1=very fast; 2=fast; 3=medium; 4=slow
k	decay rate (yr $^{-1}$)
k_{bi}	base decay rate of pool i (yr $^{-1}$)
k_i	decay rate of pool i (yr $^{-1}$)
k_e	exponential decay rate (yr $^{-1}$)
l	location
L_m	litter modifier
M	mass of the sample (g)
M_f	fractional mass remaining
n	number of included observations
N	nitrogen concentration (mg/g)
P	average precipitation (mm)
P_s	summer precipitation during July and August (mm)
P_w	winter precipitation from October through to the end of March (mm)
Q_i	Q_{10} value, temperature quotient of pool i
r	precipitation modifier parameter
R	sigmoidal fit parameter
R_b	base sigmoidal fit parameter
S	sigmoidal fit parameter
S_m	precipitation modifier
t	time (yrs)
t_{90}	time to reach 90% mass loss
T	average air temperature ($^\circ$C)
T_{mi}	temperature modifier for pool i
τ_{ci}	proportion transferred annually from pool i to slow pool
τ_{ri}	carbon transferred from pool i to slow pool (%)
v	litter modifier parameter
X_i	carbon remaining in pool i (%)
X_{si}	slow pool carbon transferred from pool i (%)

1. Introduction

The operational-scale Carbon Budget Model of the Canadian Forest Sector 3 (CBM-CFS3) is an inventory-based carbon model that consists of a linked set of submodels for live biomass, dead organic matter, forest management, land-use change, and disturbance (Kurz et al. 2009; Kurz and Apps 1999; Kull et al. 2006). The model is an integral part of Canada's National Forest Monitoring, Accounting and Reporting System (Kurz and Apps 2006) and, in accordance with the Intergovernmental Panel on Climate Change (IPPC) Good Practice Guidance (IPCC 2003), should be verified with the best available data for the country.

This study focusses on the verification of components of the dead organic matter submodel of the CBM-CFS3. The submodel controls the dynamics of all dead organic matter pools, the release of decayed material to the atmosphere, and the transfer of carbon to the humified organic material (the model's slow carbon pool).

Limited data on long-term litter decomposition rates were available when the CBM-CFS was formulated in the early 1990s. A national litterbag experiment, the Canadian Intersite Decomposition Experiment (CIDET) was initiated to provide this information (Trofymow and CIDET Working Group 1998). With a final collection in 2004, CIDET provides an unusually long (12-year) decomposition time series for model calibration. CIDET measured decomposition at 18 upland forested and three wetland sites across Canada, using foliar litters of eight forest tree and two understorey plant species, and blocks of wood from one tree species. All litterbags were placed on the forest floor surface; a second wood-block litterbag was also buried at each site. The resulting time series of measured carbon remaining was used to determine the optimal decomposition rates for use in the model and also to determine the correct proportion of carbon transferred to the slow pool.

The key science questions in this study relate to litter decomposition and how it is affected by climate. Specifically, how well does the model represent litter decomposition? And, does it provide accurate predictions of carbon remaining and decomposition rates across Canada? The approach was to:

1. Compare measured carbon remaining time series to dead organic matter submodel predictions obtained from plot-level simulations at each of the experimental sites;
2. Determine optimal decay parameters that are applicable nationally, and;
3. Identify and test model modifications that could improve predictions.

The analysis is specifically directed at improving CBM-CFS3 carbon predictions, as opposed to creating a general modelling framework. CBM-CFS3 is used to produce estimates of Canada's forest dead organic matter and soil carbon; tuning its decay parameters will improve national estimates. Additionally, error assessment will provide guidance on possible model modifications and future research directions.

Section 2 briefly describes the CIDET experimental design and the CBM-CFS3 dead organic matter submodel theory.

Section 3 includes results for foliar litter measurements and model predictions for the very fast pool. Optimal parameters were identified for several scenarios, including subsets of litters (coniferous and deciduous), and adjusted slow pool decay parameters. Multiple scenarios were tested because CBM-CFS3 was designed to accommodate multiple applications; individual users may wish to adjust decomposition parameters to match their particular applications. Optimal parameters were also obtained for the submodel modified to include additional climate variables. The addition of a climate modifier will allow for decomposition to be affected by anticipated changes in precipitation patterns due to climate change.

Section 4 repeats the above analysis and presents the results for wood-block measurements and model predictions for the fast pool. Optimal parameters for the fast pool were identified for several scenarios, including adjusted slow pool decay parameters and altered decay algorithms. Several scenarios relating to alternative decay functions and a time delay in decay were tested to assess whether model uncertainty could be appreciably reduced by changing the submodel's structure.

Section 5 summarizes results and includes summary tables of optimal decay parameters for all scenarios.

2. Background and Theory

2.1 Experiment description

The Canadian Intersite Decomposition Experiment (CIDET) is a national litterbag experiment that measured long-term litter decomposition (see Trofymow and CIDET Working Group 1998; Trofymow et al. 2002; http://cfs.nrcan.gc.ca/subsite/cidet). Litterbags contained 10 standard foliar litter materials—from eight forest tree species (trembling aspen: *Populus tremuloides,* American beech: *Fagus grandifolia*, Douglas-fir: *Pseudotsuga menziesii*, white birch: *Betula papyrifera*, jack pine: *Pinus banksiana*, black spruce: *Picea mariana*, tamarack: *Larix laricina*, western redcedar: *Thuja plicata*) and two understorey plant species (bracken fern: *Pteridium aquilinum*, plains rough fescue: *Festuca hallii*)—and one block of western hemlock wood (*Tsuga heterophylla*). The approximately 11 000 litterbags were all laid out in 1992 at 18 upland sites and three wetland sites across Canada, with four replicate plots per site. Data from this experiment represent 10 collections and 12 years of decomposition, an unusually long time series for a litter decomposition experiment.

Foliar material for the litterbags was collected from senescent plants or newly senescent leaves or needles that had fallen onto mesh traps. Approximately 10 g of dried foliar litter material were enclosed in each mesh litterbag made of 20-cm x 20-cm polypropylene shade cloth with 0.25-mm x 0.5-mm openings. Each wood block (5 cm x 5 cm x 10 cm; approximately 50 g) was cut from the heartwood of a western hemlock log, dried, and placed in a litterbag. Litterbags of each of the 10 foliar litters and two wood blocks were strung on nylon line, with 10 strings of litterbags placed in each of four replicate plots at each of 21 sites. Foliar litters and one wood block were placed on the forest floor surface; the second wood block was buried at about 20 cm depth.

One string of litterbags was collected annually during the first eight years, and biennially for the ninth and tenth collections. After each collection, samples were dried at 70° C, and masses were recorded. Samples were then ground, and carbon concentration was determined on a LECO CR-12 carbon system (Leco Corporation, St. Joseph, MI). For each litterbag, carbon remaining at time t was estimated for all litters as:

$$C_r(t) = 100 \; \frac{C_c(t)M(t)}{C_c(0)M(0)} \tag{1}$$

where C_c is the carbon concentration, and M is the mass of the sample.

Carbon concentration estimates of the wood blocks at $t = 0$, one year, and five years were unusually low. Carbon concentrations are being re-analyzed, but at the time this report was written, new concentration measurements were not yet available. Consequently, mass remaining data were used in all wood-block analyses.

For comparison with model predictions, a subset of the data was selected: eight litters (aspen, beech, Douglas-fir, birch, jack pine, black spruce, tamarack, and western redcedar), and the surface and buried wood blocks from 16 forested sites. Data from the three non-forested sites were not used, nor were data from two forested sites, Petawawa (PET) and Prince Albert (PAL), included in the analysis, as fires had destroyed some of those samples before the experiment was complete. Two other non-tree litters (bracken and fescue) were excluded from this study.

The total number of litterbags considered for analysis was 6400: 10 collections × (8 litters + 2 wood blocks) × 16 sites × 4 replicate plots per site. Of these, 67 litterbags could not be recovered or had inaccurate mass or concentration measurements and were therefore excluded.

Climate variables included average annual air temperature (T), summer precipitation in July and August (P_s), and winter precipitation from October through to March (P_w). Table 1 lists the 16 sites and their climate variables averaged from January 1992 to December 2004. Climate data were obtained from nearby Atmospheric Environment Service weather stations or were derived as ANUCLIM-interpolated climate data (McKenney et al. 2001), as described in Appendix A.

Table 1. CIDET sites and climate variables: average air temperature, summer precipitation (P_s), and winter precipitation (P_w). Climate data were averaged from January 1992 to December 2004.

Site Code	Site	Latitude (N)	Longitude (W)	T (° C)	P_s (mm)	P_w (mm)
INU	Inuvik, NT	68° 19′	133° 32′	–7.64	73	96
SCH	Schefferville, QC	54° 52′	66° 39′	–4.16	233	326
GI1	Gillam, MB	56° 19′	94° 51′	–3.77	139	176
NH1	Nelson House, MB	55° 55′	98° 37′	–2.88	141	137
WHI	Whitehorse, YT	60° 51′	135° 12′	0.01	66	95
MON	Montmorency, QC	47° 19′	71° 08′	0.92	291	774
TOP	Topley, BC	54° 36′	126° 18′	1.50	93	288
CHA	Chapleau, ON	47° 38′	83° 14′	1.85	158	361
KAN	Kananaskis, AB	51° 00′	115° 00′	3.62	126	162
TER	Termundee, SK	51° 50′	104° 55′	3.68	135	80
GAN	Gander, NL	48° 55′	54° 34′	4.18	194	677
CBR	CB Rocky Harbour, NL	49° 32′	57° 50′	4.49	205	683
HID	Hidden Lake, BC	50° 33′	118° 50′	6.55	94	405
MAR	Morgan Arboretum, QC	45° 25′	73° 57′	6.70	165	475
PMC	Port McNeill, BC	50° 36′	127° 20′	8.72	138	1373
SHL	Shawnigan Lake, BC	48° 38′	123° 42′	9.33	56	1028

2.2 CBM-CFS3 model theory

The four dead organic matter carbon pools in CBM-CFS of interest in this study are:

1. very fast (foliar litter and dead fine roots);
2. fast (dead woody litter, including branches, tops and stumps, trees of non-merchantable size, and dead coarse roots ≥ 5 mm);
3. medium (dead stemwood and stembark of trees of merchantable size) and;
4. slow (humified organic matter and soil organic carbon) (Kurz et al. 2009; Kurz and Apps 1999).

The current version of the model (CBM-CFS3) has aboveground (above the mineral soil) and belowground versions of the very fast, fast, and slow pools to separate inputs from roots and aboveground litter. The very fast, fast, and medium pools receive carbon input from litterfall, mortality, and disturbances. All dead organic matter entering these pools is decomposed at a given decay rate. Some of the decayed carbon is transferred to the slow pool, which represents humified organic matter, and the remainder of the carbon is released to the atmosphere. The model also includes softwood and hardwood versions of stem-snag and branch-snag dead organic matter pools, but these are not described here.

Decomposition in the first three pools is simulated using a power series:

(2) $$X_i(t,T) = 100(1 - k_i(T))^t$$

where X_i is the carbon in pool i (1= very fast; 2= fast; 3= medium), and t is time.

The decay rate (k_i) is a function of mean annual temperature and is estimated from a base decay rate at 10° C, (k_{bi}), and a temperature modifier for each pool (T_{mi}):

(3) $$k_i(T) = k_{bi}T_{mi}$$

The temperature modifier is given by:

(4) $$T_{mi} = exp\left(\frac{T - 10}{10} \; ln(Q_i)\right)$$

where T is the average annual air temperature at each site, and Q_i is the Q_{10} temperature quotient. A typical value for Q_{10} is 2, which indicates a doubling of the decay rate for every 10° C temperature increase.

According to Trofymow et al. (1995) and Trofymow and CIDET Working Group (1998), decomposition of fine litter has distinct phases or stages related to decay of separate chemical fractions of the litter. Initial rapid leaching and decay of low-molecular-weight, soluble carbon compounds are followed by a second phase of decomposition of polymeric structural carbon compounds in cell walls (cellulose and hemicellulose) and leaching of decay products, which lasts a few years. This is followed by a final meta-stable phase that lasts several decades, during which lignin and other resistant compounds in the original plant material, as well as secondary microbial products, are decomposed (Bunnell et al. 1977; Chapin et al. 2002). The model does not explicitly simulate the phases of decay; it simulates the dynamics by transferring a portion of decayed carbon from each of the very fast, fast, and medium pools to the slow pool. At each annual time step, carbon transferred to the slow pool is estimated as:

(5) $$\tau_{ri}(t) = \tau_{ci}X_i(t-1)k_i(T)$$

where the proportion transferred to the slow pool (τ_{ci}) has a default value of 0.17. The rest of the carbon (0.83) is released to the atmosphere.

For comparison with CIDET foliar litter, contributions to the slow pool from the three other pools were tracked separately. At each time step, the slow pool carbon from pool i (X_{si}) was estimated as:

(6) $$X_{si}(t) = [X_{si}(t-1) + \tau_{ri}(t)](1 - k_4)$$

where the total slow pool carbon was the sum of inputs from the three pools: $X_4 = X_{s1} + X_{s2} + X_{s3}$. For comparison with CIDET data for foliar litters, predicted carbon remaining was estimated as:

(7) $$\hat{C}_r(t) = X_1 + X_{s1}$$

The contribution to the slow pool is required, because it represents the material in the litterbag that has decomposed and reached a meta-stable state. For comparison with wood blocks, predicted carbon remaining was estimated as:

$$\hat{C}_r(t) = X_2 + X_{s2}$$

Model runs were based on a 50-year-old black spruce stand with a generalized growing curve. Initially, all of the other parameters were set to default values, including disturbance history, temperature quotients Q_{10s} (Q_1= 2, Q_2= 2, Q_4= 0.9), base decay rates (k_{b1}= 0.5 yr $^{-1}$, k_{b2} = 0.1435 yr $^{-1}$, k_{b4} = 0.0032 yr $^{-1}$), and proportions transferred to the slow pool (τ_{c1}= 0.170, τ_{c2}= 0.170). Although it is biologically not reasonable to expect a Q_{10}<1 for the slow pool dynamics, a statistical fit of observed versus predicted values of mineral soil carbon pools generated a Q_{10} of 0.9. Further work was conducted to replace the 0.9 value. (See Section 3.5 and the Known Issues document in the Help Section of the CBM-CFS3 v.1 release.) Because the belowground pools do not have foliar litter input, only the aboveground dead organic matter pools were included in the analysis.

In order to simulate the litter-decay conditions of the experiment, the CBM-CFS3 had to be run in an unusual way. The model run was prescribed to have a clearcut; then a non-growing forest was specified. The non-growing forest prevented annual litterfall from occurring, but allowed for the decay of dead organic matter. To be consistent with litterbag data, all contributions from roots were transferred to belowground pools, and the transfer rate from aboveground slow pool to the belowground slow pool was set to 0.

For this study, some CBM-CFS3 code (Equations 2 to 8) was translated into a SAS program (SAS Institute Inc., v 8.3 1999). Estimates of carbon remaining from the SAS program were compared to predictions from CBM-CFS3 for verification (not shown). Once the output of the SAS program was verified, carbon remaining time series were predicted for all CIDET sites, using average air temperatures for each site. The purpose of writing the SAS program was to determine the decay parameters (k_{b1}, k_{b2}, Q_1, Q_2) that gave the best match between predicted and measured carbon remaining. Additionally, the SAS program could be altered easily to test model modifications, such as including additional climate variables and alternative decay functions. Model identification numbers were assigned to each version of the SAS code to identify the parameters that were used in each run. For example, the model run with default parameters is identified as Model ID=1.0, whereas the model run with an adjusted slow pool base decay rate is identified as Model ID=1.3.

As an example of the SAS model predictions, carbon remaining time series for the very fast pool and the fast pool were estimated using default model parameters at a mean annual air temperature of 10° C. Time series of carbon remaining in the very fast pool and the contribution of carbon to the slow pool were well described by an asymptotic fit (Figure 1). After a few years, the carbon from the very fast pool was mostly decayed, and the slow pool carbon accounted for most of the total. The decay rate of the slow pool is small, and therefore little change occurred over 12 years.

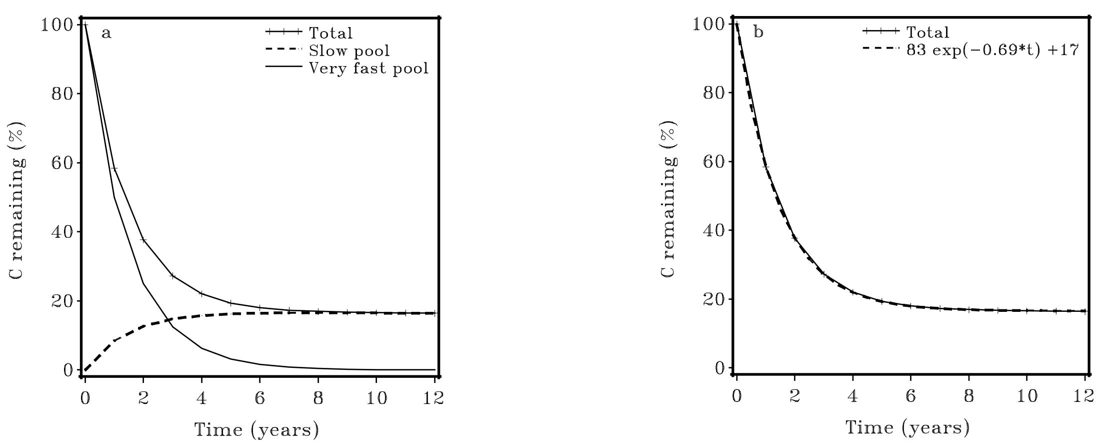

Figure 1. (a) Time series of total carbon remaining, as estimated from the sum of the very fast and slow pool contributions; (b) total carbon remaining and an asymptotic fit

The fast pool has a smaller base decay rate; a simple exponential fit to the predictions was adequate (Figure 2). The fit was only slightly improved by an asymptotic fit.

