A Comparison of Existing Models for DBH Estimation from Large-scale Photos

by

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Abstract

The performance of 12 diameter prediction models suggested in the literature was studied in a controlled operational test. These models were linear and logarithmic transformations of tree height and/or crown area and were analyzed for white spruce, lodgepole pine, and trembling aspen and balsam poplar combined. Overall, all models were statistically significant, with differences due to variations in species and model form. Although simpler models may be adequate depending on operational objectives, two models emerged as deserving further investigation. It was unclear whether both tree height and crown area were needed as predictors of tree dbh for all species. Tree height was more highly correlated with dbh than crown area for all species except lodgepole pine. Measuring both tree height and crown area in comparison with tree height alone, however, increases measurement cost substantially from \$10.29 to \$17.50 per plot (1987 dollars).

Résumé

On a étudié la performance de 12 modèles de prévision du diamètre présentés dans la documentation consacrée à ce sujet en les soumettant à un essai en conditions opérationnelles contrôlées. Ces modèles consistaient en des transformations linéaires et logarithmiques de la hauteur des arbres ou de la superficie de la cime; on en a étudié l'application à l'épinette blanche, au pin tordu latifolié ainsi qu'au peuplier faux-tremble et au peuplier baumier ensemble. En général tous les modèles ont donné des résultats statistiquement significatifs; les différences observées étaient dues aux variations d'espèces et de formes de modèle. Les modèles simples peuvent donner de bons résultats, tout dépendant de l'objectif visé; dans deux cas toutefois, il y aurait lieu d'approfondir l'évaluation. Il n'est pas clairement établi s'il faut nécessairement connaître la hauteur de l'arbre et la superficie de la cime pour prévoir le dbh de toutes les espèces. On a constaté que la hauteur de l'arbre est en plus forte corrélation avec le dbh que la superficie pour toutes les espèces sauf le pin tordu latifolié. Si l'on n'utilise pas seulement la hauteur de l'arbre, mais qu'on veut aussi employer la superficie de la cime, le coût des mesures monte considérablement, passant de 10,29 à 17,50 \$ par parcelle (dollars de 1987).

Introduction

The ability to reliably predict individual tree diameters at breast height (dbh) from measurements of tree size on large-scale photos (LSP) is an important concern in forest inventory. The use of dbh information in height-dbh curves, and diameter distributions for stand and stock tables, cover type volume tables, and single tree volume tables is fundamental to forest mensuration. With field survey data, dbh is usually a predictor of tree height. With LSP and photomensuration, this relation is

reversed so that tree height is a predictor of tree dbh. Although the question of estimating dbh from LSP measurements of total tree height and crown width⁴ or crown area⁵ has received some attention in the literature (Aldred and Sayn-Wittgenstein 1972; Kirby and van Eck 1977; Aldred and Lowe 1978; Jano 1978; Nielsen *et al.* 1979; Mervart 1984; Hagan and Smith 1986), it was evident that the relationship between these variables is not simple, nor obvious. The difficult selection of appropriate model forms for the prediction of dbh was therefore addressed by comparing the relative performance of existing published models, to answer the following questions:

1. What is the relationship between tree height, crown area, and dbh?
2. What existing, published mathematical model(s), using height and/or crown area as predictors, is best for the prediction of dbh?

Methods

Study Area

The study area was located 30 km northwest of Whitecourt, Alberta, on National Topographic System map

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⁴Either crown width or crown area have been used as independent variables in estimating tree dbh. Results from either have similar interpretations. Crown width estimates tend to be conservative compared with ground measurements, however, and exhibit greater variability than tree crown area measurements (Aldred and Sayn-Wittgenstein 1972). Only tree crown area was considered in this study since it is a more consistent and frequently used variable than crown width in tree dbh estimation.

⁵Crown area is defined as the area occupied by the projection of a tree crown onto a ground horizontal plane (Aldred and Sayn-Wittgenstein 1972).

Figure 1. The study area.

sheet 83J (Figure 1) within the Mixedwood Boreal Forest Region B.18a (Rowe 1972). The area consisted of a narrow corridor approximately 1.6 km in length that traversed a variety of cover types exhibiting a considerable diversity in species composition, typical of the boreal forest. The species in the study area included white spruce (*Picea glauca* [Moench] Voss), lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.), trembling aspen (*Populus tremuloides* Michx.) and balsam poplar (*Populus balsamifera* L.).

