Assessing model performance in forecasting long-term individual tree diameter versus basal area increment for the primary Acadian tree species

Matthew B. Russell, Aaron R. Weiskittel, and John A. Kershaw, Jr.

Abstract: Tree basal area (ba) or diameter at breast height (dbh) are universally used to represent tree secondary growth in individual tree based growth models. However, the long-term implications of using either ba or dbh for predictions are rarely fully assessed. In this analysis, Δba and Δdbh increment equations were fit to identical datasets gathered from six conifer and four hardwood species grown in central Maine. The performance of Δba and Δdbh predictions from nonlinear mixed-effects models were then compared with observed growth measurements of up to 29 years via a Monte Carlo simulation. Two evaluation statistics indicated substantial improvement in forecasting dbh using Δdbh rather than Δba. Root mean squared error (RMSE) and percentage mean absolute deviation (MAD%) were reduced by 14% and 15% on average, respectively, across all projection length intervals (5–29 years) when Δdbh was used over Δba. Differences were especially noted as projection lengths increased. RMSE and MAD% were reduced by 24% when Δdbh was employed over Δba at longer projection lengths (up to 29 years). Simulations found that simulating random effects rather than using local estimates for random effects performed as well or better at longer interval lengths. These results highlight the implications that selecting a growth model dependent variable can have and the importance of incorporating model uncertainty into the growth projections of individual tree based models.

Résumé : La surface terrière de l’arbre (G) ou le diamètre à hauteur de poitrine (D) sont universellement utilisés pour représenter la croissance secondaire dans les modèles de croissance d’arbre individuel. Cependant, les implications à long terme de l’emploi de G ou D pour les prédictions sont rarement pleinement évaluées. Dans cette analyse, les équations d’accroissement ΔG et ΔD ont été ajustées à des ensembles de données identiques recueillies à partir de six conifères et quatre feuillus dans le centre du Maine. La performance des prédictions de ΔG et ΔD à l’aide des modèles non linéaires à effets aléatoires a été comparée aux mesures de croissance prises sur une période de 29 ans en utilisant une simulation de Monte Carlo. Deux statistiques d’évaluation indiquent une amélioration substantielle de la prévision de D en utilisant ΔD plutôt que ΔG. Lorsque ΔD a été utilisé à la place de ΔG, l’écart type résiduel et l’écart moyen absolu en pourcentage ont été réduits respectivement de 14 et 15 % en moyenne pour tous les horizons de projection (5–29 ans). Ces différences étaient particulière-ment marquées lorsque les horizons de projection s’allongeaient. En effet, l’écart type résiduel et l’écart moyen absolu en pourcentage ont été réduits de 24 % lorsque ΔD a été employé au lieu de ΔG pour les horizons de projection plus longs (jusqu’à 29 ans). Les simulations ont montré que la simulation des effets aléatoires permet d’atteindre un bon ajustement que les estimations locales des effets aléatoires lorsque les horizons sont longs. Ces résultats mettent en évidence, d’une part, les impacts causés par la sélection de la variable dépendante pour un modèle de croissance et, d’autre part, l’importance d’intégrer l’incertitude des modèles dans les projections de croissance par des modèles d’arbre individuel.

[Traduit par la Rédaction]

Introduction

Diameter (at breast height, dbh) or basal area (ba) can be used to predict secondary growth of individual trees in forest growth models. The circumference of the tree at breast height is commonly measured in the field using diameter tapes, and this value is then converted into corresponding diameter or basal area. Because basal area increment measures the increase in geometric area of the bole at breast height measured at two time periods, it represents individual tree increment differently than does the linear distance measure of diameter.

Given that a significant portion of the variability in basal area increment (Δba) can be attributed to initial tree diameter, Δba will generally display a higher correlation with initial tree diameter than will diameter increment (Δdbh; West 1980). Employing basal area as the dependent variable in tree increment models is also appealing because basal area is directly related to silvicultural practices (Peng 2000). Despite the relative importance of these assumptions, relatively little work has been done quantitatively comparing effectiveness of Δdbh or Δba as the dependent variable in growth modeling.

