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Validation of FIBER 3.0 for Tolerant Hardwood Stands in Ontario

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Validation of FIBER 3.0 for Tolerant Hardwood Stands in Ontario

by

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Abstract

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Growth and yield projections aid foresters in assessing timber management opportunities and in making management decisions. With these uses, questions arise about the reliability and limits of growth and yield simulators. Using long-term studies of hardwood stands in Ontario the growth simulator FIBER 3.0 has been tested. Short-term (5 years) projections of stand growth are reliable (modelling efficiency from 70% to 90%). Errors for individual stand projections, however, range from -30% to 40%. The magnitude of error in individual stand projections is influenced by species composition and size of sample plots. Small sample sizes do not fully account for the variation in stand structure. The best results (prediction errors below 20%) occur when projecting stands that have 50% to 70% sugar maple and are sampled using plots > 0.2 ha. When the length of the projection period increases, the reliability of FIBER 3.0 decreases and errors increase. Long-term (15- and 20-year) projections underestimate key stand characteristics and the performance of the model is less satisfactory. An examination of various site class options suggests that the site class component does not significantly influence model performance. A comparison of predicted and observed diameter distributions indicates that FIBER 3.0 is more accurate in uneven-aged stands than in even-aged. The model is more reliable in basal area prediction of small sawlog classes than of larger sawlog classes.

In subsequent reports FIBER 3.0 performance will be compared with other stand growth models.

Keywords: growth model, tolerant hardwood, thinning, timber class, basal area, stand density, stand volume

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Introduction

Computer programs that simulate stand growth are used in forest planning and in evaluating management options. Several stand growth models are available for hardwood species in North America: for example, SILVAH (Marquis and Ernst 1992), TWIGS (Belcher, D.M. 1982), OAKSIM (Hilt 1985) and FIBER 3.0 (Solomon *et al.* 1995). Each program was developed using data from a distinct geographic area in the United States. The relative performance of these models and their suitability for use in a particular forest type and geographic area were compared in the northeastern United States (Schuler *et al.* 1993). FIBER 3.0 performed the best for most locations in the northern hardwood forest type. In Ontario we plan to test four simulators (FIBER 3.0, SILVAH, TWIGS, and FPS (Arney 1995)) and to evaluate their performance in tolerant hardwood stands. The suitability of each simulator will be determined for specific forest conditions in central and southern Ontario. In this report, we evaluate the performance of FIBER 3.0 in tolerant hardwood stands in different geographic locations in Ontario. Growth projections are made for 5- to 20-year periods in managed and unmanaged stands.

Description of FIBER 3.0

FIBER 3.0 predicts the growth of hardwood, spruce-fir and mixed hardwood-softwood stands in the Northeastern United States, New Brunswick and Nova Scotia. It is based on 4,000 independent plots (0.08 and 0.14 ha in size). These plots were remeasured every 5 years for 15 years.

FIBER 3.0 is a 2-stage matrix model. For each species, a matrix U_t of predicted transitional probabilities is applied to a stand table vector y_t which contains the number of live trees at time t in each 1-inch diameter at breast height (DBH) class. After 5 years of growth, the stand vector (y_{t+5}) for each species is generated by adding the ingrowth (I_t) to the growth matrix:

$$y_{t+5} = U_t\ (y_t - h_t) + I_t$$

where,

h_t = number of trees harvested from the diameter class at time t;

I_t = ingrowth of trees into the 5" class during the period from t to t+5;

The matrix of predicted transitional probabilities (U_t) includes:

- the probability that a tree survives and remains in a diameter class during the time interval from t to t+5;
- the probability that a tree beginning in diameter class j at time t survives and progresses into diameter class j+1 at time t+5;
- the probability that a tree beginning in diameter class j at time t survives and progresses into diameter class j+2 at time t+5.

Mortality may be calculated using the following vector equation:

$$z_{t+5} = m_t * (\ y_t - h_t\ )$$

where,

m_t = vector of mortality probabilities by diameter class;

z_{t+5} = number of trees that died in each diameter class over the 5-year growth period.

Transitional probabilities and mortality probabilities are modelled as a linear function of :

- diameter class

- initial basal area before harvest
- residual stand basal area after harvest
- proportion of hardwoods in the stand
- elevation of the plot
- habitat type (there are 6 habitat types)
- site index.

For specified time intervals FIBER 3.0 predicts the growth and yield of either individual stands or large forested areas receiving similar management treatments. FIBER 3.0 has several desirable features:

1. It covers a wide range of habitat types (sugar maple-ash, beech-red maple, oak-white pine, hemlock-red spruce, spruce-fir, cedar-black spruce).
2. The requirements of input are limited to a stand table with the number of trees in each diameter class for each species and tree quality class.
3. It has an automated ingrowth function.
4. The program accepts various thinning scenarios (removal priorities can be specified by species, DBH class or quality class).

The limitations of FIBER 3.0 include:

1. The prediction period is limited to 5-year intervals.
2. The list of species does not include some important Ontario tree species, e.g., red pine and black cherry.
3. Program input and output are expressed in imperial units.

FIBER 3.0 requirements for input and output are shown below:

Input:

Stand table: number of trees in 1" DBH classes by species and quality class

Site index

Elevation

Treatment specification

5-year projection

Output:

Mean quadratic DBH

q-factor

Characteristics by stand, species, size class, quality class, timber class:

- number of trees / acre
- basal area
- volume

Table 1. Description of data sets used for the validation test of FIBER 3.0

Data set	Latitude	Elevation (m)	Area of plot/ system (ha)	Number of plots per plot/ system	Proportion of sugar maple (% basal area)	Prediction periods (years)	Period of data collection	Number of stands (plot/ systems)	Basal area of plot/ system (m^2/ha)	Age (years)	Stand density (trees/ha)	Mean quadratic DBH (cm)	Basal area thinned (m^2/ha)	Basal area removed (%)
Algonquin Regional Growth Study	44° 40'- 45° 50'	240-480	0.20 -1.33	5 - 33	38 - 84	5	1977-1982	10	20.9 - 27.1	UA	350- 530	24.2 - 30.3	n/a	-
						10	1977-1987	10	20.8 - 28.2	UA	340- 490	25.6 - 30.9		
Turkey Lakes	47° 03'	330	0.10 - 0.80	1 - 8	82 - 98	5	1980-1985	13	19.2 - 33.2	UA	390- 550	23.6 - 31.1	n/a	
						10	1980-1990	13	20.6 - 30.9	UA	370- 525	23.1 - 31.5		
Beckwith	43° 56'- 44° 54'	80 - 350	0.04 - 0.26	1	10 - 98	5	1971-1991[a]	20	9.8 - 38.8	46- 95	296-1125	16.4 - 28.7	n/a	
						10		16	11.9 - 40.7	55-100	315-1125	16.6 - 30.1		
						15		11	14.3 - 42.9	60-100	330-1175	18.8 - 31.5		
						20		4	15.8 - 44.7	65-105	320- 750	22.5 - 32.2		
Corry Lake Woodlot	46° 00'	150	0.65 - 0.66	4 - 8	12 - 50	5	1973-1978	4	17.7 - 25.3	UA	380- 510	23.5 - 28.3	2.3 - 10.3	9 - 49
						10	1973-1983	8	17.7 - 28.2	UA	360- 560	22.5 - 28.7	2.3 - 10.3	9 - 49
						20	1973-1993	8	19.9 - 27.8	UA	380- 530	23.1 - 29.9	3.3 - 13.6	18 - 48
Algonquin Polar Plots	45° 10'- 46° 00'	390 - 540	0.04 - 0.48	1 - 12	9 - 100	5	1986-1991	88	8.1- 29.4	UA	100- 490	21.5 - 37.6	2.1 - 23.3	10 - 23

Note: a- measurements for each period were done in various calendar years; UA - uneven-aged stands

Data description

Data from 5 long-term silvicultural studies in Ontario were used in the validation test. Stands used in the test were classified as unmanaged (Algonquin Regional Growth Study, Turkey Lakes and Beckwith) and managed tolerant hardwoods (Corry Lake Woodlot and Algonquin Polar Plots). A total of 139 plots/systems (stands) were used in the evaluation of FIBER 3.0. The summary of stand and data characteristics are shown in Table 1. All but the Beckwith plots are located in uneven-aged tolerant hardwood stands. Data sets originated from different projects, which led to a substantial variation in:

- original purpose of data collection
- sampling design (plot size, number of plots per stand, and spatial distribution of plots)
- site quality
- silviculture system (unmanaged, single tree selection or shelterwood harvest)
- location of plots (latitude and elevation)
- stand characteristics (species composition, stand density and age)
- measured tree characteristics (variation in the range of tree diameters measured and precision with which DBH was measured).

Algonquin Regional Growth Study (ARGS):

At the time of establishment ARGS had 2 basic objectives:

- to determine how site, stocking, structure, and spatial distribution of trees influence tree and stand growth in tolerant hardwood stands in the Algonquin Region of Ontario
- to show how this growth data could be used in conjunction with post-cut cruise data from other stands to predict growth in stands that have been treated (e.g., modelling growth of stands to be used as a management tool).

The ARGS data set consists of 10 stands, each with varying numbers of square plots (area of 0.04 ha or 0.1 acre) measured from years 1977-1992. All measurements, except those from 1992, were in imperial units and included trees larger than 3.6" DBH.

In the 1992 inventory, the smallest measured DBH was 1.5". Due to boundary changes, 5 plots measured in 1987 and 1992 included trees that were omitted in previous inventories. The major tree species are: sugar maple (from 38% to 84% of the total basal area), hemlock, yellow birch, white ash, beech, red oak, red maple and species classified by FIBER 3.0 as "other hardwoods" (basswood, elm).

There is a lack of information about site quality, but the site conditions are considered to be better than average.

Turkey Lakes:

The original purpose was to define:

- the impact of atmospheric deposition of acidifying substances and other pollutants on undeveloped aquatic and terrestrial ecosystems
- the effects of anthropogenic perturbations to these ecosystems.