Data acquisition

Large-scale photographs were acquired in October, 1985, following leaf-off, using Kodak Double-X Aerographic 2405 film at a nominal scale of 1:1 000. Measurement photos were taken with a Vinten⁶ 492 camera and calibrated Ernst Leitz 152 mm lens. The aircraft speed was varied according to flying conditions to ensure that the photogrammetric parameters of overlap (70% nominal), camera cycling, and image motion (not greater than 25 micrometers) across all photos were as equal as possible. Focusing shims were used to maintain sharp focus. Contact prints were used for photo

interpretation, and a calibrated flying height for each stereopair was calculated (Kirby and Hall 1980).

Fourteen plots covering a variety of tree species and stand densities were selected along the photo flight line. Plot size was approximately 100 m². Height and dbh for all trees in each plot were measured on the photos and in the field. Photo measurements were performed using a Zeiss G-2 Stereocord and a Hewlett Packard 9825 microcomputer with Dendron Resource Survey LSP compilation software⁷. The tree species sampled for analysis included white spruce, lodgepole pine, and deciduous (trembling aspen and balsam poplar combined).

Data analysis

A paired T-test was employed to determine whether tree heights derived from the aerial photos were significantly different from field measurements. Scattergrams and Pearson's product-moment correlations followed to examine the relationships between photo estimates of tree height and dbh, and photo estimates of crown area and dbh.

Fit statistics for dbh regression models included the adjusted R² (Verbyla 1986), standard error of the estimate, significance levels of coefficients, and estimates of bias (Ek 1973) to describe the performance of each regression model. The prediction biases were tabulated for the four smallest and largest trees, and for the four trees closest to mean diameter. T-tests were performed to assess the contribution of the regression estimators for tree dbh at $p \leq 0.05$. Several statistics were therefore used to compare the relative performance of the regression models.

Regression models analyzed

A variety of regression models have been published for estimating tree dbh from photo measures of tree height and/or crown area (Table 1). These models are either linear, quadratic, or logarithmic transformations of the predictor variables. Models 1 and 2 were simple linear regressions of tree height and crown area, and model 3 was a multiple linear regression. Models 4, 5, 6 and 7⁸ were simple linear models with tree height and crown area combined as a single predictor variable.

Models 8 and 9 were polynomial regressions utilizing various transformations of tree height as the predictor variables. Models 10, 11, and 12 were logarithmic transformations of tree height and/or crown area to estimate tree dbh. The R² for Model 9 was not directly comparable to R² values from regression models that have an intercept coefficient and was therefore estimated from the ratio of regression and total sum of squares (SS). Similarly, the R² and standard error of estimates for models 4, 10, and 11 were calculated from untransformed predicted values. For models 10 and 11, the logarithmic transformation uses the geometric mean rather than the arithmetic mean. The standard error of estimate was therefore calculated from the untransformed residual mean squares. A more precise estimate of the standard error can be achieved by employing the correction for logarithmic bias recommended by Baskerville (1972).

Impact of measuring crown area

There is controversy on whether both tree height and crown area are needed as predictors of dbh. Tree height is more convenient and economical to measure on LSP than

⁶Trade names are mentioned for information only and do not apply endorsement by the authors.

⁷Ibid.

⁸An alternative identical model $DBH = a + b \log(CA)^{0.5}$ was presented by Jano (1978) since $\log x = 2 \log(x)/0.5$.

Table 1. Models for dbh estimation using total tree height and/or crown area.

Equation	Regression model ¹	Source (if applicable)
1.	DBH = a + bH	
2.	DBH = a + bCA	
3.	DBH = a + bH + cCA	
4.	DBH ² = a + bHCA	Aldred and Kippen 1967
5.	DBH = a + bH(CA) ^{0.5}	Aldred and Sayn-Wittgenstein 1972 Jano 1980 Mervart 1984
6.	DBH = a + bHlogCA	Aldred and Sayn-Wittgenstein 1972 Jano 1980
7.	DBH = a + bH + cH(CA) ^{0.5} + d(CA) ^{0.5}	Aldred and Sayn-Wittgenstein 1972 Kirby and van Eck 1977
8.	DBH = a + bH + cH ²	Kirby and van Eck 1977
9.	DBH = aH + bH ² + c(sinH)H	Aldred and Lowe 1978
10.	DBH = aH ^b CA ^c or logDBH = loga + blogH + clogCA	Nielsen <i>et al.</i> 1979
11.	DBH = aH ^b or logDBH = loga + blogH	Cited in Spencer 1984
12.	DBH = a + blnCA	Hagan and Smith 1986