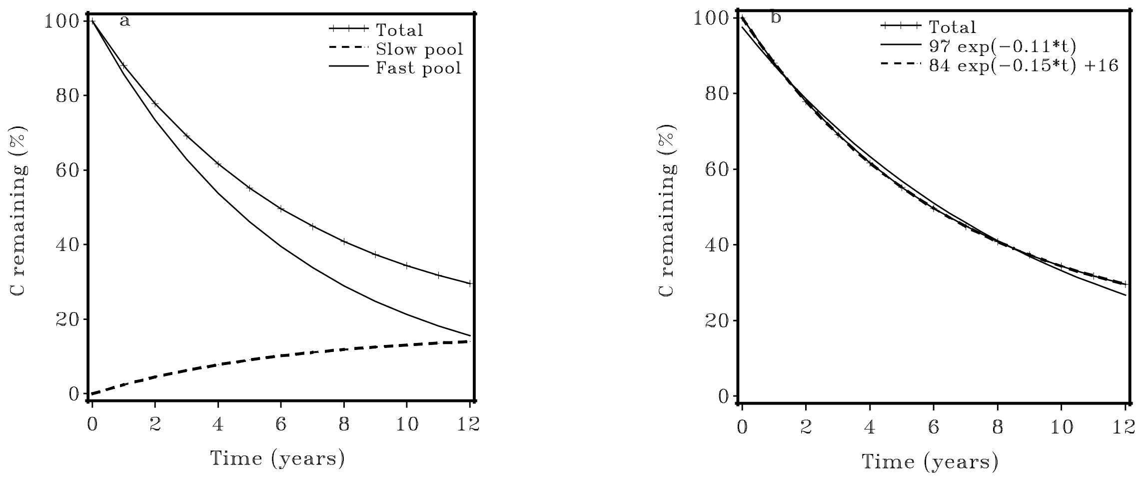

Figure 2. (a) Time series of total carbon remaining (X_1+X_s), as estimated from the sum of the fast and slow pool contributions; (b) total carbon remaining and an exponential fit and an asymptotic fit

3. Comparison to foliar litterbag data

3.1 Model default values

Initial comparisons between measured carbon remaining and model predictions assumed default decay parameters (Model ID=1.0). Time series were predicted for 16 CIDET sites using the 12-year-average annual air temperature. Predicted carbon remaining was compared to measured carbon remaining averaged over eight foliar litters at each CIDET site. As expected, decomposition was a strong function of temperature, and results are presented as a function of average site temperature instead of site name.

Predicted carbon remaining after one year was consistent with measurements except at warmer sites, where predictions underestimated carbon remaining (Figure 3a). After six and 12 years, predictions and measurements at warmer sites agreed better, but predictions markedly underestimated carbon remaining at colder sites. The underestimates at colder sites suggests that the temperature quotient was too low. Increasing the temperature quotient will decrease the decay rates at lower temperatures and thus increase the amount of carbon remaining after 12 years.

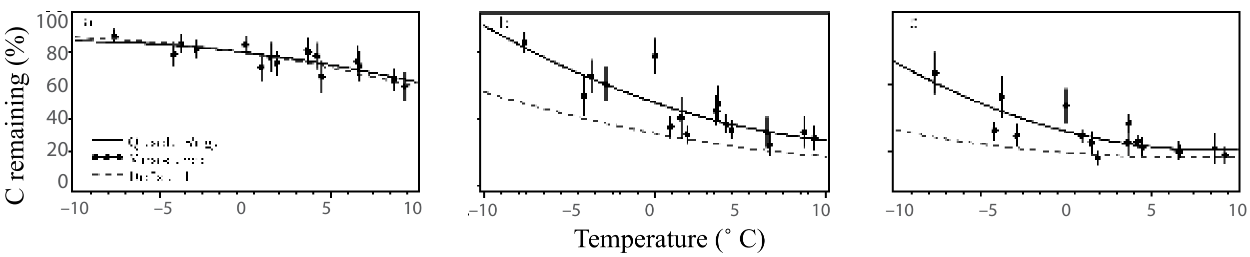

Figure 3. Measured and predicted carbon remaining after (a) one year, (b) six years, and (c) 12 years, as a function of temperature. Error bars indicate the standard deviation of measurements of eight foliar litter types; solid lines indicate quadratic regressions to the data. Predictions were based on default decay parameters (Default, Model ID = 1.0).

3.2 Optimal decay parameters

Optimal base decay rates and temperature quotients for the very fast pool were determined by minimizing the error between measured and predicted carbon remaining time series. Predictions were estimated for a wide range of decay parameters, and the parameters that gave the smallest errors were selected. The proportion transferred to the slow pool (τ_{c1}) was varied between 0.170 and 0.190 and, for each τ_{c1}, k_{b1} was varied by 0.01 yr^{-1} from 0.2 yr^{-1} to 0.5 yr^{-1} and Q_1 was varied by 0.05 from 2 to 4.

The proportion transferred to the slow pool was chosen to be similar to the measured asymptote of the litters. The average asymptote was estimated from an asymptotic fit to the foliar carbon remaining time series using:

(9) $$C_r = Ae^{-kt} + B$$

where k is the decay rate, B is the asymptote, and $A+B$ is the intercept (Trofymow et al., in preparation). The average asymptote (± standard error) for litters that had reached a meta-stable phase was 0.185 ± 0.073 ($n = 73$).

The absolute error between predicted and measured carbon remaining (E_a) was estimated for each of the decay parameters at each time step, and then averaged over the 16 sites. The absolute error was chosen instead of the squared error in order to reduce the impact of the error in the first few time steps. The model does not account for leaching of cell solubles in the first few years; these errors can dominate the overall error. See Section 3.10 for a possible mechanism to reduce this initial error. The absolute error was estimated as:

(10) $$E_a(t) = \frac{1}{16} \sum_{l=1}^{16} | \hat{C}_r(t,l) - C_r(t,l) |$$

where C_r is the measured carbon remaining averaged over the eight foliar litters, $\hat{C}_r$ is the predicted carbon, l represents the site, and t includes all collection years (t=1 to 8, 10, and 12 years).

The absolute error averaged over time was then defined as:

(11) $$\bar{E}_a = \frac{1}{10}\sum_{t=1}^{10} E_a(t)$$

The absolute difference between predicted and measured carbon remaining after 12 years of decomposition was also estimated:

(12) $$E_{12} = \frac{1}{16}\sum_{l=1}^{16} | \hat{C}_r(12,l) - C_r(12,l) |$$

The 12-year mark was chosen because some litters had reached the meta-stable decay phase at the end of the experiment. Minimizing the absolute error after 12 years constrains τ_c, as the carbon remaining at this stage is dominated by the carbon that has been transferred to the slow pool.

The average error was estimated for the 10-point time series as:

(13) $$E_t = \frac{1}{16}\sum_{l=1}^{16} \hat{C}_r(t,l) - C_r(t,l)$$

and is shown for reference. The average error was not used to constrain decay parameters, as it was found to have a trend with temperature. A very small average error could result from overestimates at colder sites and underestimates at warmer sites. The absolute error was used instead.

Determining optimal decay rates (k_{b1}, Q_1 and τ_{c1}) is difficult, as the problem is overdetermined: three parameters can co-vary to give the same error, but have very different parameter values. This problem was mitigated in two ways: τ_{c1} was specified over a small range; and the error was minimized in two different ways. The first error was estimated as the absolute error over the entire time series: minimizing this error gave good agreement in the first few years of decay when carbon remaining values were high. The second error was estimated as the absolute error at 12 years: minimizing this error provided good agreement between measurements and predictions at the end of the experiment. Optimal parameters were obtained by finding decay parameters that produced low errors for both error estimates, and then these values were averaged to obtain a robust estimate of the base decay rate and temperature quotient.

The lowest 9th percentiles of $\bar{E}_a$ and E_{12} were estimated from the 1500 predicted time series. The 9th percentile was chosen because it gave a workable number of parameter combinations that overlapped in parameter space (Figure 4). Temperature quotients and base decay rates corresponding to the lowest 9th percentile of $\bar{E}_a$ were similar for all four values of τ_{c1}. In contrast, decay parameters corresponding to the lowest 9th percentile of E_{12} were separated by τ_{c1} and covered a wider range of decay parameter space. E_{12} constrained errors only after 12 years, which resulted in more possible combinations of temperature quotients and base decay rates that could give the same predicted amount of carbon remaining.

There was no overlap of k_{b1} and Q_1 for the lowest 9th percentiles of $\bar{E}_a$ and E_{12} for τ_{c1}= 0.170. There were five cases of overlap for τ_{c1}= 0.180, nine cases for τ_{c1} = 0.185, and 14 cases for τ_{c1}= 0.190. For each τ_{c1}, the base decay rate averaged from 0.38 yr^{-1} to 0.40 yr^{-1}, and the temperature quotient averaged from 2.83 to 2.95 (Table 2, Model ID= 1.1). The use of optimal decay parameters approximately halved the absolute error averaged over the time series.

Table 2. Very fast pool default and optimal decay parameters, and absolute errors between predictions and measurements using default slowpool decay parameters (k_{b4}= 0.0032 yr $^{-1}$ and Q_4= 0.9)

Model ID	Description	k_{b1} (yr $^{-1}$)	Q_1	τ_{c1}	$\bar{E}_a$ (%)
1.0	Default decay parameters	0.500	2	0.170	14.1
1.1	Optimal decay parameters	0.376	2.83	0.180	7.5
		0.390	2.90	0.185	7.5
		0.403	2.95	0.190	7.4

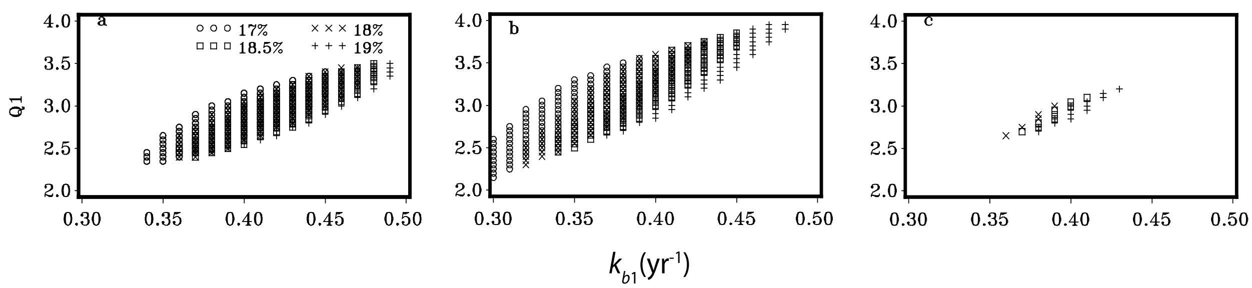

Figure 4. Temperature quotients (Q_1) and base decay rates (k_{b1}) corresponding to the lowest 9th percentile of absolute errors (a) $\bar{E}_a$, (b) E_{12}, and (c) their intersection for Model ID 1.1. Symbols identify values for the proportion transferred to the slow pool (τ_{c1}).

Predictions of carbon remaining that use optimal decay parameters (from Table 2) resulted in lower absolute and average errors compared to those estimated from default decay parameters (Figure 5). Varying τ_{c1} had little effect on the errors, as the base decay rate and temperature quotient compensated for the variation in τ_{c1}.

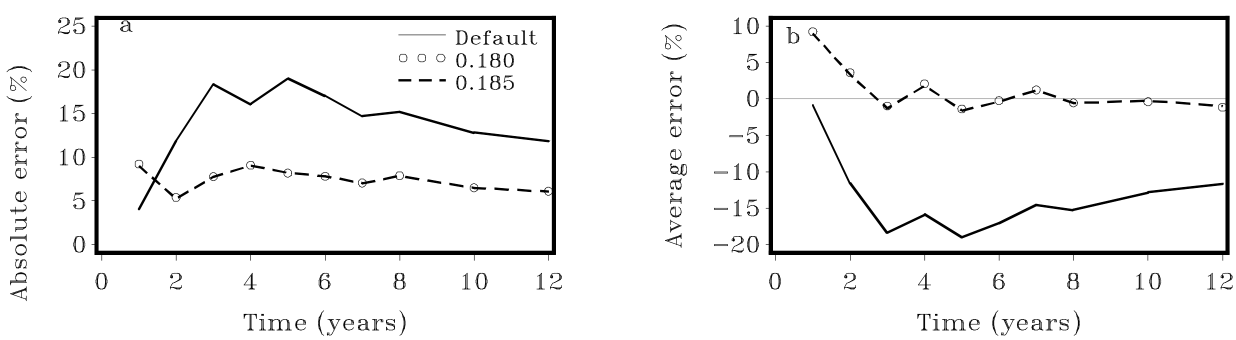

Figure 5. Time series of (a) absolute error (E_a) and (b) average error (E) for τ_{c1}= 0.180 or 0.185 for optimal (Model ID = 1.1) and default values of the temperature quotient and base decay rate (Default, Model ID = 1.0).

Predictions of carbon remaining after one year using optimal decay parameters were slightly larger than predictions using default decay parameters. After six and 12 years, however, predictions estimated from optimal decay parameters were in much closer agreement with measured carbon remaining (Figure 6). The data had a wide range of mean annual temperatures (–7.7° C to 9.3° C), and thus the optimization included most of the mean annual temperatures encountered in Canada's forests.

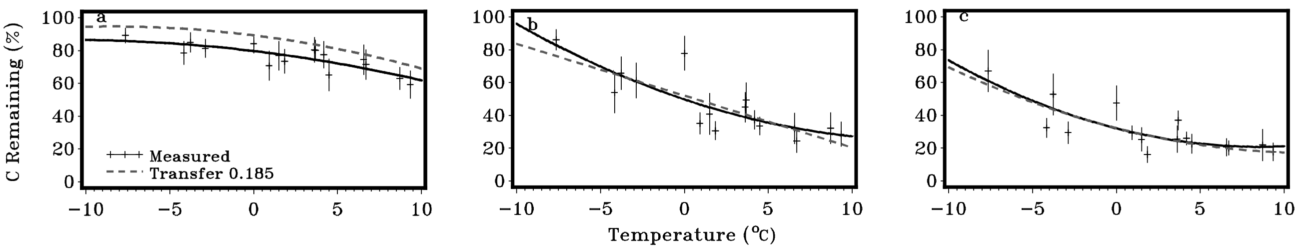

Figure 6. Foliar carbon remaining after (a) one year, (b) six years, and (c) 12 years versus mean annual temperature at each CIDET site. Optimal decay parameters (Model ID = 1.1) were used to predict carbon remaining for T_{c1} = 0.185. Symbols indicate measurements, with error bars representing one standard deviation. Solid and dashed lines indicate quadratic regressions.

Predictions of carbon remaining estimated from optimal decay parameters were generally closer to measurements at each site (Figure 7). There were only two sites for which predictions estimated from default parameters were closer to the actual measurements: Chapleau (CHA) and Montmorency (MON); in both cases, predictions of carbon remaining estimated from optimal decay parameters were too high.

Predictions for Prince Albert (PAL) and Petawawa (PET) were closer to actual measurements when optimal decay parameters were used (Figure 7). These sites were not included in the analysis because their time series were incomplete. However, these data offer independent verification that the optimal decay parameters improved the predictive capability of the model.

Time series plots (Figure 7) and average errors (Figure 5) show that carbon remaining was generally overpredicted in the first year. There may be an additional process that occurs in the first year that was not explained by power series decay; this possibility is discussed in Section 3.10.

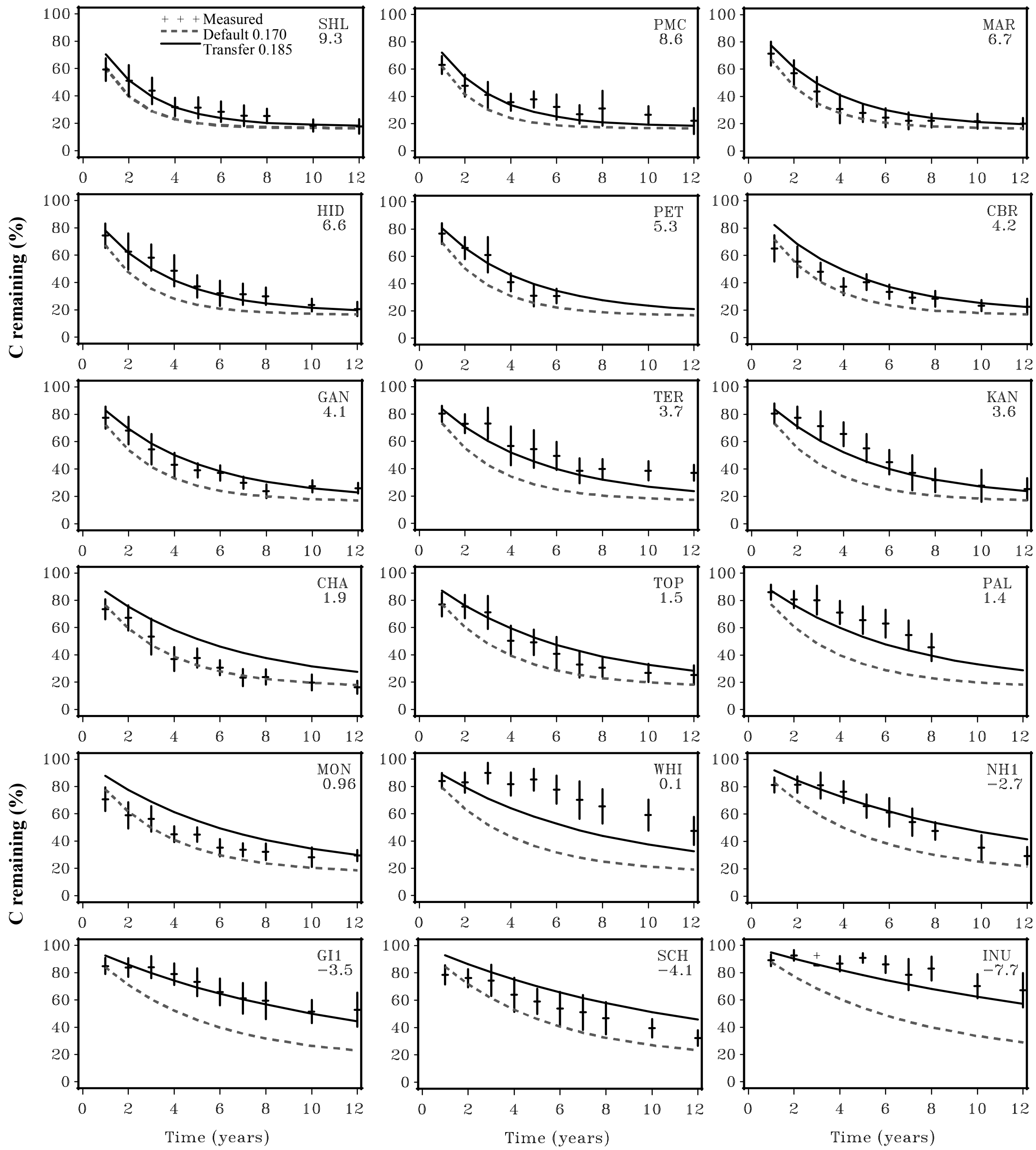

Figure 7. Predicted and measured foliar carbon remaining time series for each CIDET site. The three-letter site identifier (see Table 1 for site names) and the average annual air temperature in degrees Celsius are indicated in each upper-right corner. Measurements are averaged over eight foliar litters at each site, and predictions were estimated from optimal decay parameters (τ_{c1} = 0.185, Model ID = 1.1).