The Turkey Lakes Watershed (TLW) data set includes 13 stands located in Norberg and Wishart townships (47° N latitude), Algoma District, Northern Ontario. The study site is located approximately 60 km north of Sault Ste. Marie and approximately 13 km inland from Batchawana Bay on Lake Superior. The TLW is 10.5 sq. km in area. In 1981-83, total precipitation at the watershed averaged 1,300 mm per annum. Growing season length is estimated to be 175 days. Soils are generally shallow on crests and upper slopes and increase in depth downslope. The dominant soil profile type is Humo-Ferric Podzol. The principal tree species are: maples (90%), with lesser amounts of other hardwoods (9%) (e.g., yellow birch), and various conifers (1%). Most of the plots were classified as Site Class II or lower (Plonski 1974).

In 1980, circular 0.01 ha plots were established along a gradient of vegetation types and site quality classes. All inventories (in 1980, 1985 and 1990) included measurements of trees larger than 5 cm in DBH. In recent years, no major insect or disease outbreaks have been reported in the watershed or the general area. On average, stand quality is low (Morrison 1990).

Beckwith Plots:

The original purpose was to monitor stand dynamics in southern and central Ontario.

The Beckwith data set consists of 478 permanent sample plots established in 1967 in southern Ontario. However, only 20 plots from 8 townships were selected for this analysis. The criteria for plot selection were the availability of 5-year measurements, the sugar maple content, and the lack of thinning. Each stand is represented by 1 rectangular plot from 0.04 to 0.23 ha in size. All inventories included measurements of trees larger than 1.5 cm DBH. Of the 21 species present on the plots, the following are the most common: sugar maple, American beech, red oak, yellow birch, white ash and white birch. Information on soil and site quality conditions is not available.

Corry Lake Woodlot:

In 1973, this project was initiated to:

- determine the effects of 2 upper diameter limits, 2 levels of growing stock and 2 cutting cycles on stand growth
- identify the optimum growing stock level in stands managed by the single-tree selection system.

The Corry Lake Woodlot is 18.6 ha in area and is located at the Petawawa National Forestry Institute. Much of the area is level. The soil is a brown podzolic loamy sand derived from glacial till. The soil moisture regime over most of the area is classed as fresh (after Hills 1952), but locally soils in drainage channels are moist to very moist. The study was established in 8 adjacent, uneven-aged stands. Although 20 native tree species are present, only 5 are of major importance (sugar maple, American beech, white pine, yellow birch and basswood). The height/age data for sugar maple indicates that the area is a productive site and that growth would be comparable to Plonski's (1960) Site Class I for tolerant hardwoods in Ontario and Westveld's (1933) Site Class 80 for sugar maple in the Lakes States. The plot system includes 0.081 ha circular and 0.3-0.4 ha rectangular plots. The total area of sample plots per stand was 0.65 ha. All trees larger than 5 cm DBH were included in the measurements. One combination of growing stock (140 or 210 m^3/ha), maximum diameter (40 or 50 cm), and cutting cycle (5 or 10 years) was assigned to each of the 8 stands in 1973 (Berry 1981). In 1988, a windstorm caused substantial tree mortality.

Algonquin Polar Plots:

This project was designed in 1986 to provide information on a number of factors, including:

- pre-marking stand conditions
- quality of tree marking
- utilization of harvested trees
- logging damage during harvest operations
- long-term tree and stand growth data in silviculturally treated stands.

The Algonquin Polar Plots include 320 plots from 88 stands located in 10 townships. Plots were established in stands of various hardwood and conifer working groups throughout Algonquin Park. These plots were located in stands that had been rated as Site Class I by the Ontario Forest Resource Inventory (FRI). Establishment of at least 3 randomly located plots (0.04 ha each) was recommended for each stand, but the actual number of plots per stand varies from 1 to 12. For each tree within the plot, the following data was collected (years 1986 and 1991): tree species, DBH and tree quality class (Algonquin Park 4-class system).

The species composition included: sugar maple (from 9% to 100% in basal area), hemlock, balsam fir, American beech, yellow birch, northern white cedar, red maple, white pine, white spruce, and "other species" (ironwood, basswood, black ash, white birch, poplar and silver maple). In 1986 the prescribed treatment (a selection or uniform shelterwood system) was applied by removing from 2 to 23 m^2/ha of basal area, which was 10-23% of the residual basal area.

The 1986 measurements were taken in imperial units and included all trees larger than 2.0" DBH. In 1991, the metric system was used, and trees larger than 5.0 cm DBH were measured.

Testing Procedures

All data sets were edited, and plots with unusually high undocumented mortality (over 30% within a given 5-year period) were eliminated from further analysis (Turkey Lakes, ARGS). Trees were grouped into 1" DBH classes (from 5" to 32") for each tree species and quality class. The 2 quality classes are: AGS (acceptable growing stock) and UGS (unacceptable growing stock) based on stem quality. Only trees with DBH larger than 4.5" were included in further testing. Due to differences in data collection, age structure and management system, data sets were tested separately. Measurements from plots were grouped by stands (plot/systems), and stand growth was projected by the number of 5-year periods equal to the measured intervals (1 to 4, 5-year intervals).

For most projections, no site quality information was available; thus the average value of site index was selected (e.g., 70 for sugar maple). For the Corry Lake and Turkey Lakes projections however, 2 site index options were evaluated: average value and value indicated by stand description (80 in Corry Lake and 60 in Turkey Lakes sugar maple stands).

Thinning options in managed stands

a. Algonquin Polar Plots

The objective was to simulate field thinning as accurately as possible. Therefore, trees "cut" in FIBER 3.0 projections were removed from the same DBH range as those cut in the field. However, the removal priority was set up as "thinning from above". The specified residual basal area was attained by choosing the largest DBH class and working toward the smallest DBH class until the specified residual stand density was obtained. In addition, the option of thinning by removing trees from a simulated tree list was used to mimic the actual cutting.

b. Corry Lake

The simulated thinning reflected the actual number of trees cut in each DBH class.

Diameter distribution projections

The Kolmogorov-Smirnov Two-Sample Test (Steel and Torrie 1980) was used to determine whether the observed and predicted DBH distributions were identical. In this test all trees from each diameter class were assumed to have a DBH equal to the midpoint of the diameter class. The test was performed for all stands and prediction periods.

Error evaluation

Results of stand growth simulation with each data set were examined by comparing the predicted and observed values of stand density, mean quadratic DBH, basal area and volume. The calculation methods for predicted and "observed" stand volumes are identical (volume tables from FIBER 3.0). To evaluate FIBER 3.0's ability to predict basal area by merchantable timber classes, trees were grouped by DBH classes that corresponded to the following product classes:

- Poles (10-24.9 cm)
- Small sawlogs (25-40.9 cm)
- Medium sawlogs (41-49.9 cm)
- Large sawlogs (≥50 cm).

The observed basal area of each class was compared to the predicted basal area for each product class in each stand. All values were processed in imperial units and then translated to metric units. The model error was analyzed using plots of the residuals (r) vs. predicted values of density, basal area, volume and mean quadratic DBH. Similarly, residuals were plotted vs. basal area for each of the 4 merchantable timber classes. Residuals values were computed as follows:

$$r = \frac{y - y'}{y'}$$

where,

y' = predicted value, y = observed value, r = residual value.

Model performance in relation to stand characteristics and merchantable timber classes was evaluated using the following criteria:

- average model bias or average error ($\sum r / n$; n- number of stands)
- absolute error ($\sum |r| / n$)
- range of error (minimum and maximum values of r).

Average model bias is a measure of the expected error when several observations are combined by totalling or averaging, while absolute error indicates the average error associated with a single prediction (Vanclay 1994). The Wilcoxon Rank Test was used to evaluate statistical significance of the model bias (Steel and Torrie 1980).

Another useful technique for comparing predictions with observed data is modelling efficiency (E_m), a statistic that is analogous to R^2:

$$E_m = 1 - \frac{\sum (y_i - y'_i)^2}{\sum (y_i - \mu)^2}$$

where,

y_i = observed value ; y_i' = predicted value; E_m = modelling efficiency; and μ = mean observed value.

Modelling efficiency provides a simple index of performance on a relative scale, where 1 indicates a "perfect" fit, 0 reveals the model is no better than a simple average, and a negative value indicates a poor model fit.

Finally, trends in residual distribution were examined by plotting residuals of basal area vs. sample plot area and species composition (proportion of sugar maple).

Results

Diameter distribution

FIBER 3.0 reliably predicts distribution for most of the uneven-aged stands. The Kolmogorov-Smirnov test shows that less than 15% of predicted diameter distributions are statistically different ($p<0.05$) from the observed DBH distributions (Table 2). However, for 25-45% of the even-aged stands, predicted DBH distributions are significantly different from the observed distributions.

Error evaluation for predictions of selected stand characteristics

The variation among data sets greatly affects the magnitude of prediction errors for stand density, basal area, mean quadratic DBH and stand volume. This variation results from the choice of plot selection method, the size of plot/system area, and stand structure (species composition).

Figure 1 illustrates how the plot/system area affects residuals of basal area predictions. When sample plots are larger, the basal area is predicted more accurately and variance of basal area residuals is smaller. The model appears to underestimate basal area for stands with low amounts of sugar maple and to overestimate when the proportion of sugar maple is above 70% (Figure 2).

The Corry Lake and Turkey Lakes projections with 2 site index options do not show substantial discrepancies in stand volume, basal area, density and mean quadratic DBH (results are not shown). Thus, site index values in the range of 60 to 80 do not appear to influence model predictions significantly.

I. Uneven-aged, unmanaged stands

The 5- and 10-year predictions of all stand characteristics except mean quadratic DBH are unbiased for the ARGS data set (Tables 3-6, Figures 3-6). FIBER 3.0 estimates of mean quadratic DBH are significantly less than observed diameters in the ARGS data set ($p<0.002$). FIBER 3.0 estimates of stand basal area, volume and mean quadratic DBH are significantly greater than observed values in the Turkey Lakes data ($p<0.006$). The expected error for a single stand prediction (absolute error) is 2-7% in 5-year predictions and 3-12% in 10-year predictions for both data sets (Table 7). The modelling efficiency for 5-year predictions in the ARGS stands is approximately 20% higher than in the Turkey Lakes data set. In longer predictions (10 year), the modelling efficiency decreases significantly, especially for Turkey Lakes stands.