¹DBH: diameter at breast height
H: photo-measured tree height
CA: photo-measured crown area
a,b,c,d: regression coefficients
log: log to base 10
ln: natural log

crown area. Reduced error in estimating dbh from crown area must therefore be substantial enough to warrant its use in production inventory programs.

To assess the impact of measuring crown area on operational cost, 21 random LSP forest inventory plots from Alberta Forestry, Lands and Wildlife were interpreted and measured. The time to measure each plot with and without crown area was recorded. Learning bias was minimized by ensuring that the interpreters did not view results or have access to field data prior to interpretation.

Results and Discussion

Aerial photographs were acquired on October 4, 1985, and were judged usable and representative of operational photos. On both photos and the ground, 154 trees were measured. Although there was some variation in the number of trees sampled for each species, a representative range and distribution was attained (Table 2)⁹. White spruce trees

⁹The distribution of diameters included in this study was dictated by conditions encountered in the forest stands.

exhibited the greatest variability in both diameter and height (Table 2).

For all tree species, photo estimates of tree height were not significantly different from felled measurements (Table 3). The height of aspen and balsam poplar trees were, however, an average of 0.67 m higher than ground values (Table 3). Field work was conducted in November, and difficulty in measuring true tree lengths of trees with broken tops were encountered due to tree felling in sub-zero temperatures (-20 degrees C). Lodgepole pine trees were measured and had the smallest mean difference between photo and ground measurements. Photo measures were concluded to be an acceptable estimate of actual tree heights, and standard deviations were commensurate with other published results (Titus and Morgan 1985).

Correlation tests and scattergrams

Ground-felled and photo-measured tree heights were significantly correlated with tree dbh for all species (Table 4). The lowest correlation coefficient was with the ground-felled tree height of aspen and balsam poplar (0.585) compared with photo tree height (0.831); this was attributable to the broken tops during tree felling. Tree height was more highly correlated

Table 2. Sample statistics for ground and photo measurements of tree heights and diameters

Tree species	N	Mean	Range	Standard deviation	Standard error of the mean	Coefficient of variation (%)
White spruce	58					
Ground felled ht(m)		14.181	3.2-26.7	6.089	0.800	42.9
Photo measured ht(m)		13.655	3.2-25.5	5.641	0.741	41.3
Ground measured dbh(cm)		16.609	3.0-41.5	8.832	1.16	53.2
Lodgepole pine	38					
Ground felled ht(m)		17.884	6.2-23.5	3.904	0.633	21.8
Photo measured ht(m)		18.003	9.9-22.9	3.473	0.563	19.3
Ground measured dbh(cm)		19.382	12.0-35.3	4.872	0.79	25.1
Aspen and balsam poplar	58					
Ground felled ht(m)		17.317	8.3-26.0	4.706	0.618	27.2
Photo measured ht(m)		17.983	9.7-26.2	3.939	0.517	21.9
Ground measured dbh(cm)		18.250	7.0-31.0	7.043	0.92	38.6

Table 3. Paired T-test results by species for ground felled vs photo-measured tree heights

Tree species	N	Correlation coefficient	Mean difference (m)	Standard deviation (m)	Calculated T-value	Probability level ¹ (2-tail)
White spruce	58	0.914	0.526	2.477	1.62	0.111
Lodgepole pine	38	0.716	-0.118	2.808	-0.26	0.796
Aspen and balsam poplar	58	0.571	-0.666	4.062	-1.25	0.217

¹Neither of these values was statistically significant at the 5% probability level.

with tree dbh than crown area for all species except lodgepole pine (Table 4), for which crown area was more important. This may be a characteristic of the species or an artifact of the sample. A larger sample would be needed to verify the consistency of this association.