3.3 Estimated slow pool decay rate

Carbon transferred from the very fast pool to the slow pool decays according to the slow pool decay rate. The slow pool base decay rate was included in the optimization process to determine if the 12-year time series could estimate the very small base decay rate of semi-stable material. It was assumed that the temperature quotient of the slow pool was the same as that of the very fast pool.

Best fit was determined by minimizing the absolute error between predicted and measured carbon remaining, and the slow pool decay rate was varied by 0.001 yr^{-1} from 0.001 yr^{-1} to 0.021 yr^{-1}.

Optimal base decay parameters (k_{b1}, Q_1, and k_{b4}) for each proportion transferred to the slow pool were estimated using the lowest 4th percentiles of $\bar{E}_a$ and E_{12}. Errors overlapped in many cases, as some cases had the same k_{b1} and Q_1, but several values of k_{b4}. Average values of k_{b1} and Q_1 were estimated as usual, and k_{b4} was selected as the average of values within one standard deviation of averaged k_{b1} and Q_1. There were seven cases of overlap for k_{b1} and Q_1 for the lowest 4th percentiles and τ_{c1}= 0.170. There were 42 cases of overlap for τ_{c1}= 0.180, 60 cases for τ_{c1}= 0.185, and 77 cases for τ_{c1}= 0.190. For each τ_{c1}, the base decay rate averaged from 0.36 yr^{-1} to 0.42 yr^{-1}, the temperature quotient averaged from 2.74 to 3.04, and the slow pool base decay rate averaged from 0.0021 yr^{-1} to 0.0035 yr^{-1} (Table 3).

Table 3. Optimal very fast pool decay parameters and associated error for a model modified to estimate the slow pool decay rate. The slow pool temperature quotient (Q_4) was set to equal Q_1.

Model ID	Scenario	k_{b1} (yr^{-1})	Q_1	τ_{c1}	k_{b4} (yr^{-1})	$\bar{E}_a$ (%)
1.2	Estimate slow pool decay rate	0.359	2.74	0.170	0.0021	7.6
		0.388	2.90	0.180	0.0031	7.5
		0.402	2.96	0.185	0.0035	7.4
		0.419	3.04	0.190	0.0036	7.4

The estimated base decay rate for the slow pool was similar to the default base decay rate. However, the slow pool base decay rate is so small that decay over 12 years is difficult to determine from the data. Without the lower bound of 0.002 yr^{-1} on the slow pool base decay rate, the optimal decay parameters would be closer to zero.

3.4 Adjusted slow pool parameters

Default parameters for the slow pool comprised a base decay rate (k_{b4}) of 0.0032 yr^{-1} and a temperature quotient (Q_4) of 0.9. However, new values of the slow pool parameters (k_{b4}= 0.015 yr^{-1} and Q_4= 2.65) were used for the 2007 National Inventory Report (Environment Canada 2007), based on a model-calibration procedure using soil carbon estimates at ~600 plots (Shaw et al. 2005; Ecological Land Classification Group 2005). The adjusted slow pool base decay rate was more than four times higher than the default value.

Optimal values of k_{b1} and Q_1 were estimated for each value of τ_{c1} using the lowest 12th percentiles of $\bar{E}_a$ and E_{12}. There was no overlap of k_{b1} and Q_1 for the lowest 12th percentiles for τ_{c1}= 0.170. There was one case of overlap for τ_{c1}= 0.180, three cases for τ_{c1}= 0.185, and seven cases for τ_{c1}= 0.190. For each τ_{c1}, the base decay rate averaged from 0.35 yr^{-1} to 0.37 yr^{-1}, and the temperature quotient averaged from 2.65 to 2.78 (Table 4, Model ID= 1.3). These optimal decay parameters were smaller than, but similar to, those found with default slow pool parameters (Table 2, Model ID= 1.1). Average errors were similar in both cases.

Table 4. Optimal very fast pool decay parameters and associated error using adjusted slow pool parameters (k_{b4}= 0.015 yr $^{-1}$ and Q_4= 2.65)

Model ID	Scenario	k_{b1} (yr $^{-1}$)	Q_1	τ_{c1}	$\bar{E}_a$ (%)
1.3	Adjusted slow pool parameters	0.350	2.65	0.180	7.7
		0.360	2.70	0.185	7.6
		0.373	2.78	0.190	7.6

3.5 Coniferous litters only

The process of finding optimal decay parameters was performed on a subset of the data that contained only coniferous litters. This scenario was included because CBM-CFS3 was designed with flexibility to adjust decomposition parameters to accommodate particular applications—in this case, a pure softwood forest.

The five coniferous litters included western redcedar, Douglas-fir, black spruce, jack pine, and tamarack. The average asymptote for coniferous litters estimated from asymptotic fits of the measurements was 0.177 ± 0.074 (n=48). This asymptote was slightly smaller than (but not significantly different from) the average of all tree foliar asymptotes.

Optimal values of k_{b1} and Q_1 were estimated for each value of τ_{c1} using the adjusted slow pool parameters (k_{b4}= 0.015 yr $^{-1}$, Q_4= 2.65). There was no overlap of k_{b1} and Q_1 for the lowest 6th percentiles for τ_{c1}= 0.170. There were two cases of overlap for τ_{c1}= 0.180, seven cases for τ_{c1}= 0.185, and 12 cases for τ_{c1}= 0.190. For each τ_{c1}, the base decay rate averaged from 0.38 yr $^{-1}$ to 0.41yr $^{-1}$, and the temperature quotient averaged from 2.95 to 3.13 (Table 5). Optimal decay parameters estimated for coniferous litters only (Model ID= 1.4) had higher base decay rates and temperature quotients than decay parameters estimated for all eight tree foliar litters (Model ID= 1.3). The net result was that the decay rates for coniferous litters were higher at warm sites and lower at cold sites compared to decay rates for all eight tree foliar litters.

Table 5. Optimal very fast pool decay parameters and associated error, based on five coniferous litters and using adjusted slow pool decay parameters (k_{b4}= 0.015 yr $^{-1}$ and Q_4= 2.65)

Model ID	Scenario	k_{b1} (yr $^{-1}$)	Q_1	τ_{c1}	$\bar{E}_a$ (%)
1.4	Coniferous litters	0.375	2.95	0.180	7.7
		0.387	2.99	0.185	7.6
		0.408	3.13	0.190	7.6

3.6 Deciduous litters only

The process of finding optimal decay parameters was repeated for deciduous litters only, for application of the CBM-CFS3 in a pure hardwood forest. These three litters included white birch, aspen, and beech. The average asymptote for deciduous litters estimated from asymptotic fits of the measurements was 0.199 ± 0.074 (n=25). This asymptote was slightly larger than the average of all tree foliar asymptotes.

Optimal values of k_{b1} and Q_1 were estimated for each value of τ_{c1} using the adjusted slow pool parameters (k_{b4}= 0.015 yr $^{-1}$, Q_4= 2.65). There were five cases of overlap of k_{b1} and Q_1 for the lowest 11th percentiles for τ_{c1}= 0.170. There were four cases of overlap for τ_{c1}= 0.180 and τ_{c1}= 0.185, and two cases for τ_{c1}= 0.190. For each τ_{c1}, the base decay rate averaged from 0.32yr $^{-1}$ to 0.35 yr $^{-1}$, and the temperature quotient averaged from 2.28 to 2.40 (Table 6). Optimal decay parameters estimated for deciduous litters only (Model ID= 1.5) had lower temperature quotients than those for all eight tree foliar litters (Model ID=1.3). The net result was that the decay rates for deciduous litters were lower at warm sites and higher at cold sites compared to decay rates for all eight tree foliar litter types.

Table 6. Very fast pool optimal decay parameters and associated error, based on three deciduous litters and using adjusted slow pool decay parameters (k_{b4}= 0.015 yr $^{-1}$ and Q_4= 2.65)

Model ID	Scenario	k_{b1} (yr $^{-1}$)	Q_1	τ_{c1}	$\bar{E}_a$ (%)
1.5	Deciduous litters	0.316	2.28	0.170	8.1
		0.333	2.36	0.180	8.0
		0.345	2.44	0.185	8.0
		0.345	2.40	0.190	7.9

3.7 Error regression analysis

Residual errors were regressed against climate variables to determine if additional climate variables should be included in the decay function to improve predictions. Model predictions were estimated using optimal decay parameters from Model ID= 1.3 (Table 4; k_{b1}= 0.36 yr $^{-1}$, Q_1= 2.7, τ_{c1}= 0.185, k_{b4}= 0.015 yr $^{-1}$, Q_4= 2.65), and absolute and average errors were regressed (SAS proc reg) against air temperature, degree days, decomposition factor, winter precipitation (October to March), and summer precipitation (July and August).

Average error was correlated with summer precipitation (r^2= 0.49), but none of the variables tested were correlated with absolute error (r^2<0.2). Regression analysis found that decomposition rates were underpredicted at sites with higher summer precipitation and overpredicted at sites with low summer precipitation. The linear relationship between average error and summer precipitation (P_s) was:

(14) $$\bar{E} = 0.0893P_s - 11.52$$

which was zero for a summer precipitation of 129 mm.

This finding with the 12-year carbon remaining time series data was consistent with the results of Trofymow et al. (2002), who found summer precipitation to be an important variable in a multiple regression of decay rates using the CIDET six-year mass remaining time series data.

3.8 Modify model: summer precipitation

The SAS version of the model was modified to include summer precipitation that affected the decay rate (Model ID=1.6). The very fast pool decay rate was estimated as the base decay rate (k_{b1}) multiplied by a temperature modifier (T_{m1}) and a summer-precipitation modifier (S_m):

(15) $$k_1 = k_{b1}T_{m1}S_m$$

The summer-precipitation modifier was chosen as:

(16) $$S_m = 1 + (P_s - 130)/r$$

where P_s is the total precipitation in July and August (in millimetres) averaged over 12 years, and r is an adjustment parameter. The value of r was obtained by minimizing errors between predicted and measured carbon remaining. Absolute errors were estimated as usual for the grid of decay parameters, including the parameter for summer precipitation (r), which varied in increments of five (5) from 235 to 335.

Optimal values of k_{b1}, Q_1, and r were estimated for each value of τ_{c1} using adjusted slow pool parameters (k_{b4}= 0.015 yr $^{-1}$, Q_4= 2.65) and the lowest 3rd percentiles of $\bar{E}_a$ and E_{12}. Many cases had overlapping errors, because some cases had the same k_{b1}, Q_1, and proportion transferred to the slow pool, but several values of r. Optimal values of k_{b1} and Q_1 were estimated as usual, and an optimal value of r was estimated by averaging r values within one standard deviation of k_{b1} and Q_1. There were nine cases of overlap of k_{b1} and Q_1 for the lowest 3rd percentiles for τ_{c1}= 0.170. There were 28 cases of overlap for τ_{c1}= 0.180, 47 cases for τ_{c1}= 0.185, and 96 cases for τ_{c1}= 0.190. For each τ_{c1}, the base decay rate averaged from 0.35 yr $^{-1}$ to 0.39 yr $^{-1}$, the temperature quotient averaged from 2.92 to 3.03, and the adjustment parameter from 258 to 262 (Table 7, Model ID= 1.6).

Table 7. Optimal very fast pool decay parameters and associated error using: a decay rate that included summer precipitation, and adjusted slow pool decay parameters (k_{b4}= 0.015 yr $^{-1}$ and Q_4= 2.65)

Model ID	Scenario	k_{b1} (yr $^{-1}$)	Q_1	τ_{c1}	r	$\bar{E}_a$ (%)
1.6	Summer precipitation	0.354	2.92	0.170	260	6.0
		0.371	2.96	0.180	259	5.9
		0.381	3.00	0.185	258	5.8
		0.391	3.03	0.190	262	5.7

Absolute errors estimated from the modified model were ~1.5% smaller than those estimated without summer precipitation (Figure 8). Average errors were unaffected by the summer-precipitation modifier, even though E was correlated with summer precipitation. This was due to the fact that optimal decay parameters were determined by absolute errors and not by average errors.

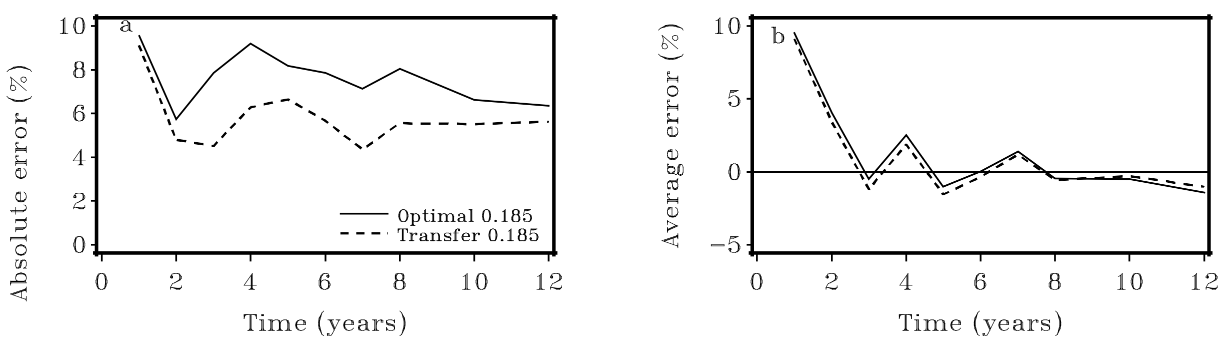

Figure 8. Time series of (a) absolute error (E_a) and (b) average error (E) for predictions that include summer precipitation (Model ID = 1.6) with τ_{c1}= 0.185 (Transfer 0.185). Errors from model predictions without precipitation (Optimal 0.185; Model ID = 1.3) are shown for comparison.

3.9 Modify model: winter precipitation

Average errors between measurements and predictions were larger than expected for the first year, even when the model was modified to include summer precipitation. This suggests that carbon loss in the first year is larger than is predicted by an exponential decay model. Trofymow et al. (2002) noted that intercepts from exponential model fits were lower for sites with high winter precipitation (total precipitation between October and March), likely because of its direct role in leaching carbon or soluble phenolic compounds from the litters.

Asymptotic and exponential fits of the measured 12-year carbon remaining time series found that the intercepts were typically lower than the 100% assumed by the model. Using multiple linear regression, the intercept was found to be a function of average winter precipitation (P_w). Winter precipitation was defined as the total precipitation in millimetres between October and March. The intercept $C(0)$ decreased with increasing winter precipitation as: $C(0)= 98.74–0.01704\ P_w$ (n=16), with a squared correlation coefficient of 0.71 (Figure 9). Restricting the regression to have an intercept of 100 gave: $C(0)= 100–0.01875\ P_w$. A similar result was produced using winter precipitation from only the first year data (October 1992 through March 1993): $C(0)= 100–0.0220P_{w1}$.

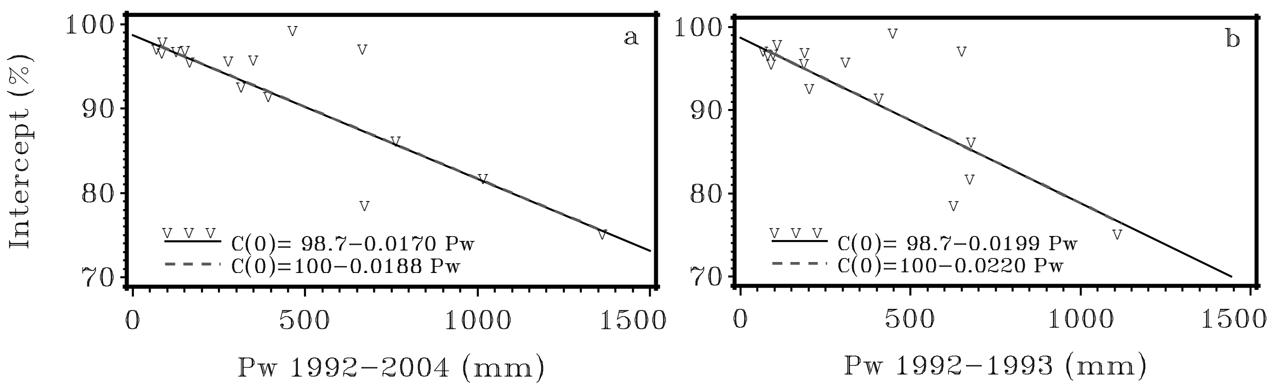

Figure 9. Intercepts from fits of measured carbon remaining versus (October to March) winter precipitation (P_w). Winter precipitation was (a) averaged over 12 years and (b) from the first year (1992 winter).