II. Even-aged, unmanaged stands

FIBER 3.0 projections of the Beckwith data underestimate (3-5%) all stand characteristics for the 5-year simulation. Model biases increase to 6-13% in 15-year predictions (Table 7). Average errors (bias) of all stand characteristics are statistically significant (Tables 3-6 and Figures 3-6). A similar trend is seen in absolute error, which ranges from 4% to 14% for all prediction periods. In the Beckwith (even-aged) stands, the modelling efficiency decreases as the prediction period increases, from 89% to 92% in 5-year projections to about 37-73% for 20-year estimates.

III. Uneven-aged, managed stands

In Corry Lake and Algonquin Polar Plot stands that were thinned, the 5-year projections of stand density, basal area and volume are comparable to those for unmanaged stands (Tables 3-6, Figures 3-6). However, in Corry Lake, the stand characteristics are underestimated. The average errors of all stand characteristics are not statistically significant. Similarly, the bias in Algonquin Polar Plot stand projections is not statistically significant ($p<0.05$), except for mean quadratic DBH, which is overestimated. The range of absolute error for all stand characteristics is similar to that observed in unmanaged stands (2-12% for all predictions). Stand volume is projected as efficiently as in unmanaged stands, e.g., above 90% for 5-year projections in Corry Lake. Modelling efficiency is lower (74%) in the Algonquin Polar Plot simulations, possibly due to the large variation in sugar maple in these stands and in plot/system size. Mean quadratic DBH is predicted with larger accuracy at Corry Lake (modelling efficiency equal to 96%) than in uneven-aged, unmanaged stands.

The longer (10-20 year) predictions at Corry Lake show a statistically significant ($p<0.05$) positive bias (underestimate) from 4% to 7% of stand basal area and volume. This error results from a large underestimation of stand density (10-16%). The estimates of number of trees are especially low in small diameter classes as illustrated in Figures 11 and 12.

Error evaluation for basal area predictions by merchantable timber classes

The basal area in pole and small sawlog timber classes is predicted with the highest accuracy (absolute error from 3% to 19% in 5- and 10-year predictions), and model efficiency ranges from 68% to 98% for 5-year projections (Tables 8a and 8b; Figures 7 and 8). The projections for larger DBH classes (medium and large sawlogs) are less reliable, with higher absolute errors (Tables 8c and 8d; Figures 9 and 10). In a few instances, the model failed to predict the presence of medium or large sawlogs.

Discussion

FIBER 3.0 was evaluated using data sets originating from various research projects located throughout the Great Lakes—St. Lawrence region in Ontario. The original objective of each project determined the spatial distribution, size of sample plot, and species compositions of stands. All these factors appear to have influenced the performance of the model.

The homogenous stand conditions and large size of plots at Corry Lake may have contributed to the small variation in error predictions, as indicated by the high model efficiency. In contrast, the Algonquin Polar stands are located in 10 townships. Plot/systems in the Algonquin Polar stands were often small, smaller than plots used for model calibration (Solomon *et al.* 1995). The small plot size may be a significant factor contributing to the large range of errors in the Algonquin Polar Plot projections (Tables 3-6 and Figures 3-7). Selection of plots 0.2 ha (and larger) may result in basal area errors being lower than +/-20% for 5- to 20-year predictions. Similarly, Solomon *et al.* (1995) reported 20% of maximum deviation in stand volume predictions when they calibrated FIBER 3.0.

The species composition appears to influence the bias of predictions. The relatively unbiased average error and the small absolute error in predictions of all stand characteristics occurred in stands with 50-70% sugar maple (e.g., ARGS plots - Tables 3-6 and Figures 2-7). In contrast, the Corry Lake (12-50% sugar maple) and Turkey Lakes (82-98% sugar maple) projections are biased. This bias may not result from differences in site quality, as various options of site index value in growth projections do not significantly affect the magnitude of errors. Therefore, species composition rather than site quality caused the poor performance of FIBER 3.0 in the Corry Lake and Turkey Lakes stands.

In all data sets used in the test, variations in stand growth may also be influenced by:

- differences in the various years in which the data was collected, and
- undocumented factors (insect infestations, diseases and timber harvest).

Summary

The results of the validation test of FIBER 3.0 performed on 139 plot/systems can be summarized as follows:

1. The model provides unbiased predictions in basal area for stands when the proportion of sugar maple ranges from 50% to 70%. Predictions of basal area are likely to be underestimated in stands with lower amounts of sugar maple and overestimated when sugar maple

comprises more than 70% of the basal area.

2. Five-year projections of basal area, stand volume, mean quadratic DBH and stand density for a single stand may produce errors from 2% to 12%. The error increases slightly for longer predictions (up to 19% for 20-year predictions in Corry Lake plots).

3. FIBER 3.0 is highly reliable (efficiency above 90%) in 5-year stand volume projections except for data sets with large variations in plot size and stand compositions (Algonquin Polar Plots - 74%).

4. The range of error in stand volume predictions is from 3% to 6% for large plots when sugar maple comprises from 40% to 80% of stand basal area (e.g., ARGS) and from 21% to 35% for smaller plots that have either less than 40% sugar maple or more than 70% (e.g., Algonquin Polar plots).

5. The plot area used for the stand growth projection should be at least 0.2 ha to ensure that errors in basal area projection are below 20%.

6. Diameter distributions and error of projections do not differ significantly between managed and unmanaged stands.

7. Diameter distribution projections in uneven-aged stands may be more accurate than in stands with even-aged structure.

8. The 2 thinning options used in growth projections e.g., thinning from above and interactively used diameter-class removal, differ little in error values.

9. FIBER 3.0 may not sufficiently adjust growth projections to site quality conditions. The model should be recalibrated to reflect site index.

10. FIBER 3.0 projects pole and small sawlog basal area with 3% to 19% average error in a 10-year period. However, it is not reliable for medium and large timber classes.

Table 2. Summary of Kolmogorov-Smirnov Two-Sample Test for the null hypothesis that predicted and observed DBH distributions are identical.

Data set	Prediction period	N	Number of stands with statistically significant difference in DBH distribution[a]
ARGS	5	10	0
	10	10	0
Turkey Lakes	5	13	1
	10	13	2
Beckwith Plots	5	20	6
	10	16	7
	15	11	5
	20	4	1
Corry Lake Woodlot	5	4	0
	10	8	1
	20	8	0
Algonquin Polar Plots	5	88	12

[a] Kolmogorov-Smirnov Two-Sample Test ($p<0.05$)

Table 3. Error statistics of basal area predictions

Data set	Prediction period	N	Average error [s]	Range of error min; max	Absolute error	Modelling efficiency
ARGS	5	10	0.00	-0.03;0.06	0.02	0.91
	10	10	-0.02	-0.15;0.09	0.06	0.03
Turkey Lakes	5	13	-0.05[s]	-0.17;0.04	0.06	0.72
	10	13	-0.10[s]	-0.27;-0.01	0.10	-0.20
Beckwith Plots	5	20	0.04[s]	-0.12;0.20	0.08	0.89
	10	16	0.07[s]	-0.16;0.25	0.09	0.60
	15	11	0.13[s]	-0.12;0.34	0.11	0.33
	20	4	0.15	-0.11;0.43	0.14	0.45
Corry Lake Woodlot	5	4	0.03	0.00;0.07	0.02	0.94
	10	8	0.05[s]	-0.01;0.10	0.05	0.87
	20	8	0.07[s]	-0.01;0.18	0.07	0.60
Algonquin Polar Plots	5	88	0.01	-0.21;0.28	0.09	0.75

[s] value statistically significant (Wilcoxon Rank Test $p<0.05$)

Table 4. Error statistics of stand density predictions

Data set	Prediction period	N	Average error ^{s}	Range of error min; max	Absolute error	Modelling efficiency
ARGS	5	10	0.00	-0.05;0.05	0.02	0.94
	10	10	-0.03	-0.17;0.09	0.07	0.34
Turkey Lakes	5	13	0.02	-0.07;0.15	0.04	0.74
	10	13	0.01	-0.08;0.10	0.04	0.73
Beckwith Plots	5	20	0.05^{s}	-0.09;0.21	0.08	0.89
	10	16	0.07^{s}	-0.14;0.27	0.08	0.84
	15	11	0.10^{s}	-0.15;0.40	0.09	0.68
	20	4	0.01	-0.23;0.19	0.10	0.73
Corry Lake Woodlot	5	4	0.05	-0.01;0.12	0.03	0.64
	10	8	0.10	-0.60;0.26	0.12	0.31
	20	8	0.16	-0.07;0.44	0.19	-0.35
Algonquin Polar Plots	5	88	-0.02	-0.30;0.41	0.12	0.06

^{s} value statistically significant (Wilcoxon Rank Test $p<0.05$)

Table 5. Error statistics of stand volume predictions

Data set	Prediction period	N	Average error [s]	Range of error min; max	Absolute error	Modelling efficiency
ARGS	5	10	-0.001	-0.03; 0.06	0.02	0.93
	10	10	-0.019	-0.15; 0.10	0.06	0.27
Turkey Lakes	5	13	-0.060[s]	-0.20; 0.04	0.07	0.73
	10	13	-0.120[s]	-0.28;-0.02	0.12	-0.09
Beckwith Plots	5	20	0.030	-0.16; 0.22	0.08	0.92
	10	16	0.060	-0.25; 0.26	0.09	0.73
	15	11	0.130[s]	-0.19; 0.36	0.11	0.50
	20	4	0.170	-0.08; 0.44	0.13	0.48
Corry Lake Woodlot	5	4	0.030	-0.01; 0.06	0.02	0.96
	10	8	0.040[s]	-0.01; 0.07	0.04	0.94
	20	8	0.040	-0.02; 0.13	0.05	0.85
Algonquin Polar Plots	5	88	-0.010	-0.21; 035	0.10	0.74

[s] value statistically significant (Wilcoxon Rank Test $p<0.05$)

Table 6. Error statistics of mean quadratic DBH predictions

Data set	Prediction period	N	Average error[s]	Range of error min; max	Absolute error	Modelling efficiency
ARGS	5	10	0.02[s]	0.01;0.04	0.03	0.76
	10	10	0.03[s]	0.01; 0.07	0.03	0.50
Turkey Lakes	5	13	-0.04[s]	-0.06;-0.01	0.04	0.75
	10	13	-0.05[s]	-0.10;-0.01	0.05	0.59
Beckwith Plots	5	20	0.04[s]	0.01; 0.09	0.04	0.92
	10	16	0.04[s]	-0.03; 0.12	0.04	0.87
	15	11	0.06[s]	-0.04; 0.14	0.04	0.75
	20	4	0.11	0.01; 0.17	0.03	0.37
Corry Lake Woodlot	5	4	-0.01	-0.03; 0.02	0.02	0.91
	10	8	-0.02	-0.09; 0.05	0.04	0.55
	20	8	-0.03	-0.12; 0.06	0.06	0.24
Algonquin Polar Plots	5	88	0.01[s]	-0.26; 0.18	0.05	0.61

[s] value statistically significant (Wilcoxon Rank Test $p<0.05$)

Table 7. Summary of error statistics for stand volume, basal area, stand density and mean quadratic DBH predictions. Data grouped by management systems and prediction periods.