Tree heights versus dbh for lodgepole pine exhibited less of a linear association than for other species (Figure 2). There was, however, a definite curvilinear pattern with crown area (Figure 3). White spruce crown areas were the most variable (Figure 3). Scattergrams of tree height and crown area with dbh for aspen and balsam poplar combined, exhibited a curvilinear pattern that was more definitive for crown area (Figure 2) than from tree height (Figure 3).

Regression results

Regression statistics for each model (Table 1) have been summarized by species in Tables 5, 6, and 7. All regression models were statistically significant, with no one model producing a substantially smaller standard error of estimate than any other. The higher the correlation with tree dbh, the higher the accuracy of the simple linear models 1 and 2 (Table 1). Regression models with higher polynomial terms (e.g., models 7, 8, 9; Tables 5-7) generally produced regression coefficients that were not statistically significant at $p < 0.05$. This result suggests simpler models may be adequate, but further investigation is warranted before use.

Across all species groups, models 3, 7, 9, and 10 ranked consistently within the top five of all models, based on adjusted R^2 and standard error values (Tables 5-7). There was no further pattern as to the ranking of regression models across all species. The highest adjusted R^2 values were not associated with the lowest standard error of the estimates. This result was due to the varying correlations of the predictor variables with dbh, the different model forms in accounting for the variation in dbh estimation, and the effects of multicollinearity. Multicollinearity was especially evident in models 7 and 9 and was exemplified by the lack of significance of some of the predictor variables. This often occurs when predictor variables are merely transformations of each other. The effect of multicollinearity was also reflected in the prediction biases across the range of data. Especially for Model 9, a large prediction bias for the large or small trees was evident (Table 8). None of the four models were

consistent in the magnitude or direction (over- or underestimate) of prediction biases over the entire data range. In general, Model 3 prediction bias was closest to zero when

Figure 2. Scattergrams of tree dbh and photo-measured tree heights.

Table 4. Correlation coefficients for tree height and crown area with ground-measured tree dbh by species

Tree Species	Correlation coefficients		
	Ground felled Tree height	Photo measured Tree height	Photo measured Crown area
White spruce tree dbh	0.961*	0.874*	0.720*
Lodge pole pine tree dbh	0.501*	0.413*	0.788*
Aspen and balsam poplar tree dbh	0.585*	0.831*	0.817*

*Highly significant at the 5% probability level (< 0.005).

Table 5. Regression statistics for white spruce

Equation ¹	Adjusted R ²	Standard error (m)	Regression Significance	Regression coefficients ² T-value and probability			
				a	b	c	d
1. DBH = -2.081+1.369H	0.760	4.326	0.0000	-1.388 0.171	13.475 0.0000*		
2. DBH = 8.322+2.070CA	0.509	6.187	0.0000*	6.200 0.0000*	7.756 0.0000*		
3. DBH = -1.402+1.113H+0.704CA	0.790	4.047	0.0000*	-0.988 0.3277	8.1712 0.0000*	3.000 0.0040*	
4. DBH ² = 93.962+3.915HCA	0.667	5.191	0.0000*	2.669 0.0099*	10.722 0.0000*		
5. DBH = 6.186+0.370H(CA) ^{0.5}	0.743	4.479	0.0000*	6.181 0.0000*	12.870 0.0000*		
6. DBH = 8.999+0.998HlogCA	0.710	4.753	0.0000*	10.056 0.0000*	11.865 0.0000*		
7. DBH = -1.209+0.888H+0.111H(CA) ^{0.5} +1.386(CA) ^{0.5}	0.796	3.986	0.0000*	-0.366 0.7158	3.626 0.006*	0.954 0.3441	0.682 0.4979
8. DBH = 2.195+0.632H+0.026H ²	0.767	4.264	0.0*	0.727 0.4703	1.361 0.1790	1.624 0.1101	
9. DBH = 0.941H+0.0165H ² +0.070(sinH)H	0.949	4.233	0.0*	6.473 0.0000*	2.076 0.0426*	1.154 0.2536	
10. logDBH = 0.165+0.802logH+0.238logCA	0.802	3.964	0.0*	1.816 0.0749	8.489 0.0000*	4.565 0.0000*	
11. logDBH = -0.0228+1.074logH	0.751	4.444	0.0001*	-0.24 0.8104	12.62 0.001*		
12. DBH = 9.228+7.023lnCA	0.505	6.216	0.0000*	7.321 0.0000*	7.685 0.0000*		

¹variable letters identified in Table 1, footnote 1²letters refer to model coefficients in Table 1

*statistically significant at 5% probability level.

all species were considered. Based on the four models selected, models 3 and 10 were selected as potential models deserving further investigation. Based on the limited data set utilized, it was not possible to recommend a single regression model for all species that would perform statistically "better" than any other. These models may therefore be considered as

a basis for consideration when developing operational equations.