In a study directly comparing performance of Δdbh and Δba equations developed for even-aged Eucalyptus forests in
Betula papyrifera (L.), paper birch, (L.), and eastern white pine (Pinus strobus L.) are the dominant species in this area. Coniferous species include black spruce (Picea mariana (B.S.G.) Carr.), northern white-cedar (Thuja occidentalis L.), and balsam fir (Abies balsamea (L.) Mill.), which are described as red spruce (P. rubens Sarg.), gray birch (Betula populifolia Marsh.), and quaking aspen (Populus tremuloides Michx.).

Ten contrasting silvicultural treatments were applied between 1952 and 1957 by the USFS. These treatments, each with two replicates, were located in a ~170 ha area of the PEF. Twenty managed stands resulted from the various silvicultural treatments that included selection systems based on 5-, 10-, and 20-year harvest cycles, an unregulated commercial harvest, a modified and flexible diameter limit harvest, a two- and three-stage uniform shelterwood treatment, a three-stage shelterwood treatment with precommercial thinning, and an unmanaged natural area (Sendak et al. 2003).

**Data**

A network of permanent sample plots was established along transects nested within each stand at the start of the study. Plots consisted of a nested design with 0.081 and 0.020 ha circular plots sharing the same plot center. All trees ≥ 11.43 cm dbh were measured in the 0.081 ha plot, whereas trees with dbh ≥ 1.27 cm and < 11.43 cm were measured in the 0.020 ha plot. Beginning in 1974, individual trees were numbered in these plots, and stand, plot number, tree number, species, dbh, and live or dead status were recorded. Tree dbh measurements were made with a diameter tape. Plots were initially measured and then remeasured at 5-year intervals. Beginning in 2000, a 0.008 ha plot was nested within the plot, and trees ≥ 6.35 cm dbh were measured on the original 0.020 ha plots and trees ≥ 1.27 cm dbh were measured in the new 0.008 ha plots. The remeasurement interval was changed from 5 years to 10 years.

Stands were selected from treatments containing individually numbered trees with consecutive dbh measurements and where harvesting did not occur during the growth interval. Growing period length of the stands ranged from an average of 3.6 to 6.6 years, and cumulative years of diameter measurement reached 29 years (Table 1).

Observed individual tree dbh increment (Δdbh; cm) was defined as the difference between two consecutive dbh measurements. These dbh measurements were converted to basal area to compute tree basal area increment (Δba; m²). Because of their abundance at the PEF and their ecological and commercial importance to the Acadian forest region, the following conifer species were chosen to develop species-specific increment equations: balsam fir, red spruce, white spruce, northern white-cedar, and eastern white pine. Similarly, equations for the following hardwood species were developed: red maple, paper birch, gray birch, and quaking aspen (Fig. 1). Because red and black spruce hybridize extensively at the PEF (Saunders and Wagner 2008), no distinction between the two species is made in the field. Hence, these species are grouped and are referred to as red spruce throughout. The number of growth observations varied between species (Table 2).

**Model development**

The Wykoff (1990) model form was selected for use in this analysis:

\[
\Delta gr = \beta_1 dbh^\beta_2 \exp\left(\frac{\beta_3 dbh^2}{100}\right)
\]
where Δgr is tree diameter (Δdbh; cm) or basal area (Δba; m²) increment and dbh (cm) is initial tree diameter at breast height. In terms of general performance and magnitude of parameter estimates, preliminary analyses indicated that eq. 1 fit the data well for the species examined.
Using a nonlinear mixed-effects modeling approach (Pin-
heiro and Bates 2000), eq. 1 was structured in a manner that
took into account both fixed and random parameters:

$$\Delta gr_{ijk} = (\beta_1 + b_i + b_j)dbh_{ijk}^c \exp \left( \frac{\beta_2 dbh_{ijk}^3}{100} \right) + \epsilon_{ijk}$$

where $\Delta gr_{ijk}$ is the annual observed increment of the $k$th tree
found in the $j$th plot in the $i$th stand, $\beta_1$, $\beta_2$, and $\beta_3$ are population-
level fixed effect parameters, $b_i$ and $b_j$ are random effect
parameters for the $i$th stand and the $j$th plot, respectively, and $\epsilon_{ijk}$ is the model error term, where $\epsilon_{ijk} \sim N(0, \mathbf{R}_{ijk})$ and
$\mathbf{R}_{ijk}$ is the variance-covariance matrix for the model error term.