Data set	Prediction period	N	Average error min;max	Range of error min;max	Absolute error min;max	Modelling efficiency min;max
Unmanaged-uneven-aged	5	23	-0.06;0.02	-0.20;0.15	0.02;0.07	0.73;0.94
	10	23	-0.12;0.03	-0.28;0.10	0.03;0.12	-0.20;0.73
Unmanaged-even-aged	5	20	0.03;0.05	-0.16;0.22	0.04;0.08	0.89;0.92
	10	16	0.04;0.07	-0.25;0.27	0.04;0.09	0.60;0.87
	15	11	0.06;0.13	-0.19;0.40	0.04;0.11	0.33;0.75
	20	4	0.01;0.15	-0.23;0.44	0.03;0.14	0.37;0.73
Managed-uneven-aged	5	92	-0.02;0.05	-0.30;0.41	0.02;0.12	0.60;0.96
	10	8	-0.02;0.10	-0.09;0.26	0.04;0.12	0.31;0.94
	20	8	-0.03;0.16	-0.12;0.44	0.05;0.19	-0.35;0.85

Table 8. Error statistics of basal area predictions for 4 merchantable timber classes

a) Poles (10-24.9 cm)

Data set	Prediction period	N	Average error [s]	Range of error min; max	Absolute error	Modelling efficiency[x]
ARGS	5	10	-0.04	-0.14; 0.03	0.05	0.92
	10	10	-0.10	-0.32; 0.04	0.11	0.54
Turkey Lakes	5	13	-0.02	-0.06; 0.32	0.07	0.84
	10	13	-0.02	-0.10; 0.15	0.05	0.89
Beckwith Plots	5	20	0.04	-0.13; 0.18	0.09	0.94
	10	16	0.03	-0.33; 0.42	0.12	0.89
	15	11	0.03	-0.24; 0.31	0.14	0.88
	20	4	0.10	-0.35; 0.70	0.36	0.50
Corry Lake Woodlot	5	4	0.04	-0.09; 0.20	0.09	0.68
	10	8	0.09	-0.15; 0.38	0.15	0.35
	20	8	0.20	-0.30; 0.77	0.30	-0.82
Algonquin Polar Plots	5	87 (1)	-0.01	-0.63; 0.54	0.15	0.74[x]

[s] value statistically significant (Wilcoxon Rank Test $p<0.05$)

[x] missing values of residuals are excluded from calculations

The number in brackets represents the number of stands excluded from calculations due to lack of residuals resulting from missing predicted or observed values.

b) Small sawlogs (25- 40.9 cm)

Data set	Prediction period	N	Average error [s]	Range of error min; max	Absolute error	Modelling efficiency
ARGS	5	10	0.01	-0.06; 0.08	0.04	0.94
	10	10	-0.01	-0.19; 0.18	0.07	0.22
Turkey Lakes	5	13	-0.01	-0.16; 0.12	0.05	0.83
	10	13	-0.04	-0.27; 0.16	0.12	0.28
Beckwith Plots	5	20	-0.03	-0.35; 0.14	0.13	0.96
	10	16	0.02	-0.45; 0.33	0.15	0.90
	15	11	0.08	-0.30; 0.38	0.19	0.77
	20	4	-0.04	-0.10; 0.02	0.05	0.91
Corry Lake Woodlot	5	4	0.02	-0.01; 0.05	0.07	0.98
	10	8	0.00	-0.10; 0.05	0.03	0.95
	20	8	0.01	-0.10; 0.27	0.07	0.82
Algonquin Polar Plots	5	88	-0.09	-0.56; 0.50	0.19	0.48

[s] value statistically significant (Wilcoxon Rank Test $p<0.05$);

c) Medium sawlogs (41- 49.9 cm)

Data set	Prediction period	N	Average error[*]	Range of error min; max	Absolute error	Modelling efficiency[x]
ARGS	5	10	0.06	-0.23; 0.53	0.22	-0.47
	10	10	-0.03	-0.37; 0.17	0.15	0.63
Turkey Lakes	5	12 (1)	-0.15	-0.48; 0.22	0.19	0.53[x]
	10	12 (1)	-0.28[*]	-0.79; 0.05	0.27	-0.29[x]
Beckwith Plots	5	3	0.00	-0.16; 0.12	0.12	0.93
	10	6 (6)	0.42	-0.54; 0.97	0.60	0.19[x]
	15	1	0.19	-	0.19	-
	20	1	0.08	-	0.08	-
Corry Lake Woodlot	5	4	0.06	-0.03; 0.14	0.07	0.89
	10	8	0.21[*]	0.02; 0.66	0.21	-0.05
	20	8	0.13	-0.24; 0.54	0.21	0.31
Algonquin Polar Plots	5	43(44)	0.03	-0.76; 0.91	0.35	0.37[x]

* value statistically significant (Wilcoxon Rank Test $p<0.05$)

x missing values of residuals are excluded from calculations

The number in brackets represents the number of stands excluded from calculations due to lack of residuals resulting from missing predicted or observed values.

d) Large sawlogs (≥50 cm)

Data set	Prediction period	N	Average error[s]	Range of error min; max	Absolute error	Modelling efficiency[x]
ARGS	5	10	-0.03	-0.27; 0.12	0.09	0.97
	10	10	0.10	-0.18; 0.51	0.16	0.84
Turkey Lakes	5	11 (2)	-0.15	-0.62; 0.08	0.16	0.77 [x]
	10	11 (2)	-0.18	-0.66; 0.04	0.17	0.59 [x]
Beckwith Plots	5	1	-0.23	-	-	-
	10	1 (3)	0.12	-	-	-
	15	0	-	-	-	-
	20	0	-	-	-	-
Corry Lake Woodlot	5	3 (1)	0.22	-0.16; 0.62	0.40	0.95 [x]
	10	6 (2)	-0.07	-0.62; 0.29	0.18	0.76 [x]
	20	8	-0.05	-0.60; 0.35	0.29	0.76
Algonquin Polar Plots	5	31(56)	0.07	-0.64; 0.93	0.31	0.35 [x]

[s] value statistically significant (Wilcoxon Rank Test $p<0.05$)

[x] missing values of residuals are excluded from calculations

The number in brackets represents the number of stands excluded from calculations due to lack of residuals resulting from missing predicted or observed values.

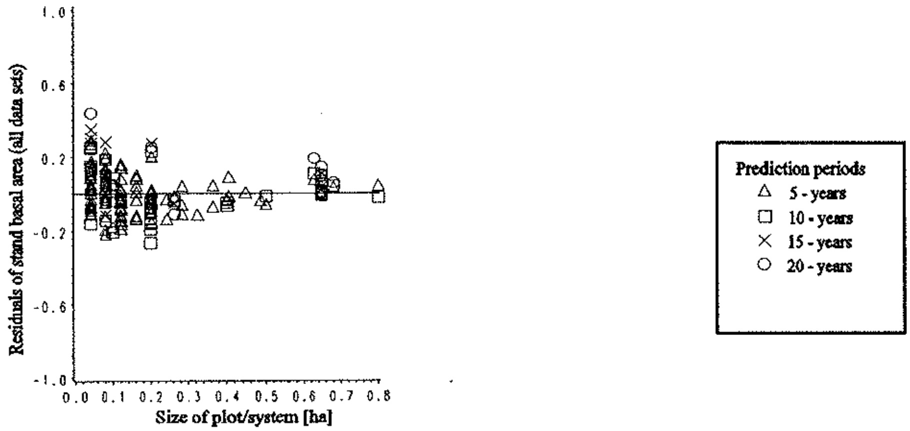

Figure 1. Relationship between residuals of stand basal area and size of plot/system. Data comes from all data sets and all available prediction periods. Residual equals "0" means the perfect fit.

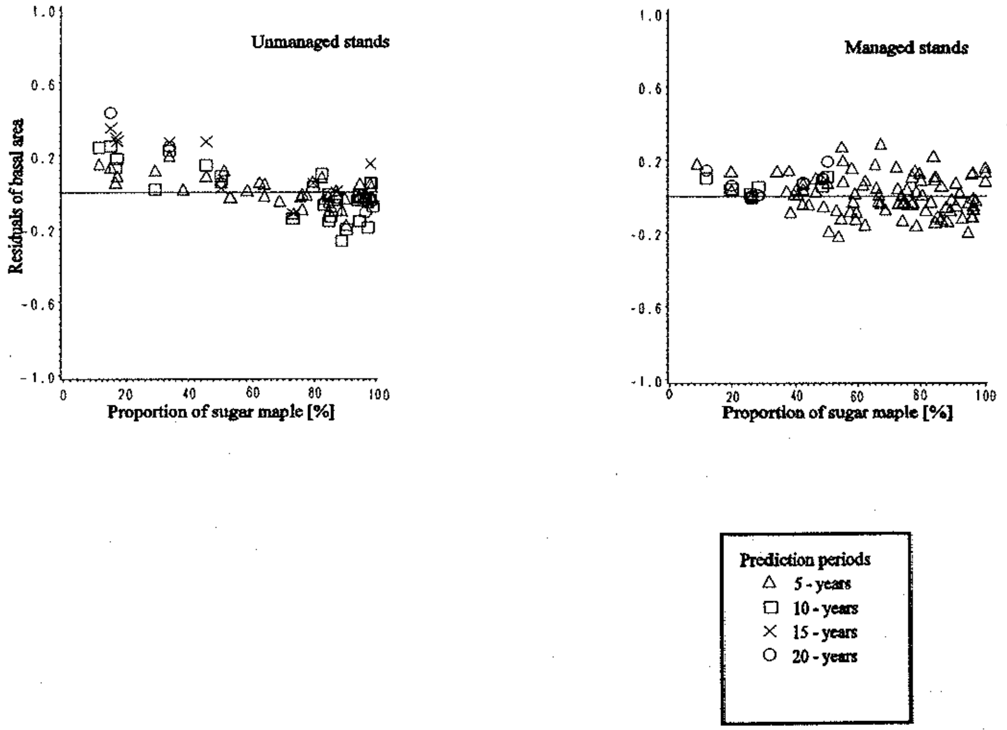

Figure 2. Residuals of stand basal area in relation to proportion of sugar maple (by basal area) for unmanaged and managed stands. The residuals for all data sets are plotted.