Impact of measuring crown area

Alberta Forestry, Lands and Wildlife budgets \$17.50 per plot for LSP inventory operations, and both tree height and

Table 6. Regression statistics for lodgepole pine

Equation ¹	Adjusted R ²	Standard error (m)	Regression Significance	Regression coefficients ² T-value and probability			
				a	b	c	d
1. DBH = 8.960+0.579H	0.147	4.500	0.010*	2.296 0.0276*	2.718 0.0100*		
2. DBH = 14.967+1.035CA	0.610	3.043	0.0000*	19.741 0.0000*	7.672 0.0000*		
3. DBH = 13.593+0.085H+0.998CA	0.601	3.074	0.0000*	4.924 0.0000*	0.518 0.6076	6.489 0.0000*	
4. DBH ² = 223.467+2.122HCA	0.618	3.054	0.0000*	7.453 0.0000*	8.118 0.0000*		
5. DBH = 12.281+0.198H(CA) ^{0.5}	0.589	3.124	0.0000*	11.252 0.0000*	7.346 0.0000*		
6. DBH = 14.366+0.524HlogCA	0.594	3.106	0.0000*	17.041 0.0000*	7.419 0.0000*		
7. DBH = 12.782-0.139H+0.099H(CA) ^{0.5} +2.897(CA) ^{0.5}	0.601	3.074	0.0000*	1.880 0.0687	-0.383 0.7039	0.454 0.6527	0.655 0.5169
8. DBH = 20.801-0.845H+0.041H ²	0.139	4.521	0.0275*	1.374 0.1781	-0.477 0.6362	0.810 0.4234	
9. DBH = 1.543H-0.025H ² +0.040(sinH)H	0.947	4.602	0.0000*	5.899 0.0000*	-1.873 0.0694	0.772 0.4452	
10. DBH = 1.260-0.086logH+0.247logCA	0.613	3.072	0.0000*	6.972 0.0000*	-0.562 0.5778	6.090 0.0000*	
11. DBH = 0.706+0.456logH	0.150	4.555	0.0142*	3.20 0.0029*	2.58 0.0142*		
12. DBH = 14.035+4.689lnCA	0.574	3.179	0.0000*	15.428 0.0000*	7.135 0.0000*		

¹variable letters identified in Table 1, footnote 1²letters refer to model coefficients in Table 1

*statistically significant at 5% probability level.

Table 7. Regression statistics for aspen and balsam poplar

Equation ¹	Adjusted R ²	Standard error (m)	Regression Significance	Regression coefficients ² T-value and probability			
				a	b	c	d
1. DBH = -8.457+1.485H	0.684	3.956	0.0000*	-3.455 0.0011*	11.164 0.0000*		
2. DBH = 11.263+1.410CA	0.662	4.096	0.0000*	13.245 0.0000*	10.609 0.0000*		
3. DBH = -3.782+0.979H+0.893CA	0.873	2.505	0.0*	-2.319 0.0242	9.731 0.0000*	9.202 0.0000*	
4. DBH ² = 104.408+2.837HCA	0.760	3.132	0.0000*	3.728 0.0005*	13.484 0.0000*		
5. DBH = 6.872+0.293H(CA) ^{0.5}	0.858	2.649	0.0000*	9.778 0.0000*	18.628 0.0000*		
6. DBH = 10.849+0.706HlogCA	0.796	3.178	0.0000*	16.766 0.0000	14.964 0.0000		
7. DBH = 0.621+0.481H+0.209H(CA) ^{0.5} +0.414(CA) ^{0.5}	0.876	2.478	0.0000*	0.140 0.8888	1.844 0.0725	1.832 0.0706	0.193 0.8473
8. DBH = 3.017+0.159H+0.0365H ²	0.691	3.918	0.0*	0.365 0.7161	0.173 0.8634	1.454 0.1517	
9. DBH = 0.471H+0.029H ² -0.025(sinH)H	0.960	3.910	0.0*	3.110 0.003*	3.791 0.0004*	-0.573 0.5689	
10. DBH = -0.0044+0.904logH+0.208logCA	0.868	2.578	0.0*	-0.038 0.9695	9.322 0.0000*	9.229 0.0000*	
11. DBH = -0.522+1.408logH	0.691	3.953	0.0001*	-3.31 0.0016*	11.12 0.0001*		
12. DBH = 11.417+5.611lnCA	0.616	4.364	0.0000*	12.506 0.0000*	9.615 0.0000*		