In an attempt to reduce the error in the first year, the model was modified to include winter precipitation (Model ID=1.7). Model equations were modified to reduce the initial value of the very fast pool. The very fast pool at time 0 was reduced from 100%, according to:

(17) $$X_1(0) = 100 - 0.0188P_w$$

where P_w is the average winter precipitation. The transfer to the slow pool was estimated as before:

(18) $$\tau_{r1}(1) = \tau_{c1}X_1(0)k_1$$

where the default proportion transferred to the slow pool (τ_{c1}) was 0.170. However, an additional term was added to the slow pool in the first time step to account for the enhanced decay or loss due to leaching in the first year:

(19) $$X_{s1}(1) = [\tau_{r1}(1) + \tau_{c1}(100 - X_1(0))](1 - k_4))$$

Optimal values of k_{b1} and Q_1 were estimated for each value of τ_{c1} using the adjusted slow pool parameters (k_{b4}= 0.015 yr $^{-1}$, Q_4= 2.65). There was no overlap of k_{b1} and Q_1 for the lowest 3rd percentiles for τ_{c1}= 0.170. There were two cases of overlap for τ_{c1}= 0.180, five cases for τ_{c1}= 0.185, and eight cases for τ_{c1}= 0.190. For each τ_{c1}, the base decay rate averaged from 0.32 yr $^{-1}$ to 0.33 yr $^{-1}$, and the temperature quotient averaged from 2.55 to 2.63 (Table 8).

Including winter precipitation in the model reduced the error in the first two years (Figure 10). This improvement decreased the absolute error ($\bar{E}_a$) by 1%.

Table 8. Very fast pool optimal decay parameters and associated error using: a decay rate that included winter precipitation, and adjusted slow pool decay parameters (k_{b4}= 0.015 yr $^{-1}$ and Q_4= 2.65)

Model ID	Scenario	k_{b1} (yr $^{-1}$)	Q_1	τ_{c1}	$\bar{E}_a$ (%)
1.7	Winter precipitation	0.315	2.55	0.180	6.7
		0.318	2.51	0.185	6.6
		0.334	2.63	0.190	6.6

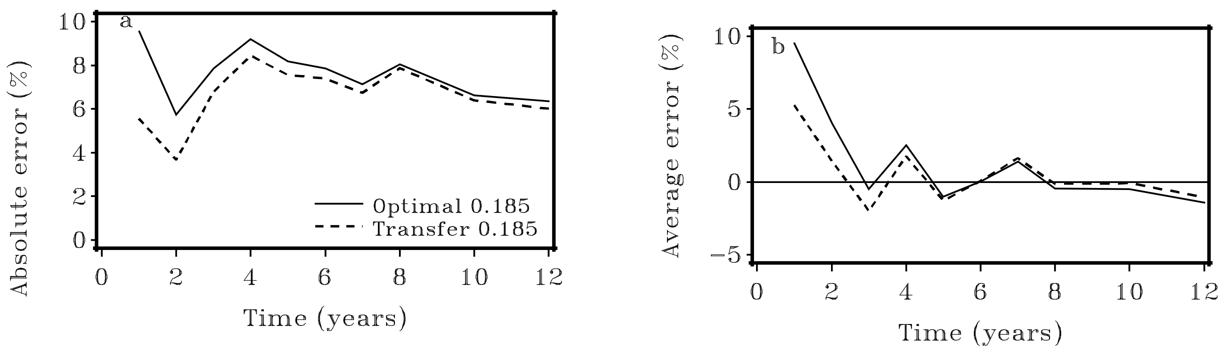

Figure 10. Time series of (a) absolute error (E_a) and (b) average error (E_{12}) for predictions that include winter precipitation (Model ID = 1.7) with τ_{c1}= 0.185 (Transfer 0.185). Errors from model predictions without winter precipitation (Optimal 0.185; Model ID = 1.3) are shown for comparison.

Although including winter precipitation reduced the residual error in the first year, further improvements were needed (Figure 11).

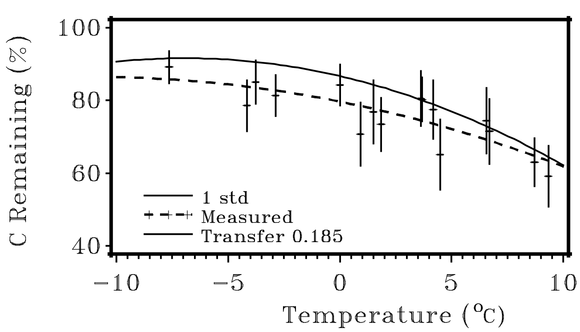

Figure 11. Carbon remaining after one year for predictions that included winter precipitation and τ_{c1}= 0.185 (Transfer 0.185; Model ID = 1.7). Quadratic regression lines for the measurements (dashed) and predictions (solid) are also shown.

3.10 Modify model: summer and winter precipitation

The addition of summer precipitation improved predictions of carbon remaining. Adding winter precipitation also improved predictions, but to a lesser extent. As summer precipitation and winter precipitation were not correlated, the model was modified to include both variables simultaneously (Model ID=1.8).

Summer precipitation was included as described in Section 3.8 (Equations 15 and 16), and winter precipitation was included as described in Section 3.9 (Equations 17 to 19). Absolute errors were estimated for the same grid of parameters.

Best fit was determined by minimizing the error between predicted and measured carbon remaining. Optimal values of k_{b1}, Q_1, and r for each value of τ_{c1} were estimated using adjusted slow pool parameters (k_{b4}= 0.015 yr $^{-1}$, Q_4= 2.65) and the lowest 5th percentiles of $\bar{E}_a$ and E_{12}. There were 137 cases of overlap of k_{b1}, Q_1, and r for τ_{c1}= 0.170, 201 cases for τ_{c1}= 0.180, 212 cases for τ_{c1}= 0.185, and 213 cases for τ_{c1}= 0.190. For each τ_{c1}, the base decay rate averaged from 0.33 yr $^{-1}$ to 0.36 yr $^{-1}$, the temperature quotient averaged from 2.85 to 2.99, and the summer precipitation variable averaged from 279 to 281 (Table 9).

Table 9. Optimal very fast pool decay parameters and associated error using: a decay rate that included summer and winter precipitation, and adjusted slow pool decay parameters (k_{b4}= 0.015 yr $^{-1}$ and Q_4= 2.65)

Model ID	Scenario	k_{b1} (yr $^{-1}$)	Q_1	τ_{c1}	r	$\bar{E}_a$ (%)
1.8	Summer and winter precipitation	0.326	2.85	0.170	279	5.3
		0.343	2.92	0.180	280	5.2
		0.354	2.96	0.185	280	5.2
		0.362	2.99	0.190	281	5.2

Absolute errors were further reduced when both summer and winter precipitation were included (Figure 12). The absolute error ($\bar{E}_a$) was reduced by ~9% compared to that of model predictions using default decay parameters with temperature alone (Model ID=1.0).

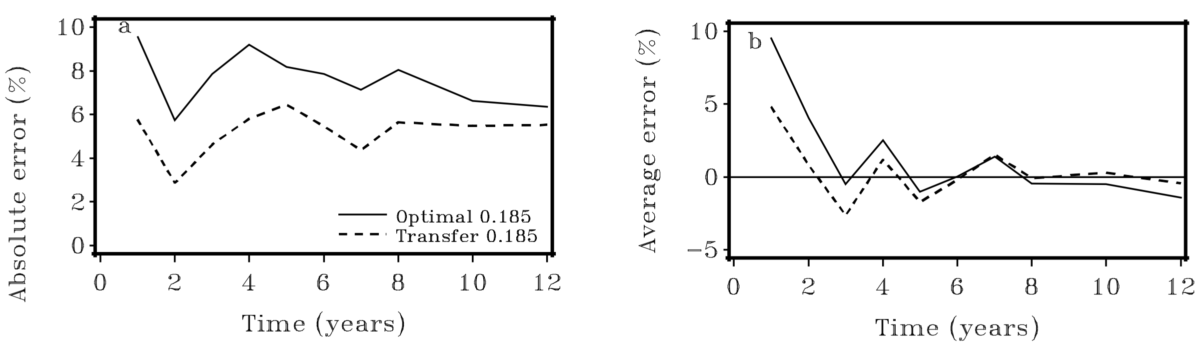

Figure 12. Time series of (a) absolute error (E_a) and (b) average error (E) for predictions that included summer and winter precipitation (Model ID = 1.8) with τ_{c1}= 0.185 (Transfer 0.185). Errors from model predictions without precipitation (Optimal 0.185; Model ID = 1.3) are shown for comparison.

Time series of predicted and measured carbon remaining for each site are shown in Figure 13. There were marked improvements in predictions for two sites, Montmorency (MON) and Schefferville (SCH), that had high winter-precipitation influences. Even with these modifications, large errors remained between predictions and measurements at Chapleau (CHA), where predictions overestimated carbon remaining, and at Whitehorse (WHI), where predictions underestimated carbon remaining. In these cases, it is possible that measured air temperature and precipitation from climate stations did not accurately represent *in situ* soil temperature and moisture due to the influences of local topography and canopy cover.

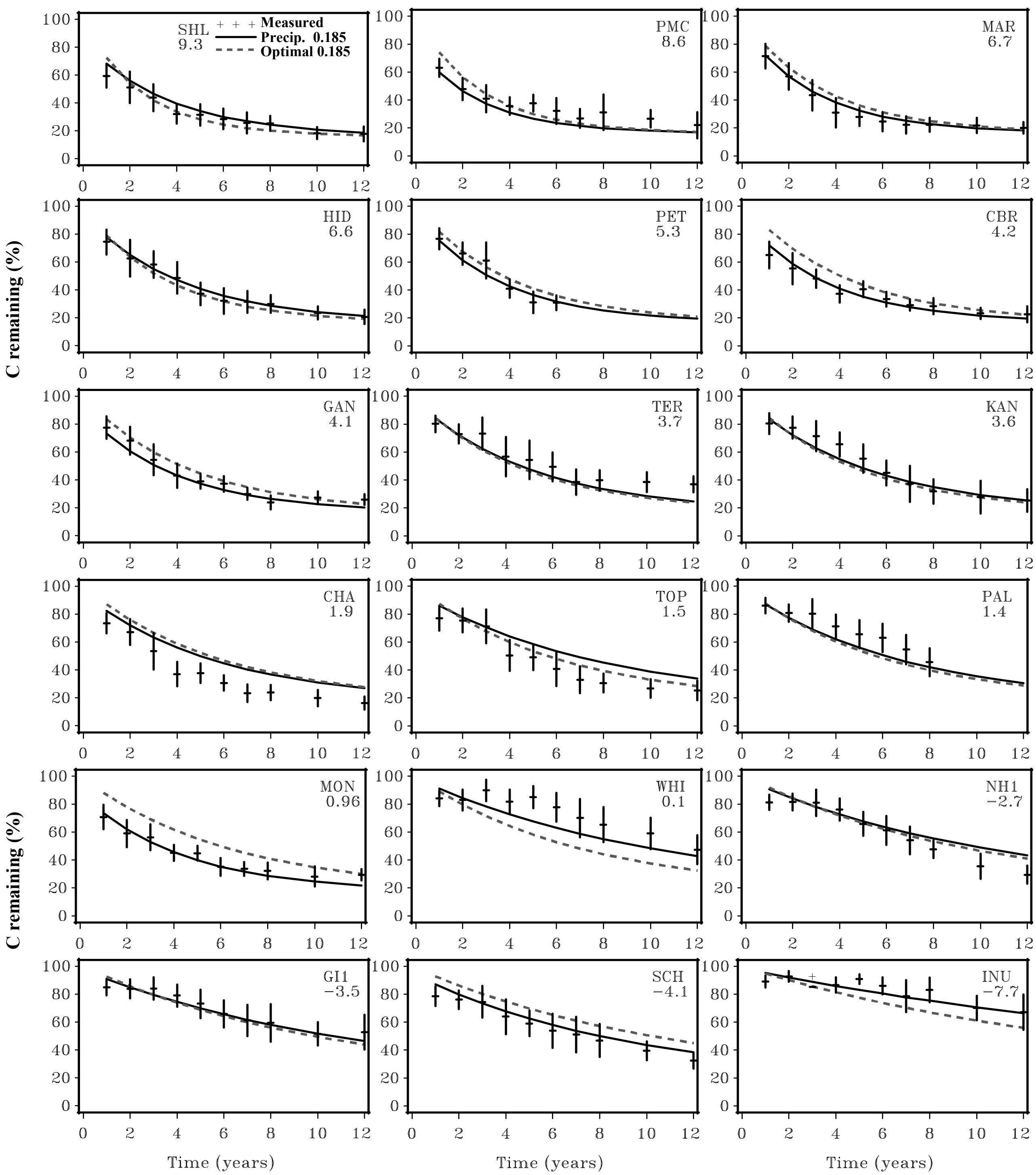

Figure 13. Predicted and measured carbon remaining time series for each site. Model equations were modified to include winter and summer precipitation. (Precipitation 0.185; Model ID = 1.8, $\tau_{c1} = 0.185$). Model predictions for temperature alone (Optimal 0.185; Model ID = 1.3, $\tau_{c1} = 0.185$) are shown for reference.

3.11 Modify model: litter variable

Average carbon remaining from eight tree foliar litters has been used thus far in this report for comparisons with model predictions. However, these litters were selected to represent a range of decomposition rates associated with different litter types. Some users may wish to have decay parameters that represent the species in their particular application. In order to consider modifying the model to include a litter variable, error as a function of litter type had to be assessed.

Errors were estimated as the difference between predicted and measured carbon remaining for each litter type:

(20) $$E'(t,g) = \frac{1}{16}\sum_{l=1}^{16}\hat{C}_r(t,g) - C_r(t,g)$$

where g represents the litter type. In general, large positive errors were found for white birch and black spruce (indicating a faster decay than predicted), and large negative errors were found for western redcedar and American beech (Figure 14).

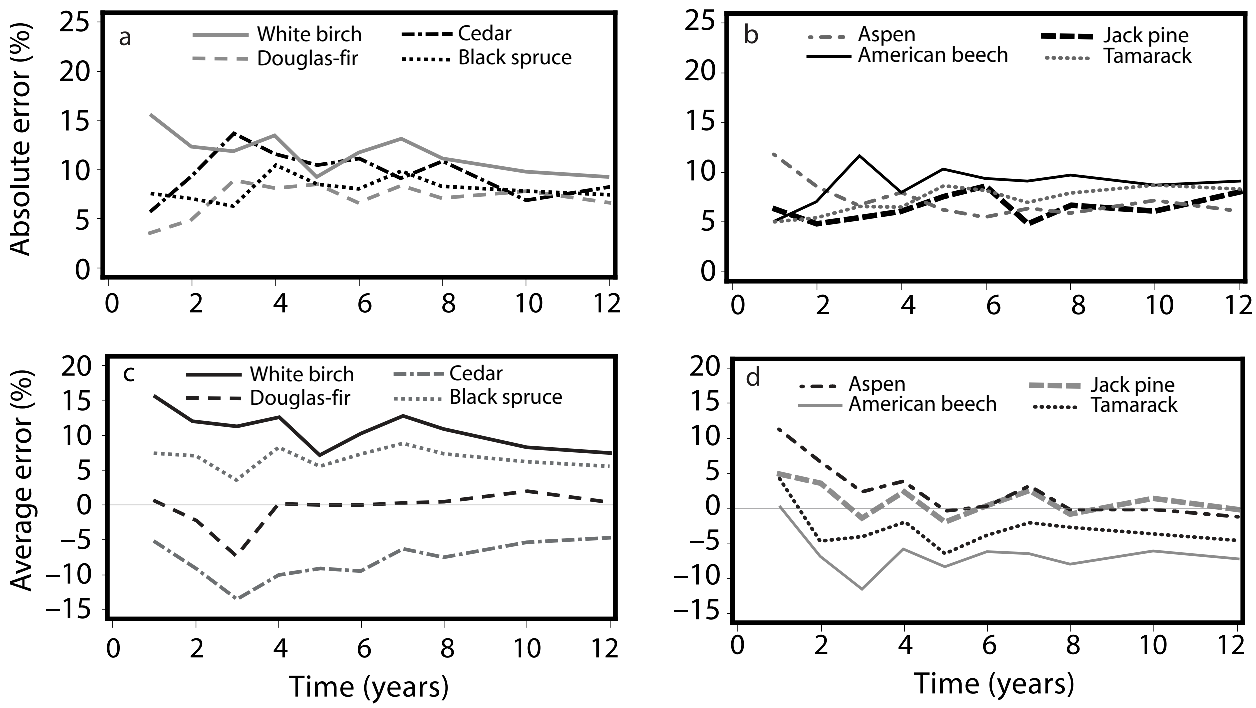

Figure 14. Time series of (a) absolute error (E_a) and (b) average error (E) for eight tree foliar litter types.