To test whether or not $ba$ would serve better as an inde-
pendent variable than $dbh$ in predicting $\Delta dbh$, a determi-
nistic prediction was made using those parameters. Simulated data were
defined as the subsample from the data used in model develop-
ment. This resulted in simulating growth for 3784 trees from
the previous year’s tree size. During the same Monte Carlo
run, random error terms and model error terms were held
costant throughout the entire length of the simulation. An-
nual variability was assigned at each annual time step. Pre-
dicted $\Delta dbh$ and $\Delta ba$ occurred within the same growth step,
so variability attributed to climate would increase or decrease
by the same relative amount for both $\Delta dbh$ and $\Delta ba$. Be-
cause correlations between equation parameters were relatively
low, it was assumed to have no influence on model predictions.

Two sets of simulations were run to test the influence of
the model random effects on the $\Delta dbh$ and $\Delta ba$ predictions.
In one simulation, the local random effects for each stand ($b_i$)
and plot ($b_j$) were extracted from model output and used
throughout the simulation. In the other, random effects were
simulated. The $b_i$ and $b_j$ random effects were simulated from
a normal distribution assuming a mean of 0 with their
associated standard error obtained from model output, i.e.,
$\sim N(0, \text{SE}(b_i))$ and $\sim N(0, \text{SE}(b_j))$.

For each of the 110 plots used in the simulation, a 1000-
run Monte Carlo simulation was performed. Equations pro-
vided annual predictions, and simulations were run up to the
maximum observed cumulative growing period length
(29 years). Simulations were carried out using R (R Develop-
ment Core Team 2009).

**Evaluation statistics**

Uncertainty in future predictions includes both systematic
and random variation. Mean bias (MB) and percentage mean
absolute deviation (MAD%) measure systematic variation,
whereas root mean squared error (RMSE) measures both
types (Kangas 1999). These measures were computed in this
analysis as follows:

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i)^2}$$

$$\text{MB} = \frac{1}{n} \sum_{i=1}^{n} (y_i - \hat{y}_i)$$

$$\text{MAD\%} = 100 \times \frac{1}{n} \sum_{i=1}^{n} \frac{|y_i - \hat{y}_i|}{\sum_{i=1}^{n} y_i}$$

where $y_i$ is the observed diameter, $\hat{y}_i$ is the mean predicted
tree diameter from the simulations, and $n$ is the number of
observations.
Table 3. Parameter estimates and standard errors for eq. 2 for predicting diameter (Δdbh) and basal area (Δba) increments using initial tree diameter (dbh) for various species using an annualized nonlinear mixed-effects fitting technique.