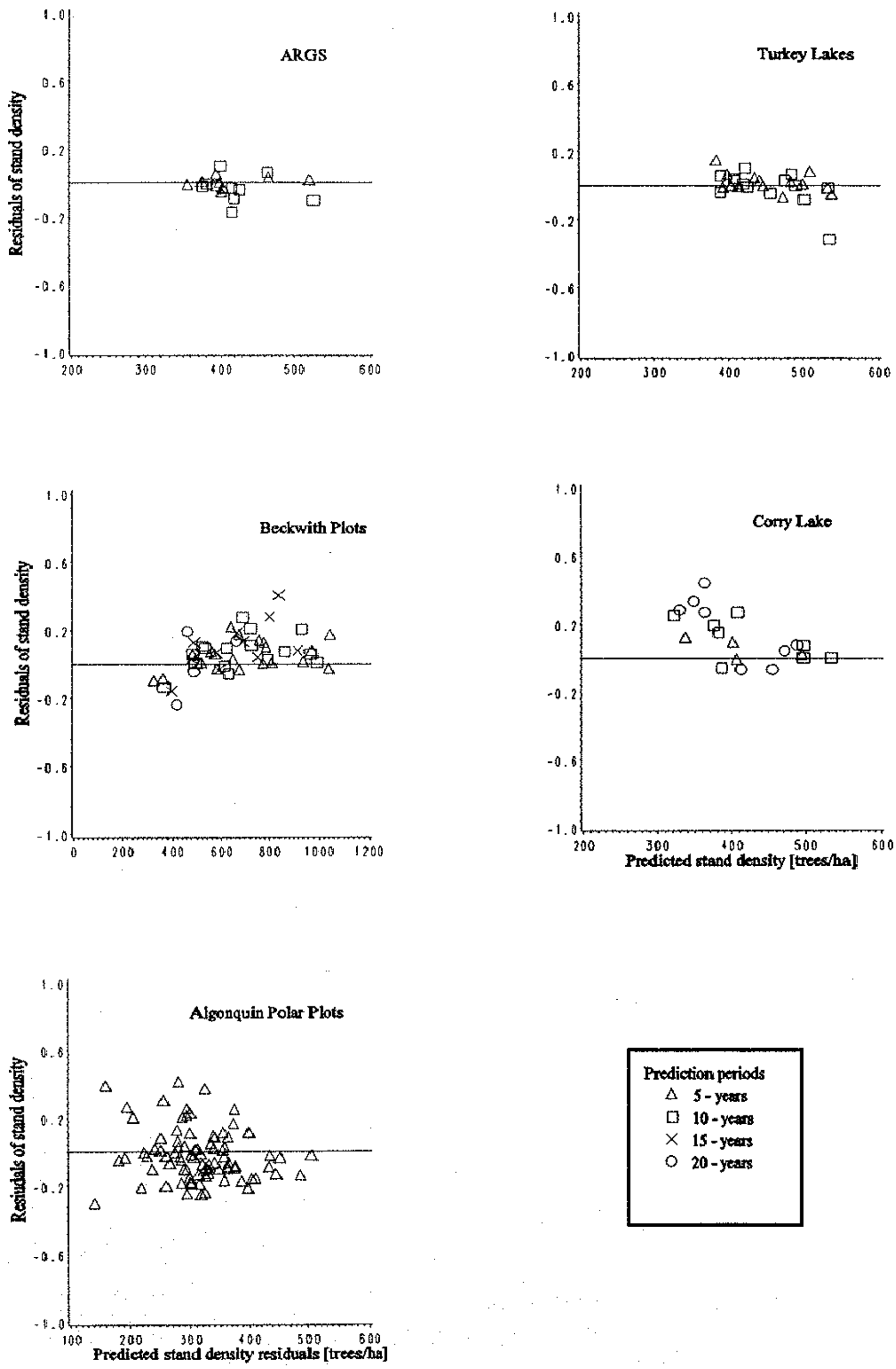

Figure 3. Residuals of stand density for the 5 data sets and all available prediction periods.

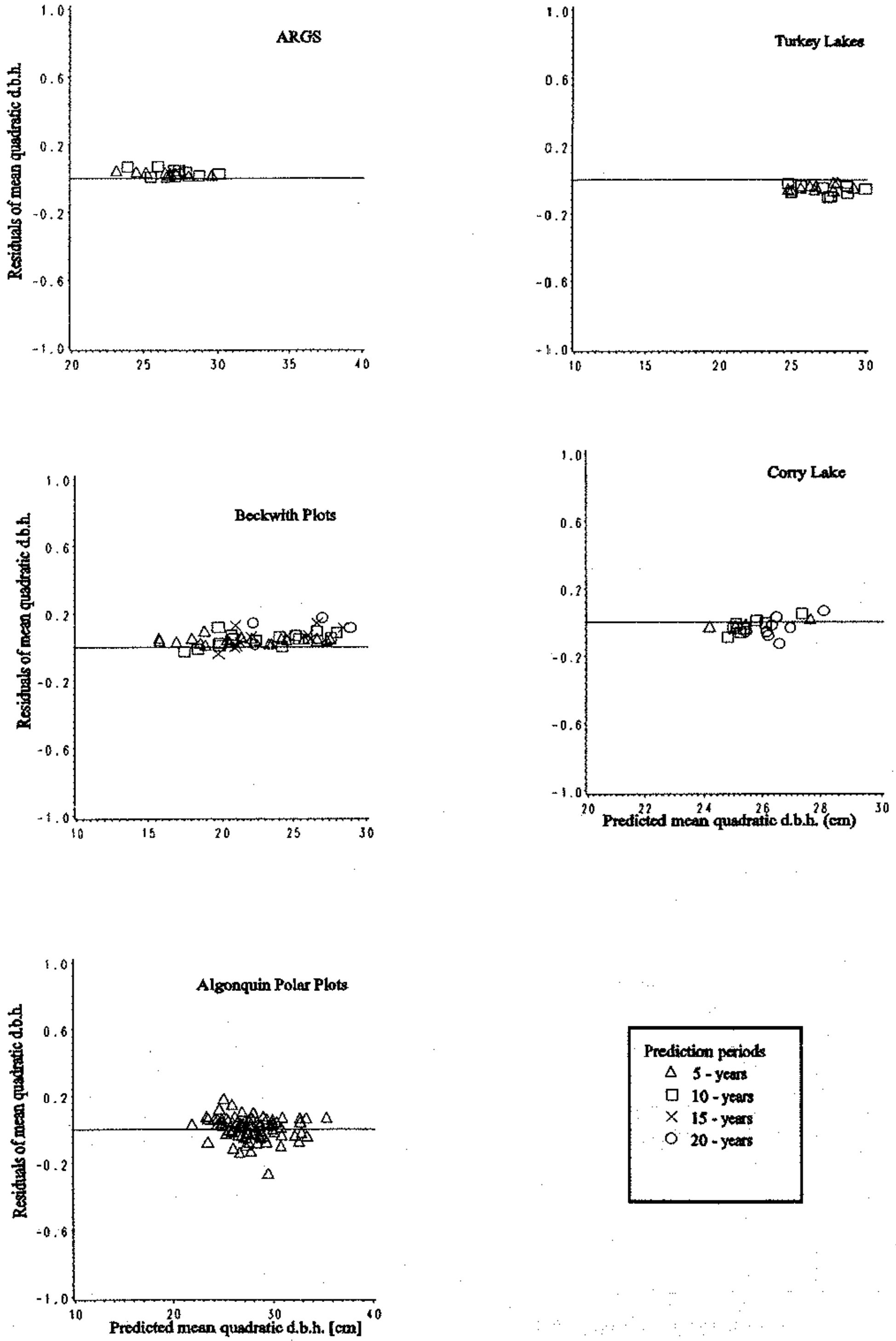

Figure 4. Residuals of mean quadratic DBH for the 5 data sets and all available prediction periods.