Errors from Equation 20 were averaged over time and regressed (SAS proc reg) with litter variables to determine if any substrate variables would improve predictions. Model predictions were estimated using optimal decay parameters that included winter and summer precipitation (k_{b1}= 0.354 yr $^{-1}$, r= 280, Q_1= 2.96, τ_{c1}= 0.185; Table 9, Model ID= 1.8), and errors were regressed against litter variables. These variables included: carbon fractions determined by proximate analysis [nonpolar extractables, water-soluble extractables, acid-hydrolyzable fraction, acid-unhydrolyzable residue (AUR), and ash], nutrient content from elemental analysis (nitrogen, phosphorus, sulphur, potassium, magnesium, and calcium), the ratio of acid-unhydrolyzable residue to nitrogen (AUR/N), and relative areas of chemical-shift regions determined by solid-state carbon-13 (^{13}C) nuclear magnetic resonance (NMR) spectroscopy (alkyl carbon, methoxyl carbon, O-alkyl carbon, di-O-alkyl carbon, aromatic carbon, phenolic carbon, and carboxyl or carbonyl carbon). Data for elemental, proximate, and ^{13}C NMR spectroscopy are presented in Trofymow et al. (2002) and Preston et al. (1997), and are based on analysis of the litters before they were placed in the field.

The litter variable corresponding to the highest squared correlation coefficient (0.37) was AUR/N. Decomposition rates were overpredicted for litters with high AUR/N and underpredicted for litters with low AUR/N. Regression of the error as a function of AUR/N gave:

(21) $$E' = -0.309AUR/N + 13.27$$

which was zero for an AUR/N value of 43.0.

This is consistent with a hypothesis by Trofymow and CIDET Working Group (1998) and results from Trofymow et al. (2002), where AUR/N was found to be important in the multiple regression for decay rates and intercepts in the analysis of the six-year carbon remaining time series.

In the SAS version of the model, the very fast pool decay rate equation was modified (Model ID=1.9) to include an AUR/N modifier:

(22) $$L_m = 1 - (AUR/N - 43)/v$$

where v is an adjustment parameter, and the decay rate equation was taken as:

(23) $$k_1 = k_{b1}T_{m1}S_mL_m$$

The value of v was obtained by minimizing errors between predicted and measured carbon remaining. Predicted carbon remaining (for each litter type, location, and time step) was estimated for a grid of decay parameters: the proportion transferred to the slow pool (τ_{c1}) ranged from 0.170 to 0.190, and for each τ_{c1}, k_{b1} varied by 0.01 yr^{-1} from 0.2 yr^{-1} to 0.5 yr^{-1}, Q_1 varied by 0.05 from 2 to 3, and v varied from 10 to 105. Both summer precipitation and winter precipitation were included in the model. The summer precipitation parameter (r) was set to 280.

Best fit was determined by minimizing the error between predicted and measured carbon remaining. Optimal values of k_{b1}, Q_1, and v for each value of τ_{c1} were estimated using adjusted slow pool parameters (k_{b4}= 0.015 yr^{-1}, Q_4= 2.65) and the lowest 3rd percentiles of $\bar{E}_a$ and E_{12}. Many cases had overlapping errors, because some cases had the same k_{b1}, Q_1, and τ_{c1}, but several values of v. There were 123 cases of overlap of k_{b1} and Q_1 for τ_{c1}= 0.170, 150 cases for τ_{c1}= 0.180, 147 cases for τ_{c1}= 0.180, and 132 cases for τ_{c1}= 0.190. For each τ_{c1}, the base decay rate averaged from 0.33 yr^{-1} to 0.36 yr^{-1}, the temperature quotient averaged from 2.80 to 2.92, and the AUR/N adjustment parameter (v) averaged from 84 to 85 (Table 10).

Table 10. Optimal very fast pool decay parameters and associated error using: a decay rate that included summer precipitation, winter precipitation, and AUR/N, and adjusted slow pool decay parameters (k_{b4}= 0.015 yr^{-1} and Q_4= 2.65)

Model ID	Scenario	k_{b1} (yr^{-1})	Q_1	τ_{c1}	v	$\bar{E}_a$ (%)
1.9	Summer precipitation,	0.330	2.80	0.170	85	5.3
	winter precipitation,	0.346	2.86	0.180	85	5.2
	and *AUR/N*	0.354	2.89	0.185	85	5.2
		0.362	2.92	0.190	84	5.2

Absolute errors estimated from the modified model were 5.2%, and were similar to those estimated from the model that includes precipitation in Table 9. These errors were estimated using carbon remaining averaged over litter type for consistency with previous tables.

The addition of the litter-quality parameter AUR/N reduced the error, particularly for western redcedar (AUR/N= 64.2; Figure 15). Absolute errors estimated for individual litters dropped from 8.2% to 7.7%.

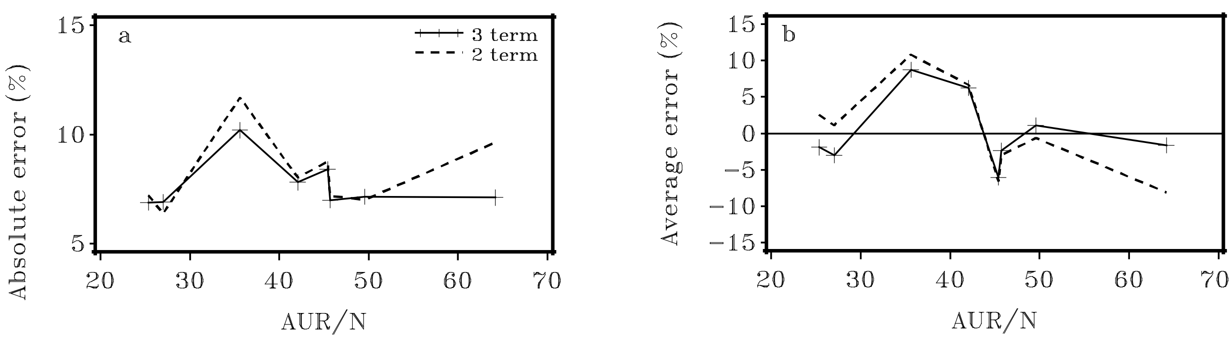

Figure 15. (a) Absolute error ($\bar{E}_a$) and (b) average error (E) as a function of litter quality variable AUR/N for eight foliar litters. Decay rates were modified by temperature and summer precipitation only (two-term; Model ID = 1.8) or with AUR/N (three-term; Model ID = 1.9).

In summary, optimized decay parameters were obtained for the very fast pool for several scenarios, including adjusted slow pool parameters, and coniferous and deciduous litters. Several model modifications were tested, including the addition of a litter variable and climate variable.

4. Comparison to surface wood-block data

In this section, the process of determining optimal decay parameters was repeated for the wood-block data. Optimal parameters were identified for various scenarios, including default and adjusted slow pool parameters. Additional analyses were then performed to determine alternative functions to represent wood decay. The goal was to assess if alternative algorithms could appreciably reduce the error between predictions and measurements.

Measured times series of mass remaining in the wood blocks placed on the surface were compared to predicted total carbon remaining in the fast pool and slow pool. Measured mass remaining was used instead of carbon remaining, because there were errors in the wood-block carbon concentration estimates made from samples in 1993 and 1997, and re-analyses were not available. The percentage mass and percentage carbon dynamics should be similar, although Preston et al. (2006) have shown that carbon concentrations tend to increase as they are enriched with more aromatic carbon compounds in very decayed wood. However, this effect would be minimal during the first stage of decomposition: mass and carbon remaining data are essentially identical at this stage.

4.1 Model default values

Carbon remaining time series were predicted using default decay parameters (Model ID=2.0) and 12-year-average air temperatures at each site. Predicted values were then compared to observed mass remaining time series.

In contrast to the foliar litters (Figure 6), most surface wood blocks had greater than 90% mass remaining after one year. Predicted carbon remaining after one year was consistent with measurements, except at warmer sites where predictions underestimated mass remaining (Figure 16). After six years, predictions underestimated carbon remaining at colder sites, but predictions were consistent with mass remaining at warmer locations. After 12 years, mass remaining at sites with temperature extremes was not well predicted. Wood blocks at the coldest site (Inuvik) had ~90% mass remaining after 12 years, but were predicted to have ~70% remaining.

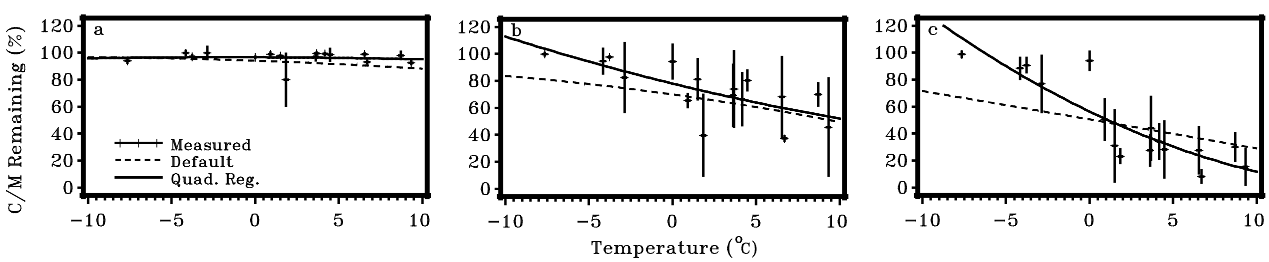

Figure 16. Measured mass remaining and predicted carbon remaining (Model ID = 2.0) after (a) one year, (b) six years, and (c) 12 years, as a function of temperature for fast pool default decay parameters. Solid lines indicate quadratic regressions to the data.

4.2 Optimal decay parameters

Optimal base decay rates and temperature quotients were again determined by minimizing the absolute error between measured and predicted mass remaining time series. The best range of the proportion transferred to the slow pool for model decay parameters was difficult to estimate, because most of the wood blocks had not reached a meta-stable decay phase and, compared to the foliar litters, variability was higher in the four replicate samples from each site. To assess whether any of the wood-block data had reached an asymptote, data were bin-averaged in 4000° C day bins of cumulative degree days, where a degree day had a daily temperature above 0° C. The average of the four replicate samples was binned, as were the minimum and maximum of the four replicate samples.

Average mass remaining still decreased at high-degree days and had not yet reached a constant level (Figure 17). However, binned minimum mass remaining reached a constant level at high-degree days, which suggests that an asymptote was reached at the warmer sites. Averaging all estimates of minimum mass remaining above 27 000° C days yielded an estimate of the asymptote (± standard error) of 0.15 ± 0.09 (n=56). Based on this estimate, the range chosen to represent the proportion transferred to the slow pool was from 0.160 to 0.185.

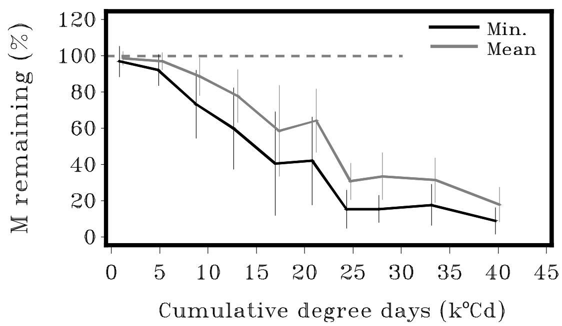

Figure 17. Bin-averaged mass remaining for the minimum observed (Min.) and mean (Mean), as a function of cumulative degree days. Error bars indicate one standard deviation; a 100% reference line (dashed) is shown.

A grid of decay parameters was used to generate model predictions. For each τ_{c2}, k_{b2} was varied by increments of 0.002 yr $^{-1}$ from 0.162 yr $^{-1}$ to 0.260 yr $^{-1}$, and Q_2 was varied by increments of 0.02 from 3.22 to 4.20.

4.2.1 Method 1

The average error and the absolute error after 12 years of decomposition were estimated for each set of fast pool decay parameters using default slow pool decay parameters (k_{b4}= 0.0032yr $^{-1}$, Q_4= 0.9). Twenty-five hundred (2500) error estimates were calculated from the grid of decay parameters, and the lowest 35th percentiles of these $\bar{E}_a$ and E_{12} were selected. There were seven cases of overlap of k_{b2} and Q_2 for the lowest 35th percentiles of $\bar{E}_a$ and E_{12} for τ_{c2}= 0.160. There were two cases of overlap for τ_{c2}= 0.170, and no overlapping cases for τ_{c2}= 0.180 or 0.185. For each τ_{c2}, the base decay rate averaged from 0.211 yr $^{-1}$ to 0.214 yr $^{-1}$, and the temperature quotient averaged from 4.15 to 4.19 (Table 11, Model ID= 2.1).

Table 11. Default and optimal fast pool decay parameters using Method 1 and default slow pool parameters (k_{b4}= 0.0032 yr $^{-1}$ and Q_4= 0.9)

Model ID	Scenario	k_{b2} (yr $^{-1}$)	Q_2	τ_{c2}	$\bar{E}a$ (%)
2.0	Default for surface wood-block data	0.1435	2.00	0.17	14.2
2.1	Optimal decay parameters (Method 1)	0.2110	4.15	0.16	12.0
		0.2140	4.19	0.17	11.9

Optimal parameters were not well constrained by this process, as the temperature quotient was too close to the upper bound (4.2) of the input values. A second method to minimize the error between measurements and predictions was therefore developed.

4.2.2 Method 2

In Method 2 (Model ID=2.2), decay rates were estimated from exponential fits of measured mass remaining time series ($M = M(0)\exp(-k_e t)$). These decay rates were used to obtain base decay rates and Q_{10} values from Equations 3 and 4:

$$k_e = k'_{b2} Q'_2{}^{[0.1(T-10)]} \quad (24)$$

where k'_{b2} is the base decay rate at 10° C, and Q'_2 is the temperature quotient. The temperature quotient from measured wood-block decay was estimated as 3.12, and the base decay rate was 0.14 yr^{-1}.

Optimal decay parameters were determined, as done in the previous section, by using a grid of decay parameters, but restrictions were placed on the base decay rate and temperature quotient. Predicted carbon remaining series were also fit exponentially, and temperature quotients and base decay rates were obtained as in Equation 24.

The grid of decay parameters varied the proportion transferred to the slow pool (τ_{c2}) from 0.160 to 0.185. For each τ_{c2}, the temperature quotient for the fast pool was varied by 0.02, from 3.22 to 4.20, and the base decay rate was varied by 0.002 yr^{-1} from 0.162 to 0.260 yr^{-1}. The slow pool parameters were set to default values (k_{b4}= 0.0032 yr^{-1}, Q_4= 0.9). From these predictions (n= 2500), only small differences in base decay rates and temperature quotients were permitted: $|\Delta k'_{b2}|<0.02$ yr^{-1}, and $|\Delta Q'_2|<0.2$. Of these predictions, three other errors were estimated: E_{12}, mean absolute residuals from the exponential fit, and mean absolute errors from the fit of Equation 24. The smallest 50th percentiles were estimated for each of these errors, and optimal decay parameters were determined where these errors overlapped. Restrictions on the errors needed to be weak, as the errors generally did not overlap in decay parameter space: small E_{12} errors tended to have higher temperature quotients (Figure 18).

For the four values of τ_{c2} considered, 900 to 1100 cases satisfied the restrictions $|\Delta k'_{b2}|<0.02$ yr^{-1} and $|\Delta Q'_2|<0.2$. Six cases satisfied the three error restrictions for τ_{c2}= 0.160, 11 cases for τ_{c2}= 0.170, 13 cases for τ_{c2}= 0.180, and 13 cases for τ_{c2}= 0.185. For each τ_{c2}, the base decay rate averaged from 0.20 yr^{-1} to 0.22 yr^{-1}, and the temperature quotient averaged from 3.68 to 3.84 (Table 12).

Table 12. Optimal fast pool decay parameters and associated error using Method 2 and default slow pool parameters (k_{b4}= 0.0032 yr^{-1} and Q_4= 0.9)

Model ID	Scenario	k_{b2} (yr^{-1})	Q_2	τ_{c2}	$\bar{E}_a$ (%)
2.2	Optimal decay parameters (Method 2)	0.197	3.68	0.160	11.9
		0.204	3.72	0.170	12.0
		0.212	3.83	0.180	12.1
		0.216	3.84	0.185	12.0

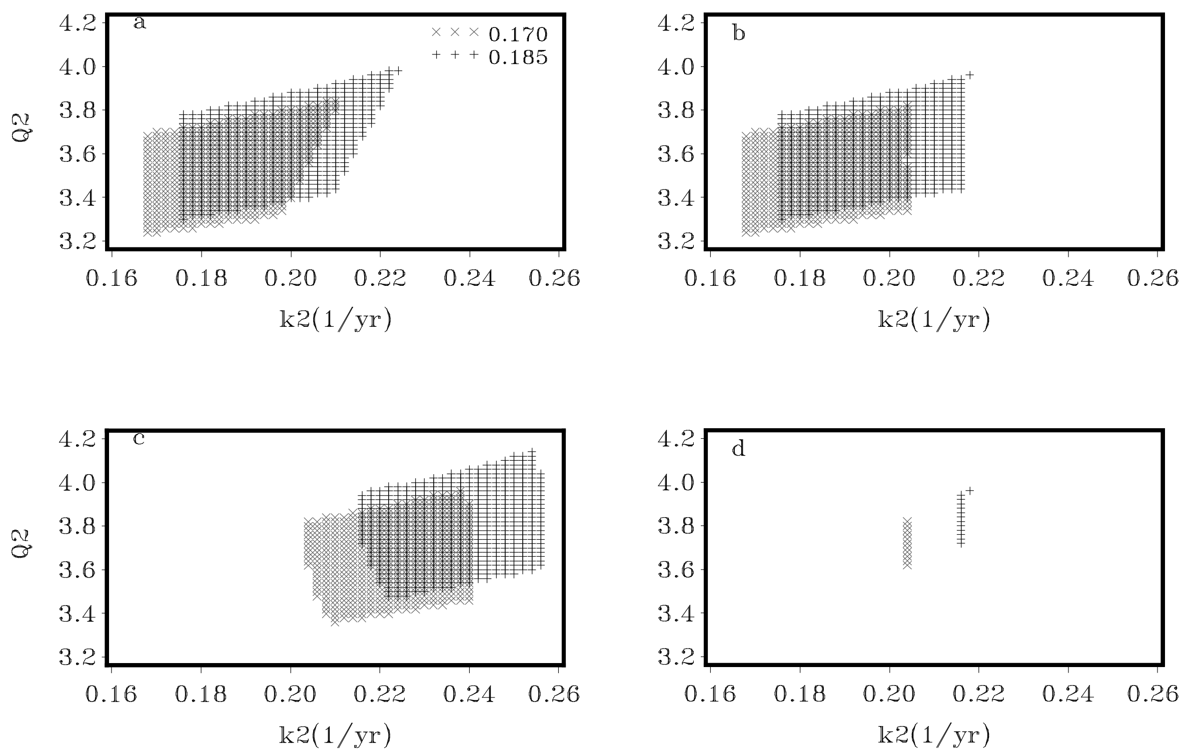

Figure 18. Decay parameters (Q_2 and k_{b2}) corresponding to the lowest 50th percentiles of (a) exponential decay fit error, (b) base decay rate fit error, (c) E_{12}, and (d) the overlap of these errors for Model ID = 2.2 with τ_{c2} = 0.170 or τ_{c2} = 0.185.