<table>
<thead>
<tr>
<th>Species</th>
<th>Δgr</th>
<th>β1 (SE)</th>
<th>β2 (SE)</th>
<th>β3 (SE)</th>
<th>SE(bj)</th>
<th>SE(bij)</th>
<th>ε_ijk</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Conifers</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Balsam fir</td>
<td>Δdbh</td>
<td>0.129 (0.015)</td>
<td>0.367 (0.0093)</td>
<td>-0.0242 (0.0062)</td>
<td>0.044</td>
<td>0.025</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>Δba</td>
<td>3.55×10⁻⁵ (4.4×10⁻⁶)</td>
<td>1.16 (0.008)</td>
<td>-0.0176 (0.0087)</td>
<td>0.057</td>
<td>0.026</td>
<td>1.2</td>
</tr>
<tr>
<td>Red spruce</td>
<td>Δdbh</td>
<td>0.132 (0.020)</td>
<td>0.325 (0.018)</td>
<td>-0.0247 (0.0085)</td>
<td>1.3×10⁻⁵</td>
<td>8.0×10⁻⁶</td>
<td>5.8×10⁻⁴</td>
</tr>
<tr>
<td></td>
<td>Δba</td>
<td>2.85×10⁻⁵ (4.7×10⁻⁶)</td>
<td>1.24 (0.026)</td>
<td>-0.0247 (0.0085)</td>
<td>1.3×10⁻⁵</td>
<td>8.0×10⁻⁶</td>
<td>5.8×10⁻⁴</td>
</tr>
<tr>
<td>Eastern hemlock</td>
<td>Δdbh</td>
<td>0.0945 (0.011)</td>
<td>0.550 (0.016)</td>
<td>-0.0331 (0.0046)</td>
<td>0.031</td>
<td>0.024</td>
<td>0.61</td>
</tr>
<tr>
<td></td>
<td>Δba</td>
<td>2.43×10⁻⁵ (3.2×10⁻⁶)</td>
<td>1.39 (0.018)</td>
<td>-0.0191 (0.0043)</td>
<td>8.6×10⁻⁶</td>
<td>8.6×10⁻⁶</td>
<td>2.1×10⁻⁴</td>
</tr>
<tr>
<td>Eastern white pine</td>
<td>Δdbh</td>
<td>0.186 (0.026)</td>
<td>0.432 (0.023)</td>
<td>-</td>
<td>0.069</td>
<td>0.028</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>Δba</td>
<td>3.23×10⁻⁵ (5.7×10⁻⁶)</td>
<td>1.42×10⁻⁵ (0.033)</td>
<td>-</td>
<td>1.4×10⁻⁵</td>
<td>6.8×10⁻⁶</td>
<td>1.1×10⁻³</td>
</tr>
<tr>
<td>Northern white-cedar</td>
<td>Δdbh</td>
<td>0.070 (0.013)</td>
<td>0.278 (0.047)</td>
<td>-</td>
<td>0.021</td>
<td>2.5×10⁻⁶</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>Δba</td>
<td>1.31×10⁻⁵ (2.4×10⁻⁶)</td>
<td>1.24 (0.050)</td>
<td>-</td>
<td>3.9×10⁻⁶</td>
<td>3.4×10⁻⁴</td>
<td>1.3×10⁻⁴</td>
</tr>
<tr>
<td>White spruce</td>
<td>Δdbh</td>
<td>0.0760 (0.015)</td>
<td>0.481 (0.048)</td>
<td>-0.0258 (0.018)</td>
<td>0.033</td>
<td>0.022</td>
<td>0.77</td>
</tr>
<tr>
<td></td>
<td>Δba</td>
<td>1.32×10⁻⁵ (2.9×10⁻⁶)</td>
<td>1.49 (0.059)</td>
<td>-0.0352 (0.019)</td>
<td>6.0×10⁻⁶</td>
<td>4.0×10⁻⁶</td>
<td>2.4×10⁻⁴</td>
</tr>
<tr>
<td><strong>Hardwoods</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red maple</td>
<td>Δdbh</td>
<td>0.105 (0.011)</td>
<td>0.266 (0.013)</td>
<td>-</td>
<td>0.032</td>
<td>0.032</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>Δba</td>
<td>2.69×10⁻⁵ (3.5×10⁻⁶)</td>
<td>1.12 (0.014)</td>
<td>-</td>
<td>9.3×10⁻⁶</td>
<td>1.2×10⁻⁵</td>
<td>2.7×10⁻⁴</td>
</tr>
<tr>
<td>Paper birch</td>
<td>Δdbh</td>
<td>0.0785 (0.012)</td>
<td>0.675 (0.030)</td>
<td>-0.244 (0.027)</td>
<td>0.034</td>
<td>0.024</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>Δba</td>
<td>1.97×10⁻⁵ (3.4×10⁻⁶)</td>
<td>1.49 (0.033)</td>
<td>-0.182 (0.026)</td>
<td>9.2×10⁻⁶</td>
<td>7.8×10⁻⁶</td>
<td>1.9×10⁻⁴</td>
</tr>
<tr>
<td>Quaking aspen</td>
<td>Δdbh</td>
<td>0.185 (0.015)</td>
<td>0.292 (0.020)</td>
<td>-</td>
<td>0.030</td>
<td>0.045</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>Δba</td>
<td>4.47×10⁻⁵ (4.5×10⁻⁶)</td>
<td>1.17 (0.028)</td>
<td>-</td>
<td>7.4×10⁻⁶</td>
<td>1.5×10⁻⁵</td>
<td>5.5×10⁻⁴</td>
</tr>
<tr>
<td>Gray birch</td>
<td>Δdbh</td>
<td>0.159 (0.019)</td>
<td>0.294 (0.040)</td>
<td>-0.130 (0.064)</td>
<td>0.041</td>
<td>0.050</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>Δba</td>
<td>4.81×10⁻⁵ (6.9×10⁻⁶)</td>
<td>1.022 (0.047)</td>
<td>-0.127 (0.066)</td>
<td>1.5×10⁻⁵</td>
<td>2.3×10⁻⁵</td>
<td>3.3×10⁻⁴</td>
</tr>
</tbody>
</table>
Results