¹variable letters identified in Table 1, footnote 1²letters refer to model coefficients in Table 1

*statistically significant at 5% probability level.

crown area are measured¹⁰. Without measuring crown area, the LSP production rate would increase to 17 plots per day and the cost would fall to \$10.29 per plot. Including the time to set up the stereomodel, total plot measurement time was 1.7x longer for measuring both tree height and crown area than for measuring tree height alone; measuring crown area therefore increases costs substantially.

Conclusions

This study compared previous work on dbh estimation from large-scale photos. Tree height was most highly correlated with dbh for all species except lodgepole pine; it was the most accurately measured of all species for tree height, but crown area was more highly correlated with tree diameter. Crown area is therefore concluded to be a stronger predictor of dbh than tree height for lodgepole pine. Further

work over a larger area and data set is recommended to confirm this association.

Of the 13 regression models analyzed (Table 1), all were statistically significant, and models 3, 7, 9, and 10 were the best performers across all species. Multicollinearity was evident in models 7 and 9 as was exemplified by the low significance of some predictor variables. Particularly for Model 9, the effect of multicollinearity was also evident by large positive or negative prediction biases across the range of data.

Regression models with a greater number of terms generally produced coefficients which were not statistically significant. Simpler models may therefore deserve more attention than what the literature has exemplified. Based on the limited data set utilized, it is difficult to recommend a single best equation. Models 3 and 10 are therefore suggested for further investigation as possible dbh functions:

Model 3: DBH = a + bH + cCa

Model 10: DBH = aHbCac

¹⁰Personal communications with H. Archibald, Land Information Services Division, Alberta Forestry, Lands & Wildlife, February 18, 1988.

Table 8. Estimates of average diameter predication bias for the top four models.

Species	Model number	Prediction bias (cm)		
		Four smallest trees	Four trees closest to mean diameter	Four largest trees
White spruce	3	-0.048	1.453	-2.427
	7	0.286	1.418	-2.107
	9	-0.095	0.634	-2.906
	10	0.468	1.023	-2.802
Lodgepole pine	3	3.791	0.739	-1.473
	7	3.329	1.225	-1.982
	9	6.132	1.407	-6.516
	10	3.101	1.10	-3.216
Aspen and balsam poplar	3	1.388	2.030	-2.751
	7	1.448	2.293	-2.687
	9	2.512	0.957	15.259
	10	1.219	2.307	-4.258

Figure 3. Scattergrams of tree dbh and photo-measured crown area.

An alternative approach to predicting dbh is in deriving the model form to fit the data. Is there, however, adequate biological justification for deriving different models for different species and stand conditions? Further investigation is suggested to investigate nonlinear modelling and incorporation of ecological rationalization through site and stand characteristics. New derived model performance could then be compared with that of existing models.

It is generally thought that including crown area with tree height to predict dbh results in greater accuracy at the expense of plot measurement production rate. Comparing the regression statistics for each species suggests, however, that crown area doesn't consistently result in more accurate dbh estimates. In 1987 dollars, including crown area increases the per plot measurement cost from \$10.29 to \$17.50. With increasing labour

costs and the well-known difficulties of measurement consistencies between interpreters, the gains from incorporating crown area will need to be more closely monitored in future inventory surveys. Its benefits at present are not obvious.

In conclusion, a comparison of existing models has resulted in two models that hold potential for application in the Mixedwood Boreal Forest of Alberta. The recommended models for future operational LSP inventory surveys in Alberta will entail a larger database and a comparison between derived models to these recommended existing models.

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