The base decay rates were similar to those obtained using Method 1, but the temperature quotients were slightly smaller. Predicted carbon remaining using optimal decay parameters from both methods had 2.0% smaller errors than when default decay parameters were used. Absolute errors in later years of the experiment were markedly lower than in the default case (Figure 19).

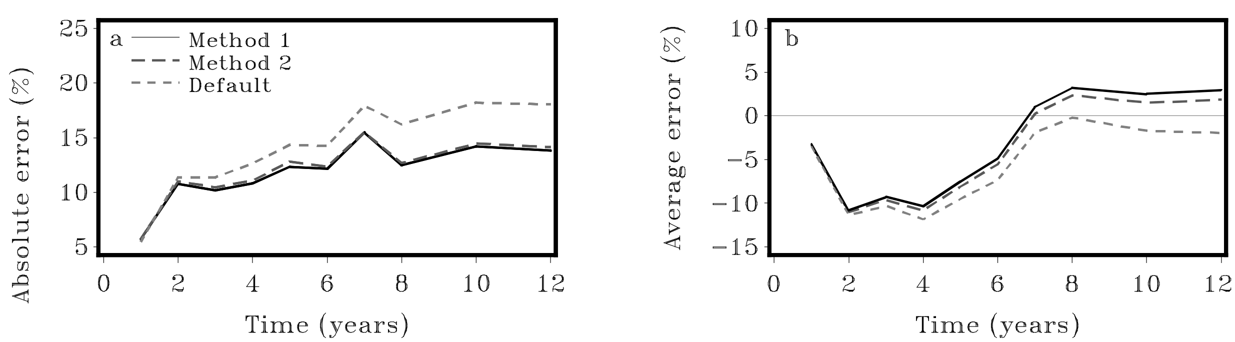

Figure 19. Time series of (a) absolute error (E_a) and (b) average error (E) based on decay parameters from Method 1 (Model ID = 2.1), Method 2 (Model ID = 2.2), and default parameters (Model ID = 2.0).

Although carbon remaining predictions improved when the decay parameters were optimized, discrepancies remained between predicted and measured time series. Mass remaining was well predicted for intermediate temperatures after six and 12 years, but errors remained at temperature extremes (Figure 20). Predictions obtained with Method 2 were very similar to those obtained with Method 1, and are not shown.

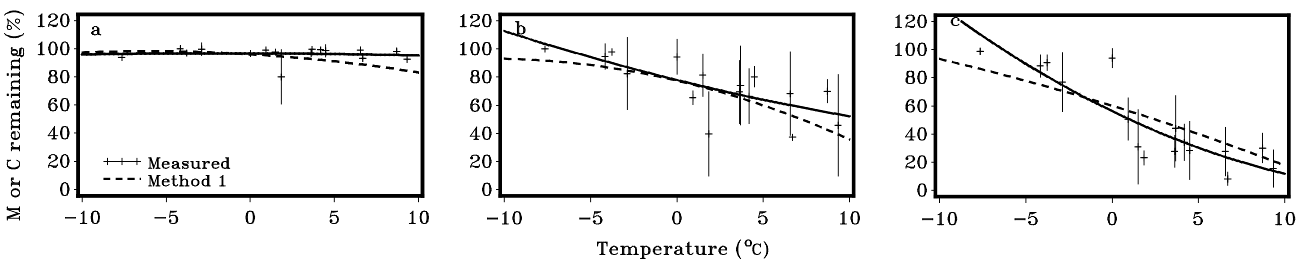

Figure 20. Measured mass remaining and predicted carbon remaining after (a) one year, (b) six years, and (c) 12 years for optimal decay parameters (Model ID = 2.1).

After one year, model predictions underestimated mass remaining at warm sites. The discrepancy may be related to delay in decomposition. Harmon et al. (2000) found that the decomposition of downed trees had several phases, starting with an initial slow phase of decomposition as the wood became colonized by decay organisms. The results obtained here suggest that the structure of the model should be modified to include either a delay in the initiation of decay or a more appropriate decay function; see sections 4.6 through 4.9 for discussion of this issue.

4.3 Adjusted slow pool parameters

The Method 2 process for determining optimal decay parameters was repeated with adjusted slow pool parameters (k_{b4}= 0.015yr $^{-1}$, Q_4= 2.65) from the 2007 National Inventory Report (Environment Canada 2007). Twenty-five cases satisfied all of the above restrictions for τ_{c2}= 0.160. There were 13 cases for τ_{c2}= 0.170, and 11 cases each for τ_{c2}= 0.180 and τ_{c2}= 0.185. For each τ_{c2}, the base decay rate averaged from 0.185 yr $^{-1}$ to 0.190 yr $^{-1}$, and the temperature quotient averaged from 3.46 to 3.51 (Table 13, Model ID= 2.3).

Table 13. Optimal fast pool decay parameters and associated error using Method 2 and adjusted slow pool parameters (k_{b4}= 0.015 yr $^{-1}$ and Q_4= 2.65)

Model ID	Scenario	k_{b2} (yr $^{-1}$)	Q_2	τ_{c2}	$\bar{E}_a$ (%)
2.3	Adjusted slow pool parameters	0.185	3.46	0.160	11.9
		0.187	3.46	0.170	11.8
		0.187	3.49	0.180	11.8
		0.190	3.51	0.185	11.7

Optimal parameters with adjusted slow pool parameters were slightly smaller than those obtained in Section 4.3.2 (compared to Table 12), but absolute errors were similar.

4.4 Comparison to a sigmoidal fit

Wood decay has been described by time-varying decomposition rates. For example, Laiho and Prescott (1999) found that a sigmoidal function better accounted for the varying decomposition rates in their study of decomposition of pine and spruce logs.

A sigmoidal function was fit to the CIDET data:

$$M_f = exp[-(Rt)^S] \quad (25)$$

where M_f is the fractional mass remaining, R controls the rate of decay, and S controls the shape of the decay. Parameters R and S were determined by non-linear fits of mass remaining time series (SAS; proc nlin; initial parameters $R = 0.01$, $S = 1.2$, and a bound of $S < 5$).

Model predictions using a sigmoidal function provided a much better fit to the data than model predictions based on optimal decay parameters from Method 2 (Model ID=2.3). The sigmoidal function had a time-varying decay rate that closely matched the initial slow-decay phase (Figure 21). After the initial slow-decay phase, the sigmoidal function decayed rapidly, and then demonstrated slower decay in later years.

At very cold sites, the mass remaining did not reach a rapid stage of decay, but remained in the initial slow-decay phase. For these sites, a linear decay of mass remaining was more appropriate than a sigmoidal fit.

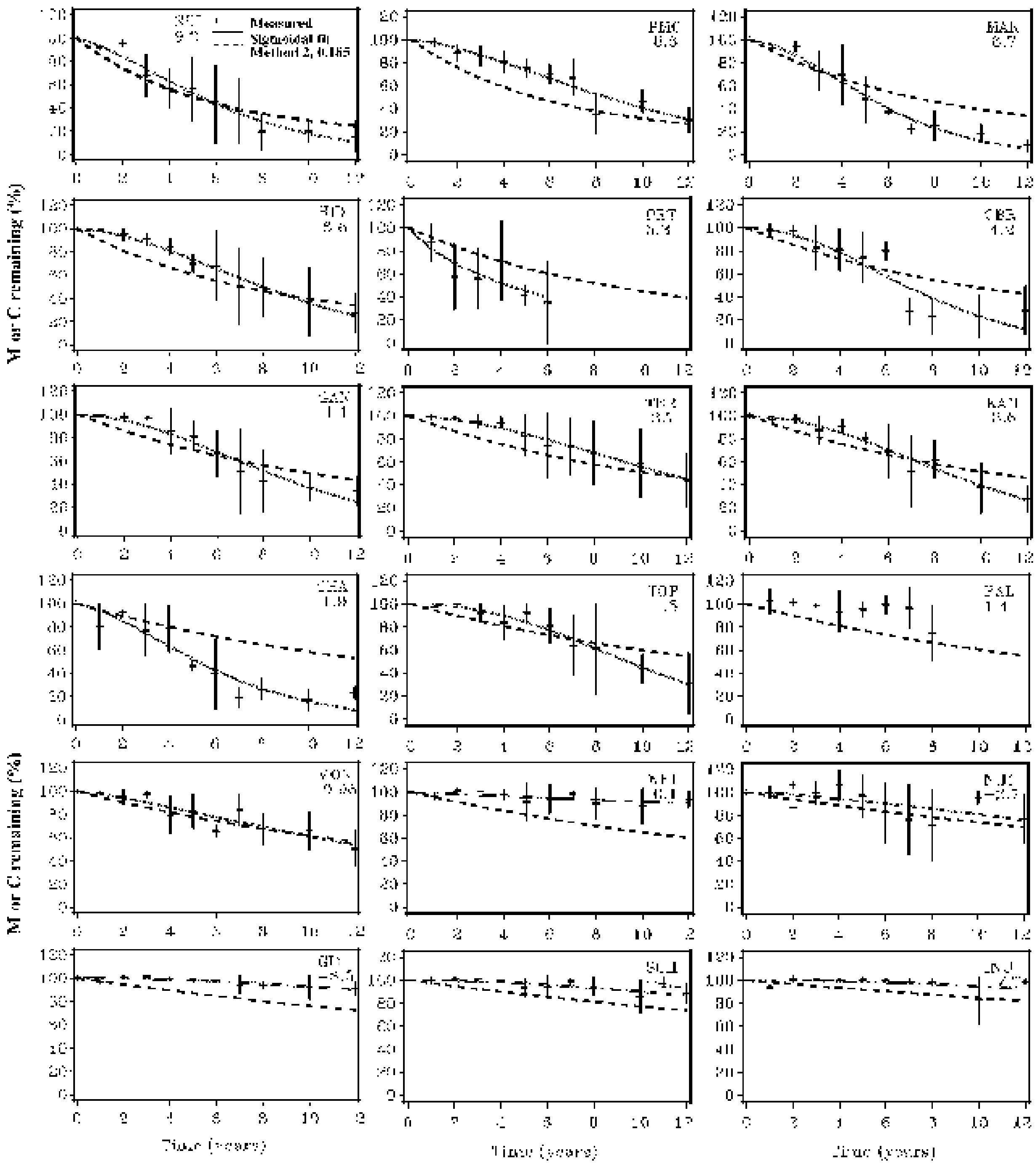

Figure 21. Predicted and measured mass or carbon remaining time series at each site. Also shown are sigmoidal fits to the measured mass remaining, and predictions from Method 2 (Model ID = 2.3) with $\tau_{c2} = 0.185$.

4.5 Modify model: time delay

The sigmoidal equation provided a good approximation to wood-block decay when fit individually to each site, but incorporating this equation requires major modifications to the existing dead organic matter submodel. In order to approximate the delay in wood decomposition without using a sigmoidal function, a time delay was added to model, and the errors were assessed.

As a first attempt, a temperature-dependent time delay was added to the model equations to prevent mass loss until a given time interval had passed (Model ID=2.4). The sigmoidal fits (Figure 21) were used to determine the appropriate delay interval. The time required for the sigmoidal fit to reach 90% mass remaining was estimated for each location, and then was linearly regressed against average temperature. The regression equation was:

(26) $$t_{90} = -0.752T + 6.834$$

where t_{90} was the time to reach 90% mass remaining, and T is the 12-year-average temperature (r^2=0.7, n=16). Time delays were then rounded to the nearest year and input into the SAS version of the model.

With this added time delay, the process of finding optimal decay parameters was repeated. The proportion transferred to the slow pool (τ_{c2}) was varied between 0.160 and 0.185, and for each τ_{c2}, k_{b2} was varied by 0.01 yr $^{-1}$ from 0.212 yr $^{-1}$ to 0.310 yr $^{-1}$, and Q_2 was varied by 0.05 from 2.22 to 3.20. Decay parameters for the slow pool were based on the adjusted values (k_{b4}= 0.015 yr $^{-1}$, Q_4= 2.65).

Twenty-five hundred (2500) error estimates ($\bar{E}_a$ and E_{12}) were calculated from the grid of decay parameters, and the lowest 30th percentiles of these errors were estimated for $\bar{E}_a$ and E_{12} (Method 1). There were 52 overlapping cases of $\bar{E}_a$ and E_{12} for τ_{c2}= 0.160. There were 33 cases of overlap for τ_{c2}= 0.170, 18 cases for τ_{c2}= 0.180, and 17 cases for τ_{c2}= 0.185. For each τ_{c2}, the base decay rate averaged from 0.227 yr $^{-1}$ to 0.233 yr $^{-1}$, and the temperature quotient averaged from 2.09 to 2.13 (Table 14). Appendix B includes results of a similar optimization process completed for buried wood blocks.

Compared to values obtained in predictions based on optimal decay parameters (Table 12), adding the time delay reduced the error by ~2%, increased the base decay rate, and decreased the temperature quotient. Error time series and mass remaining time series are shown in Figure 22.

Table 14. Optimal fast pool decay parameters and associated error for a modified model that included a time delay, and using adjusted slow pool parameters (k_{b4}= 0.015 yr $^{-1}$ and Q_4= 2.65)

Model ID	Scenario	k_{b2} (yr $^{-1}$)	Q_2	τ_{c2}	$\bar{E}_a$ (%)
2.4	Time delay	0.227	2.13	0.160	10.1
		0.230	2.11	0.170	10.1
		0.232	2.09	0.180	10.1
		0.233	2.09	0.185	10.1

4.6 Modify model: sigmoidal decay

Another approach to increase model accuracy that was tested was to change the fast pool decay rate from a power series (Equation 2) to a sigmoidal function (Equation 25). The SAS version of the model was altered (Model ID=2.5) to optimize sigmoidal parameters (R and S) instead of the power series decay parameters.

Parameters R and S were regressed against temperature to determine if both coefficients required a temperature quotient. R regressed well with temperature, and had a squared correlation coefficient of 0.61. S was not a function of temperature (r^2~0), and had a mean of 1.69 ± 0.31.

Accordingly, only the sigmoidal decay parameter (R) had a temperature modifier:

(27) $$R = R_b T_{m2}$$

where R_b is the base decay rate, and T_m is the temperature modifier. Decomposition for the fast pool was estimated as:

(28) $$X_2(t) = 100exp(-(Rt)^S)$$

At each time step, the carbon transferred to the slow pool was

(29) $$\tau_{r2}(t) = \tau_{c2}(X_2(t-1) - X_2(t))$$

where the proportion transferred to the slow pool (τ_{c2}) had a default value of 0.170.

With this change in decay function, the process of finding optimal decay parameters was repeated. The proportion transferred to the slow pool (τ_{c2}) was varied between 0.160 and 0.185, and for each τ_{c2}, R_b was varied by 0.01 yr^{-1} from 0.14 yr^{-1} to 0.24 yr^{-1}, Q_2 was varied by 0.05 from 3.12 to 4.12, and S was varied by 0.1 between 2 and 3. Adjusted slow pool parameters were used (k_{b4}= 0.015yr^{-1}, Q_4= 2.65).

For each set of decay parameters, the absolute error was estimated, as was the absolute error after 12 years of decomposition. Twenty-five hundred (2500) error estimates were calculated from the grid of decay parameters, and the lowest 6th percentiles of these errors were estimated for $\bar{E}_a$ and E_{12} (Method 1). There were 26 cases of overlap for τ_{c2}= 0.160, corresponding to the lowest 6th percentiles of $\bar{E}_a$ and E_{12}. There were 13 cases of overlap for τ_{c2}= 0.170, nine cases for τ_{c2}= 0.180, and six cases for τ_{c2}= 0.185. For each τ_{c2}, R_b averaged from 0.232 yr^{-1} to 0.239 yr^{-1}, the temperature quotient averaged from 3.33 to 3.34, and S averaged from 2.33 to 2.40 (Table 15). Appendix B includes results of a similar optimization process for buried wood blocks.

Table 15 Optimal fast pool decay parameters and associated error for a modified model based on a sigmoidal decay, and using adjusted slow pool parameters (k_{b4}= 0.015 yr^{-1} and Q_4= 2.65)

Model ID	Scenario	R_b (yr^{-1})	S	Q_2	τ_{c2}	$\bar{E}_a$ (%)
2.5	Sigmoidal decay	0.232	2.33	3.33	0.16	8.7
		0.235	2.36	3.31	0.17	8.7
		0.239	2.37	3.34	0.18	8.6
		0.238	2.40	3.31	0.185	8.6

The use of a sigmoidal decay function reduced the absolute error to ~9%—smaller than with any of the other wood-block optimization methods. It also resulted in small absolute errors in the first few years when little decay occurs (Figure 22).