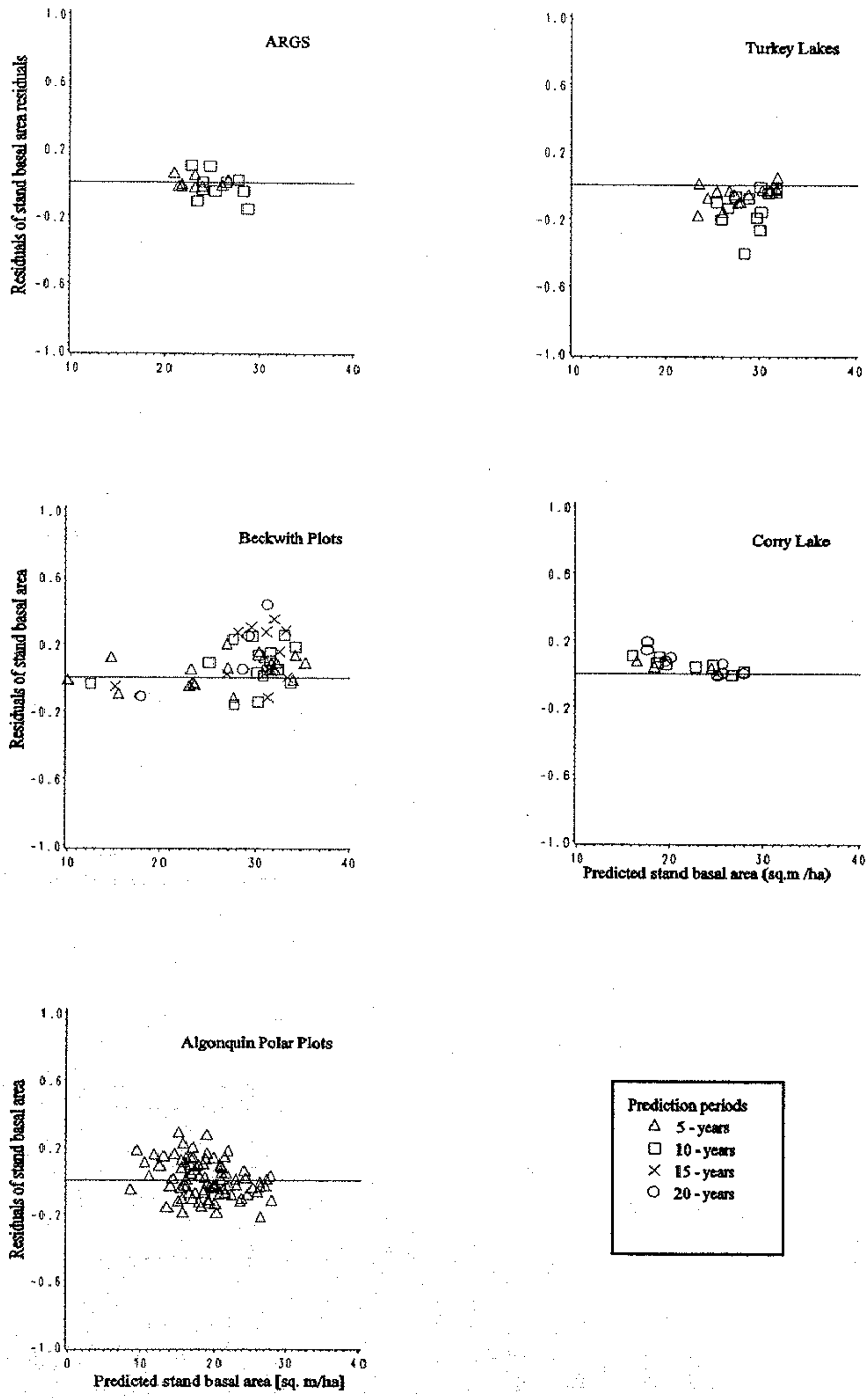

Figure 5. Residuals of stand basal area for the 5 data sets and all available prediction periods.

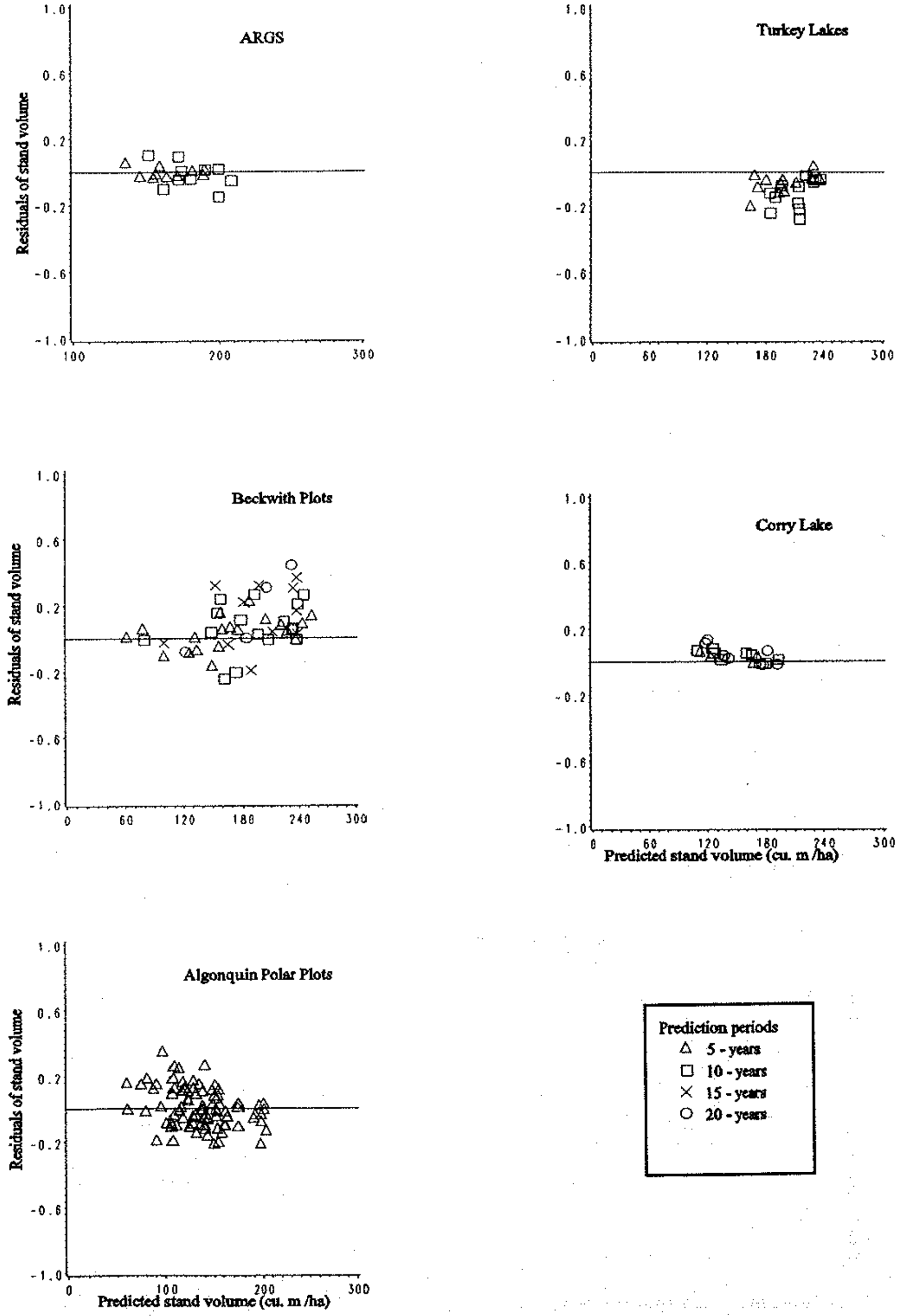

Figure 6. Residuals of stand volume for the 5 data sets and all available prediction periods.

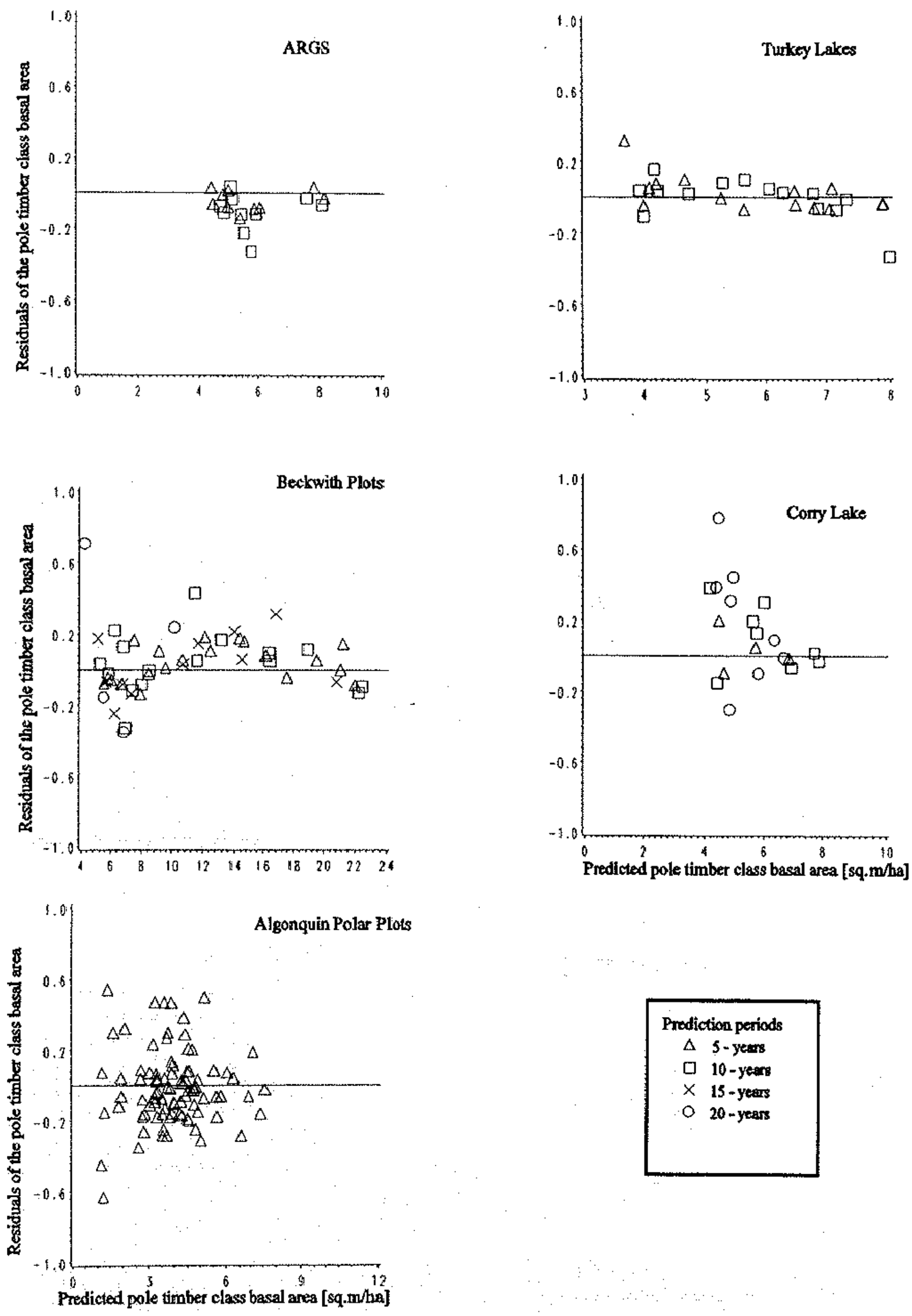

Figure 7. Residuals of the pole timber class basal area for the 5 data sets and all available prediction periods.