Model development

For the six conifer species examined, the number of growth observations ranged from 820 for white spruce to 25,111 for balsam fir. For the four hardwood species examined, the number of observations ranged from 1887 for gray birch to 8374 for red maple. Average annual Δdbh was 0.21 and 0.18 for conifers and hardwoods, respectively. The sample Pearson’s correlation coefficient between initial tree dbh and Δba (r_{dbh,Δba}) was always higher than the correlation between dbh and Δdbh (r_{dbh,Δdbh}). For all species, r_{dbh,Δdbh} ranged from 0.049 to 0.279 and r_{dbh,Δba} ranged from 0.509 to 0.789 (Table 2). On average, r_{dbh,Δba} was 0.48 higher than r_{dbh,Δdbh} for all species.

Akaike’s and Bayesian information criterions showed that including β₁ as the mixed-effect parameter rather than β₂ resulted in slightly favorable model fits. The β₁ parameters were retained such that they displayed biologically appropriate properties, i.e., were of the proper sign and approximate magnitude. Tree dbh alone proved to be an effective predictor of individual tree increment (Table 3).

Assessing model prediction uncertainty

Growth observations were grouped into 5-year intervals according to their projection length from the initial measurement year (Fig. 2). The greatest number of plots with growth observations (99) occurred in the 6–10 year projection length interval, and the fewest number of plots (9) occurred in the 26–29 year projection length interval.

Generally, deterministic predictions were similar to stochastic predictions derived from the Monte Carlo simulation (Table 4). For all projection length intervals, evaluation statistics (eq. 3) showed favorable results when predicted Δdbh was used rather than Δba and compared with observed dbh values. Minimum values for these statistics were observed in the ≤5 year projection length interval: for stochastic simulations that used local estimates of random effects, RMSE, MB, and MAD% for Δdbh equations were 1.78 cm, 0.73 cm, and 11%, respectively. Similarly for Δba equations, RMSE, MB, and MAD% were 1.89 cm, 0.84 cm, and 13%, respectively. For simulations that simulated random effects, RMSE, MB, and MAD% for Δdbh equations were 2.10 cm, 0.71 cm, and 13%, respectively. Similarly for Δba equations, RMSE, MB, and MAD% were 2.20 cm, 0.94 cm, and 14%, respectively.

Maximum values for these statistics were observed in the 26–30 year projection length interval: for stochastic simulations that used local estimates of random effects, RMSE, MB, and MAD% for Δdbh equations were 8.66 cm, −7.25 cm, and 31%, respectively. Similarly for Δba equations, RMSE, MB, and MAD% were 10.78 cm, −9.49 cm, and 39%, respectively. For simulations that simulated random effects, RMSE, MB, and MAD% for Δdbh equations were 6.01 cm, −4.62 cm, and 22%, respectively. Similarly for Δba equations, RMSE, MB, and MAD% were 7.91 cm, −6.85 cm, and 28%, respectively. Mean bias showed that models underpredicted tree growth in all but the longest projection intervals. Generally, equations that predicted Δba using ba as the independent variable produced similar evaluation statistics to Δba equations when dbh was used as the independent variable.

When simulated random effects were used, the RMSE and MAD% were reduced on average by 15% and 16%, respectively, for conifer species across all projection length intervals when Δdbh was used over Δba. Similarly, for hardwood species, both RMSE and MAD% were reduced on average by
Table 4. Comparisons of root mean squared error and mean bias for tree diameter at breast height (Δdbh) and basal area (Δba) increment equations for projections that simulated stand- and plot-level random effects or used local estimates of random effects in a stochastic simulation (eq. 2), or used fixed effects (eq. 1) in a deterministic prediction.