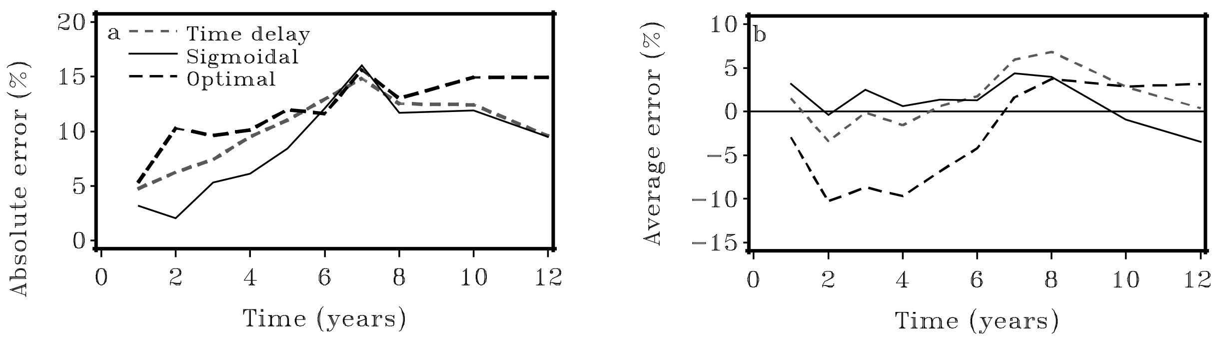

Figure 22. Time series of (a) absolute error (E_a) and (b) average error (E) for the model modified to include a time delay (Model ID = 2.4) or a sigmoidal decay (Model ID = 2.5), and for the unmodified model using optimal parameters (Model ID = 2.3).

Predictions based on modifying the model to contain a time delay (Section 4.6) or sigmoidal decay function were closer to measured mass remaining after one year, six years and 12 years (Figure 23). The time series of the data and predictions for each site (Figure 24) show that both models overestimate carbon remaining at Chapleau (CHA) and Petawawa (PET) and underestimate carbon remaining at Port McNeill (PMC).

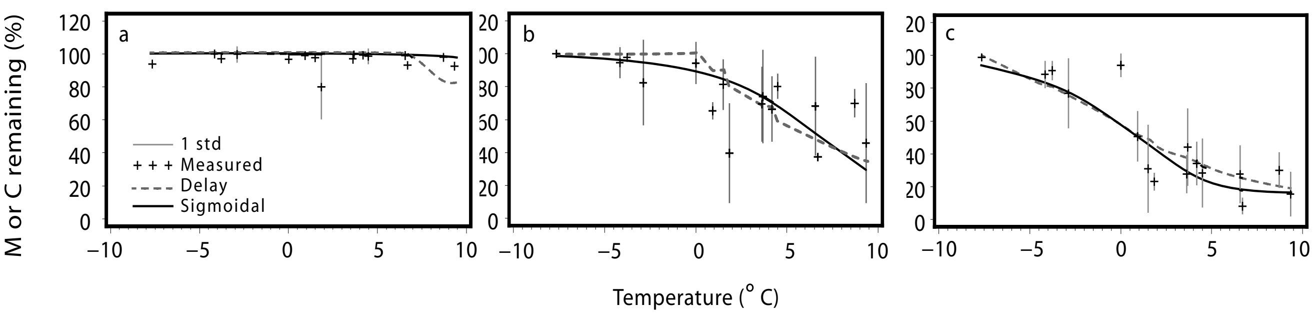

Figure 23. Predicted carbon remaining and measured mass remaining after (a) one year, (b) six years, and (c) 12 years, as a function of site temperature. Predictions are based on models modified to include a time delay model (Model ID = 2.4) or a sigmoidal decay function (Model ID = 2.5).

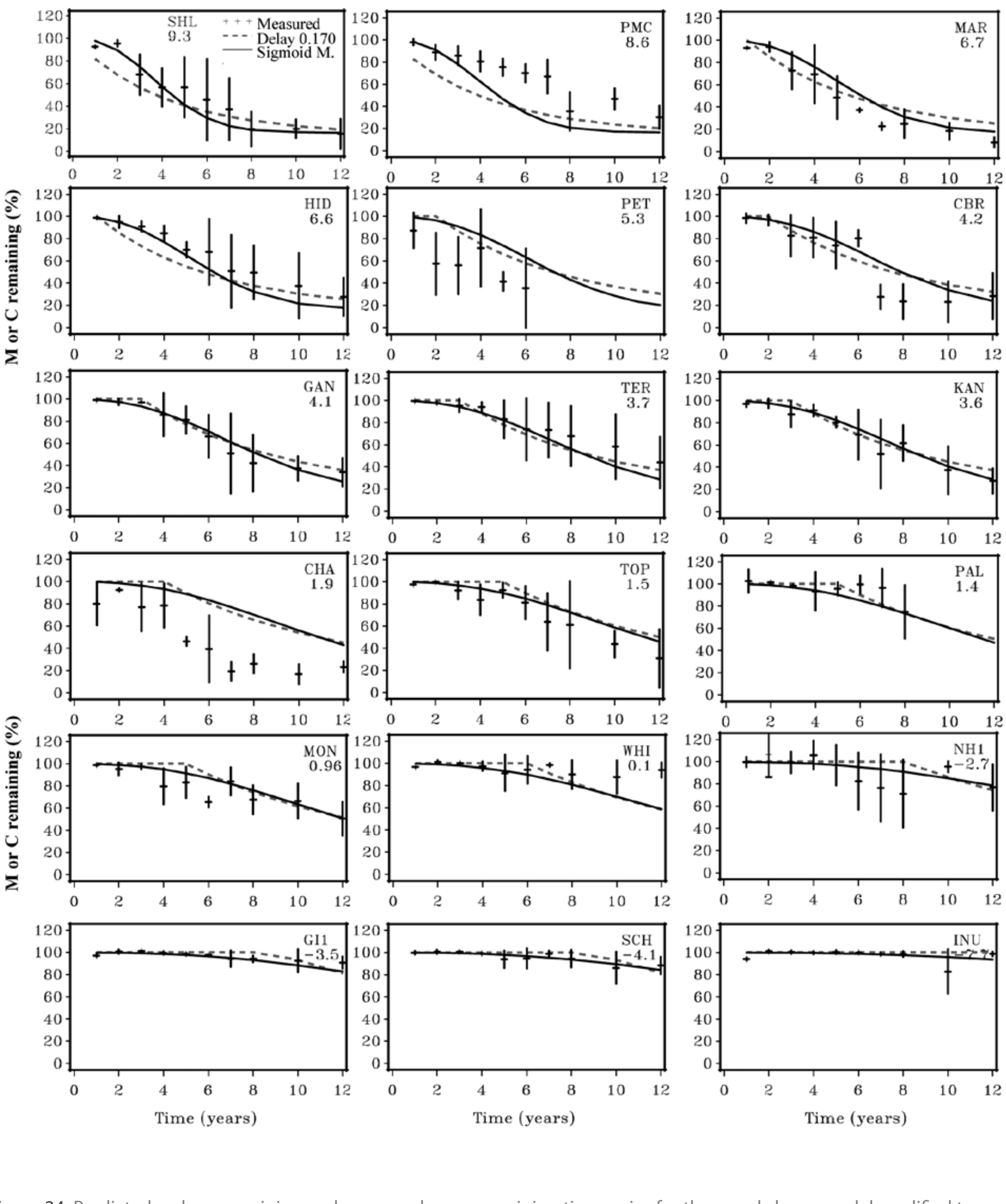

Figure 24. Predicted carbon remaining and measured mass remaining time series for the wood-decay model modified to include a time delay (dashed line, Model ID = 2.4) and a sigmoidal function (solid line, Model ID = 2.5), both with $\tau_{c2} = 0.170$.

4.7 Modify model: delayed transfer from holding pool

Yet another approach was tested to determine if modifying the decay method could substantially reduce the error. Thus far, the sigmoidal function shows the largest reduction in error, but this function is difficult to implement in CBM-CFS3, as it would require tracking the cohorts through time. A simpler approach was to modify the model to include a holding pool with a delay in the transfer of material to the fast pool (Model ID=2.6) in another approximation of the initial slow phase of decomposition. Woody material was incrementally transferred from a holding pool to the fast pool, based on the time delay estimated in Section 4.6. For example, if the time delay was estimated to be two years, then 50% of the carbon would be transferred to the fast pool each year. A 10-year time delay would transfer 10% of the carbon to the fast pool each year.

The process of finding optimal decay parameters was repeated. The proportion transferred to the slow pool (τ_{c2}) was varied between 0.160 and 0.185, and for each τ_{c2}, k_{b2} was varied by 0.002 yr $^{-1}$ between 0.192 yr $^{-1}$ and 0.292 yr $^{-1}$, and Q_2 was varied by 0.02 from 1.72 to 2.72. Adjusted parameters for the slow pool were used (k_{b4}= 0.015yr $^{-1}$, Q_4= 2.65).

For each set of decay parameters, the absolute error was estimated, as was the absolute error after 12 years of decomposition. Twenty-five hundred (2500) error estimates were calculated from the grid of decay parameters, and the lowest 40th percentiles of these errors were estimated for $\bar{E}_a$ and E_{12} (Method 1). There were 10 overlapping cases of k_{b2} and Q_2 for the lowest 40th percentiles of $\bar{E}_a$ and E_{12} for τ_{c2}= 0.160. There were 47 cases of overlap for τ_{c2}= 0.170, 109 cases for τ_{c2}= 0.180, and 141 cases for τ_{c2}= 0.185. For each τ_{c2}, the base decay rate averaged ~0.22 yr $^{-1}$, and the temperature quotient averaged from 3.58 to 3.68 (Table 16).

Table 16. Optimal fast pool decay parameters and associated error for a modified model that included a holding pool with a delayed transfer, and using adjusted slow pool parameters (k_{b4}= 0.015 yr $^{-1}$ and Q_4= 2.65)

Model ID	Scenario	k_{b2} (yr $^{-1}$)	Q_2	τ_{c2}	$\bar{E}_a$ (%)
2.6	Delayed transfer	0.220	3.68	0.160	9.9
		0.219	3.59	0.170	9.9
		0.221	3.58	0.180	9.8
		0.221	3.58	0.185	9.8

Adding the holding pool with transfer delay (Model ID=2.6) reduced the absolute error by ~2% and increased the base decay rate and the temperature quotient in comparison to optimal decay parameters (Model ID=2.3). Compared to the time delay model without a holding pool (Model ID=2.4), the temperature modifier was much higher, and errors were similar.

4.8 Modify model: decayed transfer from holding pool

The model was modified to transfer material from a holding pool to the fast pool using a power series decay (Model ID=2.7) to approximate of the initial slow phase of decomposition. Woody material was transferred from a holding pool to the fast pool based on decay with a base decay rate (k_b) and the same temperature quotient as the fast pool. The decay of the holding pool did not include a release of carbon to the atmosphere or a transfer of material to the slow pool.

With this added transfer decay, the process of finding optimal decay parameters was repeated.

The proportion transferred to the slow pool (τ_{c2}) was varied between 0.160 and 0.185, and for each τ_{c2}, k_{b2} was varied by 0.01 yr $^{-1}$ between 0.1 yr $^{-1}$ and 0.4 yr $^{-1}$, Q_2 was varied by 0.05 from 2.5 to 4.5, and the base decay rate of the holding pool was varied by 0.01 yr $^{-1}$ between 0.4 yr $^{-1}$ and 0.6 yr $^{-1}$. Adjusted parameters for the slow pool were used (k_{b4}= 0.015yr $^{-1}$, Q_4= 2.65).

For each set of decay parameters, the absolute error was estimated, as was the absolute error after 12 years of decomposition. Twenty-four hundred (2400) error estimates were estimated from the grid of decay parameters, and the lowest 12th percentiles of these errors were estimated for $\bar{E}_a$ and E_{12} (Method 1). Many cases had overlapped errors, as some cases had the same k_{b2}, Q_2, and τ_{c2}, but several values of k_b. Average values of k_{b2} and Q_2 were estimated as usual, and k_b was selected as the average of values within one standard deviation of averaged k_{b2} and Q_2. There were 14 overlapping cases of k_{b2} and Q_2 for the lowest 12th percentiles of $\bar{E}_a$ and E_{12} for τ_{c2}= 0.160. There were 37 cases of overlap for τ_{c2}= 0.170, 71 cases for τ_{c2}= 0.180, and 91 cases for τ_{c2}= 0.185. For each τ_{c2}, the base decay rate averaged ~0.35 yr $^{-1}$ and the temperature quotient averaged ~3.5 (Table 17).

Table 17. Optimal fast pool decay parameters and associated error for a modified model that included a holding pool with decayed transfer, and using adjusted slow pool parameters (k_{b4}= 0.015 yr $^{-1}$ and Q_4= 2.65)

Model ID	Scenario	k_{b2} (yr $^{-1}$)	Q_2	τ_{c2}	k_b (yr $^{-1}$)	$\bar{E}_a$ (%)
2.7	Decayed transfer	0.346	3.47	0.160	0.423	9.4
		0.348	3.47	0.170	0.429	9.4
		0.350	3.50	0.180	0.444	9.5
		0.351	3.50	0.185	0.436	9.4

Adding the transfer decay (Model ID=2.7) reduced the absolute error by ~2.5% and increased the base decay rate compared to predictions based on optimal decay parameters (Model ID=2.3). Figure 25 shows time series of absolute and average errors for the transfer delay model, the sigmoidal model, and the decay transfer model.

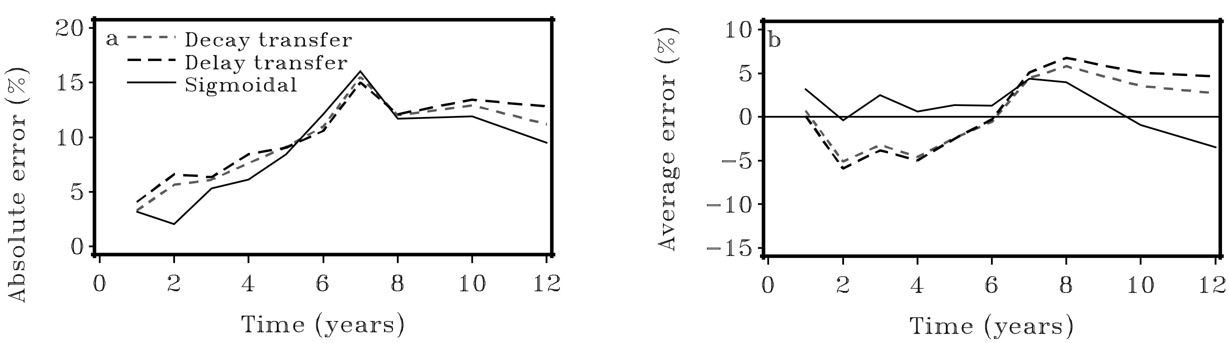

Figure 25. Time series of (a) absolute error (E_a) and (b) average error (E) for the model modified to include a holding pool with a delayed transfer (Model ID = 2.6) or with a decayed transfer (Model ID = 2.7), and for the model with a sigmoidal function (Model ID = 2.5).

Overall, the reduction in error between measurements and predictions was modestly reduced by using varying decomposition rates and by accommodating a delay in decomposition. The lowest errors were found for a sigmoidal decay function, which is difficult to implement within the model's present structure.

5. Summary and conclusions

This study examined the ability of the dead organic matter submodel of the Carbon Budget Model of the Canadian Forest Sector (CBM-CFS3) to predict litter and wood decay rates for 16 sites across Canada. Model predictions were compared to data from CIDET, a national litterbag study that included nine litter types and 12 years of decomposition time series.

Results from this study include possible revisions to CBM-CFS3's submodel decomposition parameters and alternative decay functions that would further improve model fit to data. These improvements contribute to reducing uncertainty of the model predictions, which would increase confidence in the model's ability to accurately predict carbon stocks and fluxes.

CBM-CFS3 was first developed prior to the availability of CIDET data: some parameter values in the decomposition submodel were selected based on literature from outside of Canada and on expert judgement in the early 1990s. The temperature quotients were assumed to be 2, the proportion transferred to the slow pool was assumed to be 0.170, and base decay rates for the fast and medium pool were based on softwood forest types of the moderate temperate ecoclimatic provinces (Kurz et al. 1992). These parameter values were considered in combination to ensure that model predictions would be robust over the wide range of climatic conditions encountered in Canada. Model predictions based on these early parameter values were shown to give predictions that were reasonably close to the CIDET measurements, thus demonstrating that expert judgement can be used to constrain initial model parameters where data are lacking. Model validation can then be conducted once experimental data become available.

CIDET was initiated following the 1989 CBM workshop, during which the initial design for the first version of the CBM-CFS model was proposed and refined. CIDET was established in response to the paucity of data on long-term litter decay, and involved deployment of almost 11 000 litterbags in a range of forested ecoclimatic regions across Canada. These data have had a wide-ranging effect, as they have already allowed for quantitative assessment of model parameters in two carbon dynamics models (Palosuo et al. 2005; this study) and testing of combined carbon and nitrogen models (Zhang et al. 2008); they have also contributed to the understanding of the effects of climate and litter quality on decomposition processes (Trofymow et al. 2002; Preston et al. 2000; Moore et al. 2006).

5.1 Foliar litters

A subset of the CIDET data that includes forested sites and tree foliar litters (16 sites; 8 litters) were compared to model predictions. Predictions using default parameters yielded an absolute error of 14.1%, which was reduced to 7.5% when optimized parameters were used, and could be further reduced to 5.2% with additional changes to model structure.