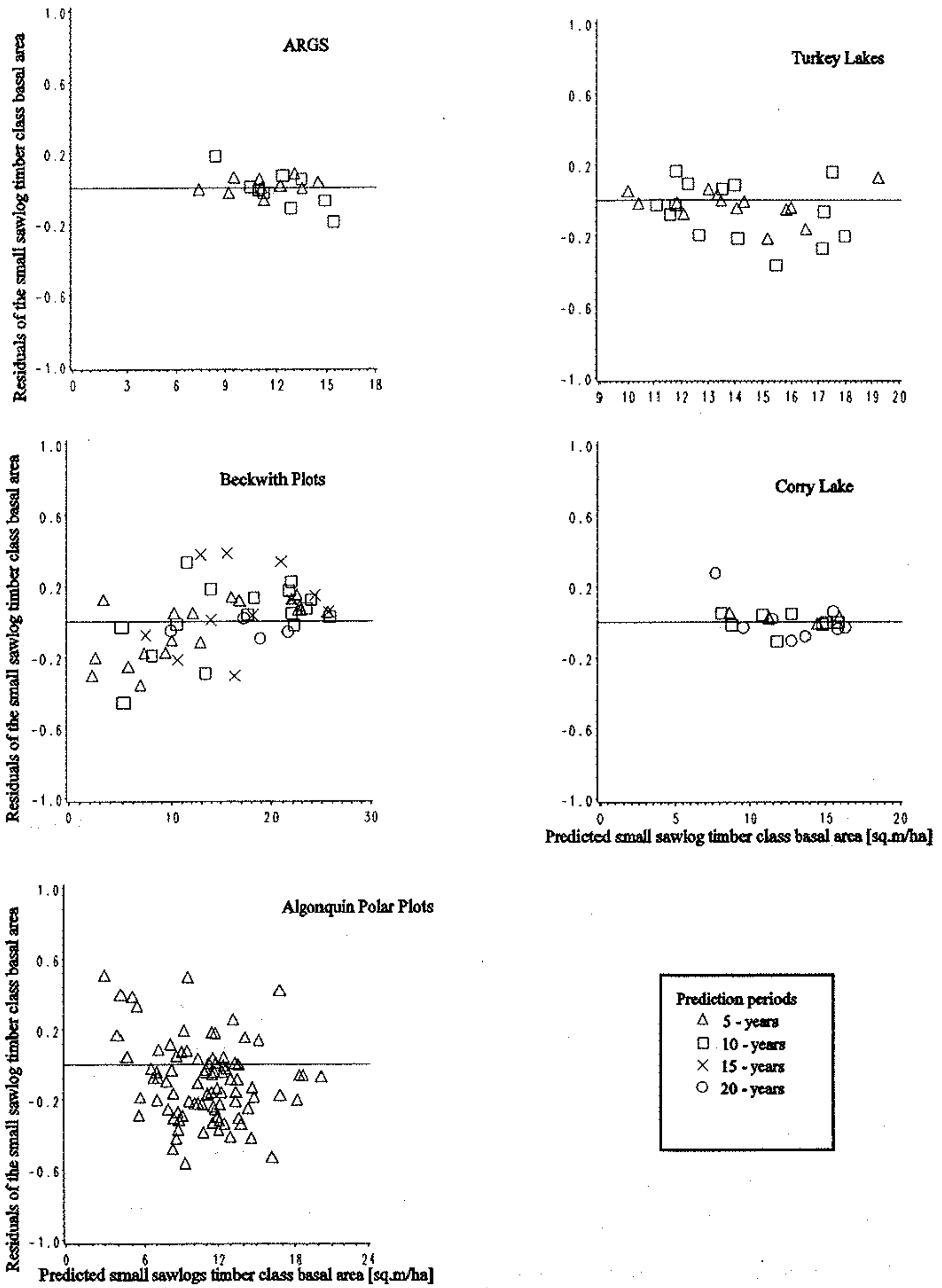

Figure 8. Residuals of the small sawlog timber class basal area for the 5 data sets and all available prediction periods.

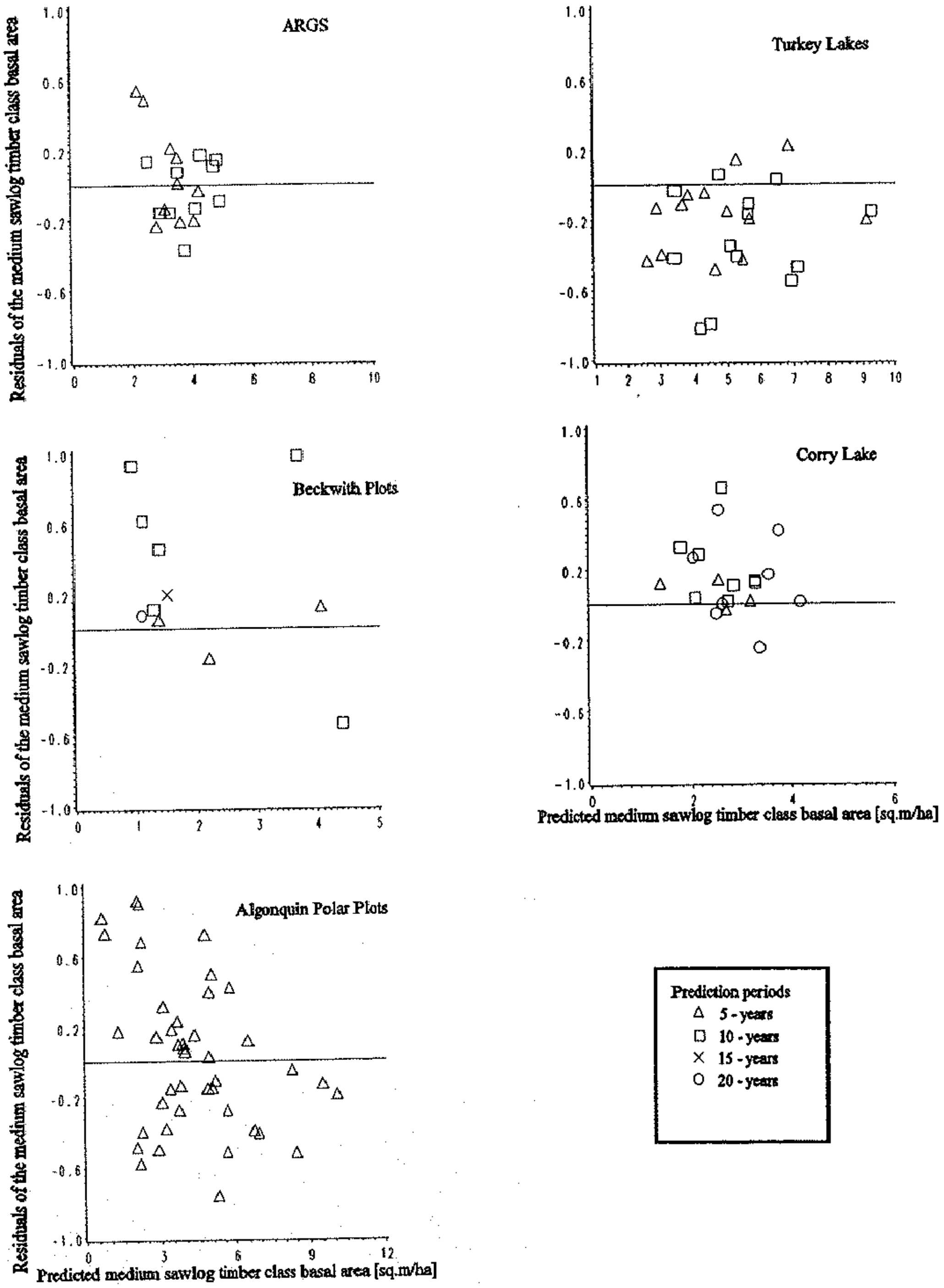

Figure 9. Residuals of the medium sawlog timber class basal area for the 5 data sets and all available prediction periods.