<table>
<thead>
<tr>
<th>Dependent variable</th>
<th>Independent variable</th>
<th>Random effects</th>
<th>Prediction</th>
<th>Projection length (years)</th>
</tr>
</thead>
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<tr>
<td><strong>Root mean squared error</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Δdbh</td>
<td>dbh</td>
<td>Simulated</td>
<td>Stochastic</td>
<td>2.10</td>
</tr>
<tr>
<td>Δdbh</td>
<td>dbh</td>
<td>Local</td>
<td>Stochastic</td>
<td>1.78</td>
</tr>
<tr>
<td>Δba</td>
<td>dbh</td>
<td>Simulated</td>
<td>Stochastic</td>
<td>2.20</td>
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<td>Δba</td>
<td>dbh</td>
<td>Local</td>
<td>Stochastic</td>
<td>1.89</td>
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<tr>
<td>Δba</td>
<td>ba</td>
<td>Simulated</td>
<td>Stochastic</td>
<td>2.21</td>
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<td>Stochastic</td>
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<td>Δdbh</td>
<td>dbh</td>
<td>Fixed</td>
<td>Deterministic</td>
<td>1.81</td>
</tr>
<tr>
<td>Δba</td>
<td>dbh</td>
<td>Fixed</td>
<td>Deterministic</td>
<td>1.88</td>
</tr>
<tr>
<td>Δba</td>
<td>ba</td>
<td>Fixed</td>
<td>Deterministic</td>
<td>1.86</td>
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<tr>
<td><strong>Mean bias</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Δdbh</td>
<td>dbh</td>
<td>Simulated</td>
<td>Stochastic</td>
<td>0.71</td>
</tr>
<tr>
<td>Δdbh</td>
<td>dbh</td>
<td>Local</td>
<td>Stochastic</td>
<td>0.73</td>
</tr>
<tr>
<td>Δba</td>
<td>dbh</td>
<td>Simulated</td>
<td>Stochastic</td>
<td>0.94</td>
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<td>Δba</td>
<td>dbh</td>
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<td>Stochastic</td>
<td>0.84</td>
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<td>ba</td>
<td>Local</td>
<td>Stochastic</td>
<td>0.92</td>
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<tr>
<td>Δdbh</td>
<td>dbh</td>
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<td>Deterministic</td>
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</tr>
<tr>
<td>Δba</td>
<td>dbh</td>
<td>Fixed</td>
<td>Deterministic</td>
<td>0.96</td>
</tr>
<tr>
<td>Δba</td>
<td>ba</td>
<td>Fixed</td>
<td>Deterministic</td>
<td>0.97</td>
</tr>
</tbody>
</table>

Discussion

After developing equations for predicting diameter and basal area increment for 10 species common to the Acadian forest, results showed Δdbh equations to be superior to Δba equations when RMSE and MB were computed for up to 29 years of observations. Nonlinear mixed-effects models fitted with stand- and plot-level random effects adequately predicted future growth, as mean bias was generally within 5 cm for up to 29 years using trees growing in a variety of stand types subject to varying silvicultural practices.

The data herein support the results that others have found in contrasting forest types, i.e., that higher correlations are observed when Δba is compared with dbh rather than Δdbh (West 1980; Shifley 1987), as noted in Fig. 1. Because accurate prediction of future dbh is the aim of most growth models, these results favor the use of Δdbh over Δba equations because improvements were observed in three evaluation statistics when using Δdbh (Table 4). This was especially true for trees simulated to long projection length intervals and at larger diameter classes. Percentage improvements in RMSE and MAD% for Δdbh versus Δba was always 10% or greater, except for shorter projection length intervals (i.e., <10 years). A sharp decrease in the percentage reduction for RMSE and MAD% in hardwood species at the 21–25 year projection interval is likely due to the relatively smaller numbers of tree observations for hardwoods in that interval (n = 104), the majority of the hardwoods being red maple (n = 91), and the data only being collected from 15 plots within two stands.