Optimal decay parameters were determined by minimizing errors between predicted and measured carbon remaining time series. A grid of decay parameters was used to produce 1500 predicted time series, and absolute error between measurements and predictions was determined. Table 18 contains a summary of the decay parameters that corresponded to the smallest errors. Using these optimized parameters, predicted carbon remaining closely matched the measurements.

Table 18. Summary of very fast pool optimal decay parameters and absolute errors for foliar litters

Model ID	Scenario	k_{b1} (yr $^{-1}$)	Q_1	τ_{c2}	k_{b4} (yr $^{-1}$)	Q_4	$\bar{E}_a$ (%)
1.0	Default very fast and slow pool decay parameters	0.500	2.00	0.170	0.0032	0.9	14.1
1.1	Default slow pool parameters	0.376	2.83	0.180	0.0032	0.9	7.5
		0.390	2.90	0.185			7.5
		0.403	2.95	0.190			7.4
1.3	Adjusted slow pool parameters	0.350	2.65	0.180	0.015	2.65	7.7
		0.360	2.70	0.185			7.6
		0.373	2.78	0.190			7.6
1.6	Summer precipitation	0.354	2.92	0.170	0.015	2.65	6.0
		0.371	2.96	0.180			5.9
		0.381	3.0	0.185			5.8
		0.391	3.03	0.190			5.7
1.8	Summer and winter precipitation	0.326	2.85	0.170	0.015	2.65	5.3
		0.343	2.92	0.180			5.2
		0.354	2.96	0.185			5.2
		0.362	2.99	0.190			5.2
1.9	Summer, winter precipitation and AUR/N	0.330	2.80	0.170	0.015	2.65	5.3
		0.346	2.86	0.180			5.2
		0.354	2.89	0.185			5.2
		0.362	2.92	0.190			5.2

The process of finding optimal decay parameters was repeated for adjusted slow pool parameters (Environment Canada 2007). The absolute error between predictions and measurements was reduced from 14.1% to 7.5% when optimal decay parameters were used.

It is recommended that the very fast pool decay parameters be changed for future model runs. The process of finding optimal decay parameters was repeated for several other scenarios, including separate coniferous and deciduous litter types. Coniferous litters had larger base decay rates and temperature quotients than deciduous litters had. Model users may wish to alter the decay rates to accommodate their specific applications.

Regression of the errors with all measured climate variables found that summer precipitation was a significant variable. Including summer and winter precipitation further reduced absolute errors between measurements and predictions to ~5%. Modifying the model to include a litter-quality variable had a modest effect on the overall error, but errors were reduced for some specific litters—in particular, western redcedar. These findings suggest that future research is needed on the effects of precipitation on litter decomposition for inclusion in CBM-CFS3.

5.2 Wood blocks

A subset of the CIDET data that included 16 forested sites and surface wood blocks were compared to model predictions. Initially, model predictions used default decay parameters for the fast and slow pools. Predicted carbon remaining for wood-block litters markedly underestimated carbon remaining at colder sites and overestimated carbon remaining at warmer locations after 12 years of decomposition.

Optimal decay parameters were determined by minimizing errors between predicted and measured carbon remaining time series. A grid of decay parameters was used to produce 2500 predicted time series, and absolute error between measurements and predictions was determined. Decay parameters associated with the smallest errors had similar base decay rates but larger temperature quotients than the default decay parameters had. Default and optimized parameters are summarized in Table 19. Using these decay parameters, predicted carbon remaining after 12 years was closer to measurements, but the absolute error between predictions and measurements was reduced by only 2%.

Table 19. Summary of decay parameters and absolute errors for surface wood blocks

Model ID	Description	k_{b2} (yr^{-1})		Q_2	τ_{c2}	k_{b4} (yr^{-1})	Q_4	$\bar{E}_a$ (%)
2.0	All default decay parameters	0.1435		2.00	0.170	0.0032	0.9	14.2
2.1	Default slow pool parameters: Method 1	0.211		4.15	0.160	0.0032	0.9	12.0
		0.214		4.19	0.170			11.9
2.2	Default slow pool parameters: Method 2	0.197		3.68	0.160	0.0032	0.9	11.9
		0.204		3.72	0.170			12.0
		0.212		3.83	0.180			12.1
		0.216		3.84	0.185			12.0
2.3	Adjusted slow pool parameters	0.185		3.46	0.160	0.015	2.65	11.9
		0.187		3.46	0.170			11.8
		0.187		3.49	0.180			11.8
		0.190		3.51	0.185			11.7
2.4	Time delay	0.227		2.13	0.160	0.015	2.65	10.1
		0.230		2.11	0.170			10.1
		0.232		2.09	0.180			10.1
		0.233		2.09	0.185			10.1
2.5	Sigmoidal decay	R_b (yr^{-1})	S					
		0.232	2.33	3.33	0.160	0.015	2.65	8.7
		0.235	2.36	3.31	0.170			8.7
		0.239	2.37	3.34	0.180			8.6
		0.238	2.40	3.31	0.185			8.6
2.6	Delayed transfer holding pool	0.220		3.68	0.160	0.015	2.65	9.9
		0.219		3.59	0.170			9.9
		0.221		3.58	0.180			9.8
		0.221		3.58	0.185			9.8
2.7	Decayed transfer holding pool	0.346		3.47	0.160	0.015	2.65	9.4
		0.348		3.47	0.170			9.4
		0.350		3.50	0.180			9.5
		0.351		3.50	0.185			9.5

The process of finding optimal decay parameters was repeated for adjusted slow pool parameters (Environment Canada 2007). Optimal decay parameters for this scenario differed slightly, but temperature quotients were consistently higher than the default value of 2. However, the reduction in error was only ~2%— possibly insufficient to warrant changing from the default fast pool decay parameters.

Predicted carbon remaining time series for the model with optimal parameters had relatively large errors when compared to measured mass remaining. The large errors were due, in part, to the inherent variability in wood-block decay. Additionally, the data were not fit well by the assumed power series decay; a sigmoidal function was identified as preferable. The model was modified to change the decay from a power function to a sigmoidal function, and subsequent errors were reduced by ~3%.

Several modifications to the model with power series decay were made, including incorporating a one-year time delay or introducing a holding pool with a temperature-dependant delayed or decayed transfer to the fast pool. These modifications to the power function model further reduced errors from the optimal fit model by 1.7% to 2.5% (3.1% to 4.9% error reduction from default), whereas the modification to include a sigmoidal function reduced errors by 3.1% (5.5% error reduction from default). This suggests that future revisions to the fast pool decay model could include optimized parameter values and modifications to the functional form of the decay.

5.3 Future validation

Not all of the model modifications suggested in this study will be immediately implemented into the CBM-CFS3. In some cases, suggested modifications require introduction of additional pools and more data to improve model parameterization.

Additional long-term decomposition data are needed to validate some parameter values and to better constrain some of the low decay rates of slowly decaying pools. Model uncertainty could be reduced further if data on fine-root litter decay were available, particularly if the proportion transferred to the atmosphere were known. Longer time series would be beneficial for assessing decay of fine woody debris (fast), as the time series for wood blocks at cold sites was not well described by asymptotic decay. The effect of the restricted time series on the optimization procedure was to increase the temperature quotient to much more than the default value of 2, thus dramatically reducing decay rates at cold sites.

Further data are also required on the effects of bark on fine-wood decomposition and the effects of macrofauna exclusion due to the use of mesh litterbags. The CIDET results did not provide information relevant to the parameterization of decay rates for the coarse woody debris pool, because wood-block sizes were small and not representative of coarse woody debris. Additional long-term data on coarse woody debris decay are needed.

With improvements to model decay parameters resulting from this study, additional work is being undertaken to calibrate the model against soil-carbon plot data (Shaw et al. 2008) and against ground-plot data collected for Canada's National Forest Inventory (Gillis et al. 2006).

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Appendix A. Weather Data

Annual and monthly climate data for each CIDET site were derived from daily (in some cases, hourly) Meteorological Service of Canada (MSC) weather records collected at climate stations mostly located within 10 km of the site. Table A1 lists names and positions for all MSC weather stations that provided data used in estimating annual climate data.

Calculation of monthly means followed rules used by the MSC for missing data; if more than three consecutive days were missing or more than five days were missing in a month, the monthly value was set to missing. All missing data were replaced with 30-year climate normals.

Climate data were also obtained from the Landscape Analysis and Application Section, based on modelled climate data (McKenney et al. 2001). Climate data at any given location were derived, based on a thin plate spline smoothing algorithm (ANUSPLIN) applied to climate. Predicted and interpolated ANUCLIM monthly temperature and precipitation data were interpolated to CIDET sites and matching locations of the MSC stations. CIDET sites were chosen for their proximity to MSC stations, but on occasion MSC stations were relocated, closed, or ceased to function. Due to these problems, weather experienced at the CIDET site could be different from the weather recorded at the nearest MSC station: in those cases, ANUCLIM data were substituted.

There were four sites at which ANUCLIM temperatures for MSC station locations were very similar to the MSC temperatures, but where a greater than 0.5° C difference existed between ANUCLIM temperatures at the CIDET sites and the MSC temperatures. These were Batoche (which used the distant Prince Albert weather station) Topley, Shawnigan Lake, and Hidden Lake (which are located at higher elevations than their nearest weather stations). Temperature data for these four sites were replaced with ANUCLIM interpolated data. Temperatures averaged from 1992 to 2004 changed from 1.34° C to 1.97° C at Batoche, 3.35° C to 1.5° C at Topley, 7.35° C to 6.55° C at Hidden Lake, and 10.04° C to 9.33° C at Shawnigan Lake.

Precipitation data for Hidden Lake was replaced with ANUCLIM data, because there was greater than a 100-mm difference between the interpolated site and MSC station data, whereas the precipitation interpolated to the MSC station was close to the measured precipitation. Average annual precipitation at Hidden Lake changed from 528 mm to 717 mm.

Table A1. Meteorological Service of Canada weather station data used for CIDET sites

Site	Station Number	Station Name	Latitude (°)	Longitude (°)	Elevation (m)
BAT	4056240	Prince Albert	53.13	105.41	428
CBR	8403096	CB Rocky Harbour	49.35	57.54	40
	8403097	8403096 moved	49.34	57.55	40
CHA	6061361	Chapleau Airport	47.49	83.21	446
GAN	8401700	Gander Int'l Airport	48.57	54.34	151
GI1	5061001	Gillam Airport	56.21	94.42	145
HID	1160483	Armstrong Hullcar	50.30	119.13	505
	1164729	Lumby	50.23	118.95	500
	1167337	Silver Creek	50.55	119.35	419
INU	2200150	Inuvik Airport	68.18	133.29	68
	2202570	Inuvik Airport	68.18	133.29	68
KAN	3053600	Kananaskis	51.02	115.02	1391
MAR	7025250	Montreal/Dorval Airport	45.28	73.45	31
	7027280	Ste Genevieve	45.30	73.51	23
MON	7016731	Ruisseau-Bureau	47.10	71.14	587
	7041330	Chateau Richer	46.97	71.03	
	7042388	Foret Montmorency	47.19	71.09	790
NH1	5062922	Thompson Airport	55.48	97.52	215
PAL	4056240	Prince Albert	53.13	105.41	428
PET	6106400	Petawa Natnl Forestry	46.00	77.26	168
	610FC98	Petawawa Hoffman	45.53	77.15	153
PMC	1026270	Port Hardy Airport	50.41	127.22	22
SCH	8504175	Wabush Lake A	52.56	66.52	551
SHL	1017230	Shawnigan Lake	48.39	123.37	137
TER	4057202	Saskatoon Water TP	52.07	106.41	483
TOP	1078209	Topley Landing	54.49	126.10	722
WHI	2101300	Whitehorse WSO	60.72	135.06	707
	2101400	Whitehorse Riverdale	60.72	135.02	643
	2101415	Whitehorse Air	60.43	135.04	703

Appendix B. Comparison to buried wood-block data

A set of wood blocks was buried at depths from 10 cm to 30 cm in mineral soil. In this section, the process of finding optimal decay parameters for surface wood blocks (Section 4.0) was repeated for the buried wood blocks. In general, buried blocks had higher decay rates and lower temperature quotients than surface blocks had.

B.1 Optimal decay parameters, Method 2

The process of determining the optimal decay parameters using Method 2 (Section 4.4) was repeated for the buried blocks using adjusted slow pool parameters (k_{b4}= 0.015yr $^{-1}$, Q_4= 2.65). This method permits only small differences in base decay rates and temperature quotients, and estimates three errors: E_{12}, mean absolute residuals from the exponential fit, and mean absolute errors from the fit of Equation 25. The smallest 52nd percentiles were estimated for each of these errors, and optimal decay parameters were determined where these errors overlapped.

Eleven cases satisfied all of the above restrictions for τ_{c2}= 0.160. There were 12 cases for τ_{c2}= 0.170, 13 case for τ_{c2}= 0.180, and 16 cases for τ_{c2}= 0.185. The optimal decay base decay rate was higher (~0.23 yr $^{-1}$) for the buried blocks than for the surface blocks, and the temperature quotients were slightly smaller (~3.4). Results are listed in Table B1, with results from surface blocks (Table 13) shown for reference.

B.2 Time delay model

The process of determining optimal parameters for the time delay model (Section 4.6) was repeated for the buried blocks. Mass remaining time series were fit to a sigmoidal function, and the time to reach 90% mass remaining was linearly regressed against average temperature. The regression result was:

$$t_{90} = -0.499T + 4.712$$

where t_{90} was the time (in years) to reach 90% mass remaining, and T is the 12-year-average temperature (r^2= 0.64, n=16).

With this added time delay, the process of finding optimal decay parameters was repeated.

The proportion transferred to the slow pool (τ_{c2}) was varied between 0.160 and 0.185, and for each τ_{c2}, k_{b2} was varied by 0.01 yr $^{-1}$ from 0.212 yr $^{-1}$ to 0.310 yr $^{-1}$, and Q_2 was varied by 0.05 from 2.22 to 3.20. The slow pool was modelled using adjusted slow pool parameters (k_{b4}= 0.015yr $^{-1}$, Q_4= 2.65).

For each set of decay parameters, the absolute error was estimated, as was the absolute error after 12 years of decomposition. Twenty-five hundred (2500) error estimates were calculated from the grid of decay parameters, and the lowest 15th percentiles of these errors were estimated for E_a and E_{12} (Method 1). There were seven cases corresponding to overlapping E_a and E_{12} for τ_{c2}= 0.160, 16 cases for τ_{c2}= 0.170, 27 cases for τ_{c2}= 0.180, and 30 cases for τ_{c2}= 0.185. For each τ_{c2}, the base decay rate averaged from 0.23 yr $^{-1}$ to 0.24 yr $^{-1}$, and the temperature quotient was ~1.9 (Table B2).

Compared to decay parameters for surface blocks, buried blocks had slightly higher base decay rates, lower temperature quotients, and shorter time delays.

B.3 Sigmoidal model

The process of finding optimal decay parameters for the sigmoidal model was repeated for the buried wood blocks following the method outlined in Section 4.7.

For each τ_{c2}, R_b averaged from 0.236 yr $^{-1}$ to 0.244 yr $^{-1}$, the temperature quotient averaged ~2.78, and S averaged 2.1. Compared to decay parameters for surface blocks, the R_b decay parameters were larger, the shape factor was smaller, and the temperature quotients were smaller. See Table B3, with results for surface blocks (Table 15) shown for reference.

Table B1. Optimal fast pool decay parameters and associated error for surface and buried wood blocks, using adjusted slow pool decay parameters (k_{b4}=0.015, Q_4=2.65)

Model ID	Scenario	k_{b2} (yr $^{-1}$)	Q_2	τ_{c2}	$\bar{E}_a$ (%)
3.1	Buried Blocks: Method 2	0.221	3.35	0.160	12.0
		0.230	3.39	0.170	12.1
		0.231	3.40	0.180	12.1
		0.232	3.40	0.185	12.1
2.3	Surface Blocks: Method 2	0.185	3.46	0.160	11.9
		0.187	3.46	0.170	11.8
		0.187	3.49	0.180	11.8
		0.190	3.51	0.185	11.7

Table B2. Optimal fast pool decay parameters and associated error for surface and buried wood blocks, using a time-delay model and adjusted slow pool decay parameters (k_{b4}=0.015, Q_4=2.65)

Model ID	Scenario	k_{b2} (yr $^{-1}$)	Q_2	τ_{c2}	$\bar{E}_a$ (%)	Time delay
3.2	Buried blocks: time delay	0.232	1.89	0.160	10.4	t_{90} = -0.499T + 4.712
		0.234	1.90	0.170	10.4	
		0.238	1.89	0.180	10.4	
		0.240	1.89	0.185	10.4	
2.4	Surface blocks: time delay	0.227	2.13	0.160	10.1	t_{90} = -0752T + 6.834
		0.230	2.11	0.170	10.1	
		0.232	2.09	0.180	10.1	
		0.233	2.09	0.185	10.1	

Table B3. Optimal fast pool decay parameters and associated error for surface and buried wood blocks, using a sigmoidal decay function and adjusted slow pool decay parameters (k_{b4}=0.015, Q_4=2.65)

Model ID	Scenario	R_b (yr $^{-1}$)	S	Q_2	τ_{c2}	$\bar{E}_a$ (%)
3.3	Buried blocks: sigmoidal function	0.236	2.1	2.78	0.160	9.8
		0.239	2.1	2.78	0.170	9.8
		0.242	2.1	2.77	0.180	9.7
		0.244	2.1	2.78	0.185	9.7
2.5	Surface blocks: sigmoidal function	0.232	2.33	3.33	0.160	8.7
		0.235	2.36	3.31	0.170	8.7
		0.239	2.37	3.34	0.180	8.6
		0.238	2.40	3.31	0.185	8.6

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