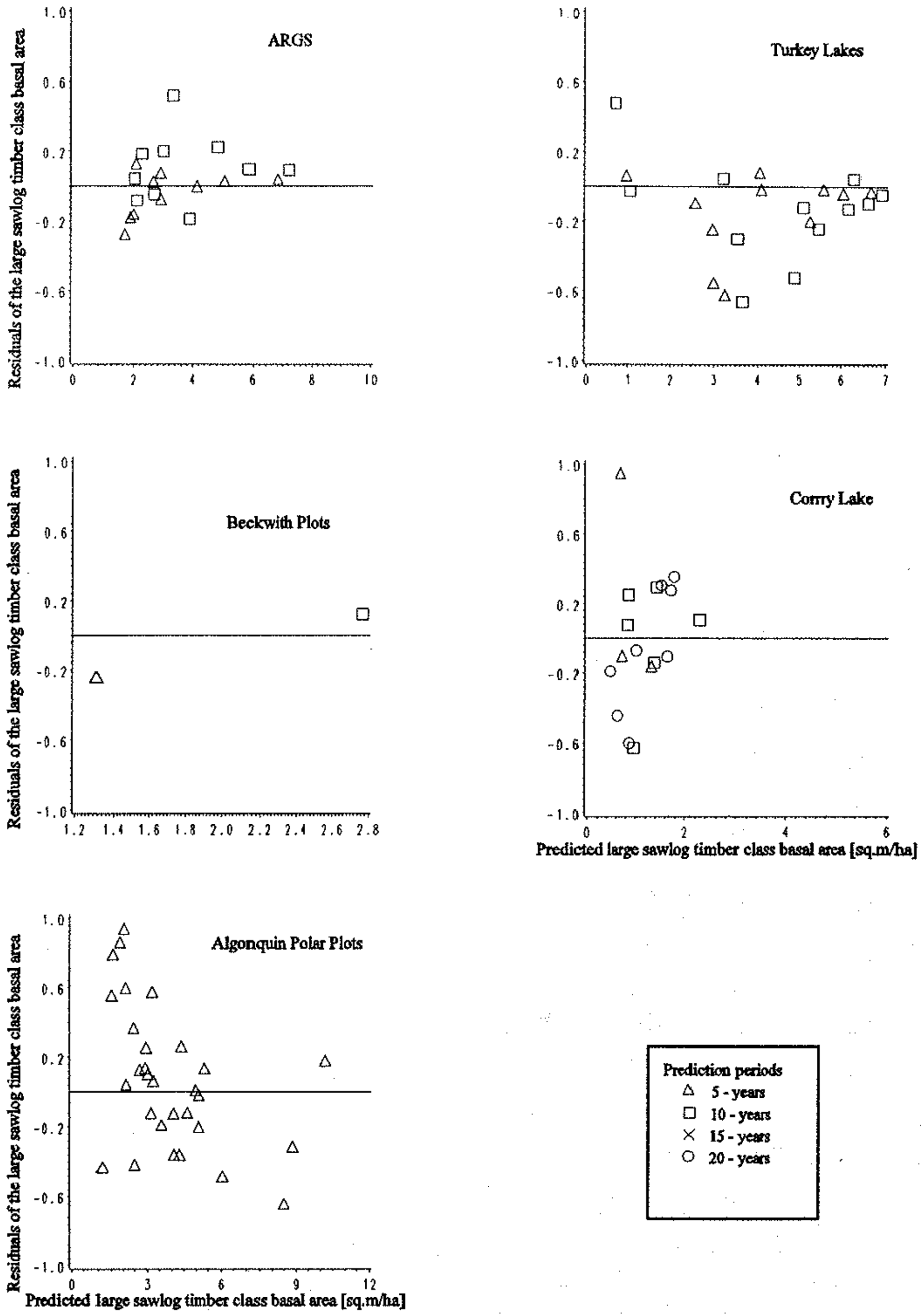

Figure 10. Residuals of the large sawlog timber class basal area for the 5 data sets and all available prediction periods.

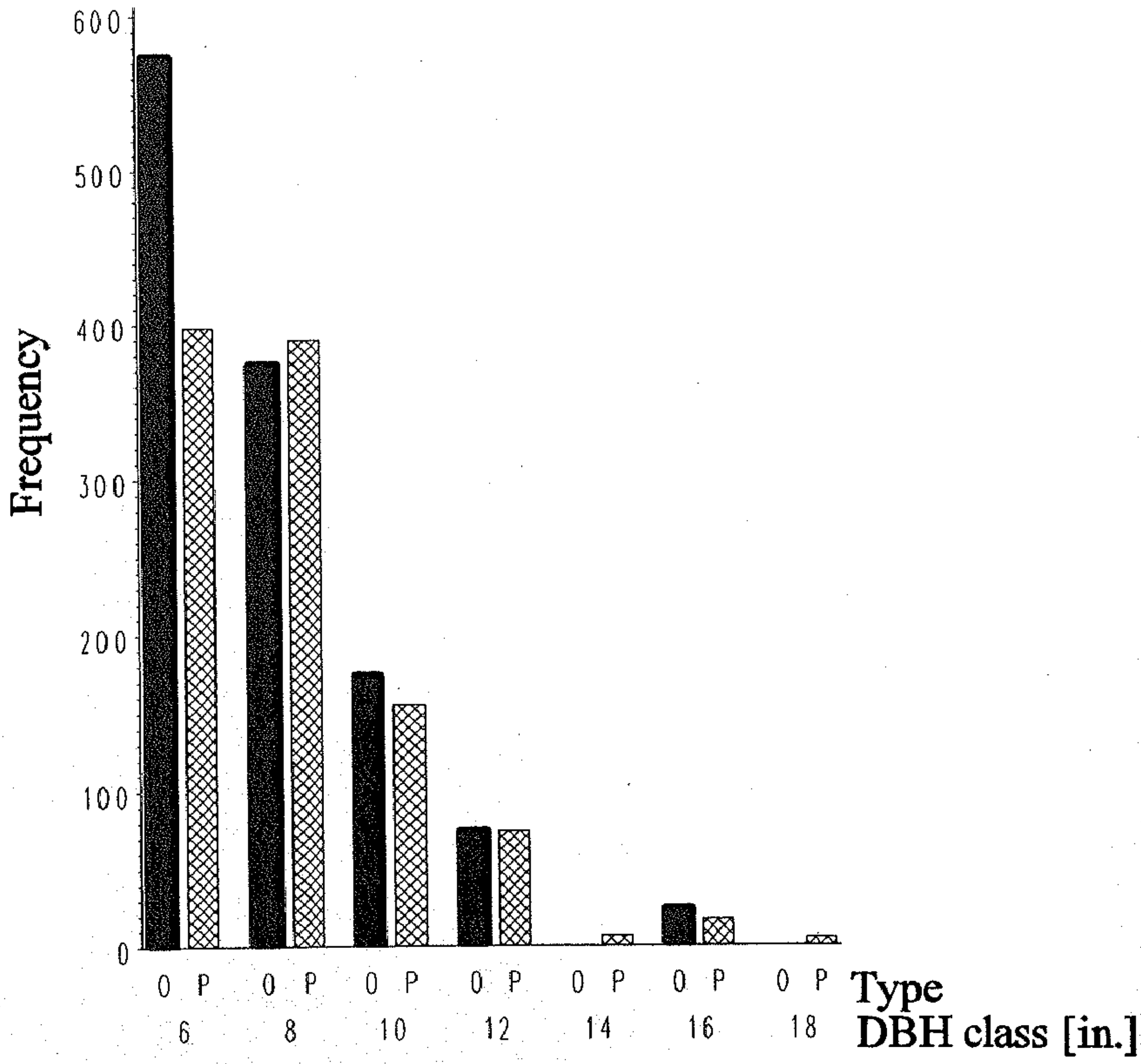

Figure 11. An example of unequal diameter distributions (predicted = "P"; observed = "O") that failed to meet the Kolmogorov-Smirnov Two-Sample Test of equality of distributions ($p<0.05$).

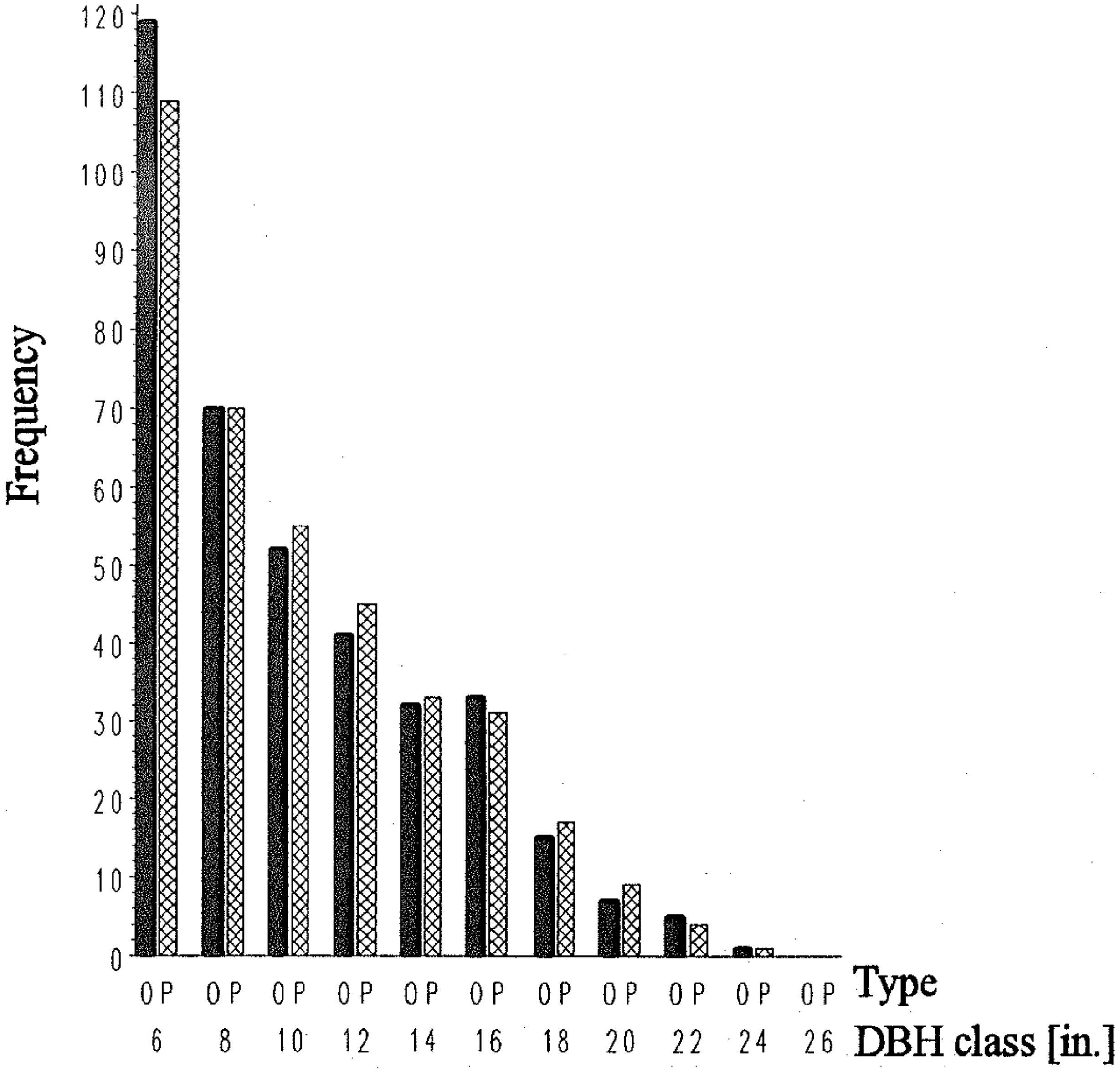

Figure 12. An example of equal diameter distributions (predicted = "P"; observed = "O") for the 5-year projection. The hypothesis of equality of distributions was supported by the Kolmogorov-Smirnov Two-Sample Test (p<0.05).

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