Regardless of the dependent variable used, simulations that employed extracted random effects from model output appeared to perform well for shorter projection lengths (i.e., <5 years). For simulations carried out past 5 years, our analyses indicated that simulating random effects rather than using extracted values performed as well or better in three of the five remaining interval lengths for RMSE and two of the five remaining interval lengths for MB. As projections at longer interval lengths contain a greater degree of uncertainty given the influence of previous growth, this analysis indicates that simulating the general error structure of equations performs nearly as well as or better than using precise estimates of random effects for longer projection lengths. Deterministic predictions made with fixed-effects equations generated evaluation statistics in agreement with statistics drawn from stochastic simulations, which highlights the role that fixed-effects parameters can play in making long-term growth projections.

Evaluating the results by species groups, the six conifer species examined tended to be more sensitive to differences in terms of Δdbh versus Δba than hardwood species. For predicting increment across interval lengths, hardwood species showed less drastic improvement in using Δdbh over Δba. In a database compiled with stem taper measurements for conifers across the Acadian region (Li et al. 2011), stem eccentricity (ratio of smaller diameter to larger diameter) for balsam fir, red spruce, and white spruce was 0.98, 0.96, and 0.97, respectively. Although these eccentricity values were
relatively low, a one-tailed $t$ test for each species indicated that the values were significantly different from 1. Tong and Zhang (2008) found that several of the conifers used in this study displayed similar eccentricity values. In a stem analysis of hardwood species found at the PEF (data not published), eccentricity was calculated as 0.93, 0.90, 0.95, and 0.92 for red maple, paper birch, gray birch, and quaking aspen, respectively. Although these hardwood data came from a small sample size for each species ($n \leq 12$) and were of relatively small dbh (up to 12 cm), supplementary data indicate that hardwood species could display more eccentric stems compared with conifer species found throughout the region. Additional data is needed to assess how these values change through time.

The biological differences between tree dbh and ba should be noted as they relate to tree radial increment. As the cross section of trees measured at breast height are rarely perfectly circular, measuring eccentrically shaped boles with diameter tapes is likely to be positively biased (Binot et al. 1995; Avery and Burkhart 2002, p. 144). Much data used in modeling $\Delta$dbh come from permanent sample plots where circumference is measured using diameter tapes. Differences in dbh error associated with the type of dendrometer used in measuring diameter exist (Binot et al. 1995); however, from the perspective of monitoring individual tree growth, diameter tapes are preferred over other dendrometers such as calipers because they provide the most consistent measurement of dbh. As circumference is measured with a diameter tape, this value is converted to diameter assuming a circular shape of the tree bole at dbh. Outlined in Husch et al. (2004, p. 89), as the major–minor axes length ratio increases, i.e., as the eccentricity of cross-sectional area at dbh becomes more pronounced, circumference of the tree and associated “diameter” increase. This will tend to overestimate the true diameter at cross section. Converting this value to a measurement of area (basal area) requires the further assumption that the stem is circular at the cross section measured at dbh. Using ba would also be more sensitive to measurement error, as error would propagate as one converted an inaccurate linear measurement (dbh) to an area measurement. We hypothesize that the improved performance of employing $\Delta$dbh over $\Delta$ba could be attributed to (i) the extension of the assumption of a circle in modeling tree basal area increment, and (ii) the supposition that error is compounding when simulating long-term increment.

Individual tree diameter increment plays a tremendous role in forest growth and yield simulators as dbh predictions are used in subsequent equations such as volume, biomass, and
mortality. If a Δba equation is employed within a growth and yield system, predicted ba is generally converted to dbh to be used in subsequent equations. As an example, a 10% bias in tree diameter could cause a 25% error in predicting stand-level basal area (Gertner and Dzialowy 1984). This warrants a thorough assessment of the performance of Δdbh equations as they relate to various sources of error at the level of the individual tree, but also as one scales to the plot and stand levels.

Conclusions

Using up to 29 years of observed growth data for 10 Acadian species grown in a range of stand types, this analysis found that Δdbh equations outperformed Δba equations by up to 16% when averaged across all projection lengths. Fitting nonlinear mixed-effects models that provided annualized output allowed the ability to incorporate model error terms and annual climate variability into a Monte Carlo simulation system to directly assess performance of Δdbh over Δba equations. Although higher correlations in the data were observed between initial tree dbh and the dependent variable Δba, incorporating model error terms into growth simulations showed Δdbh equations to more accurately project future growth. Results showcase the importance of incorporating attributes of model error into projections and assessing the stochastic elements of forest growth and yield models.

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