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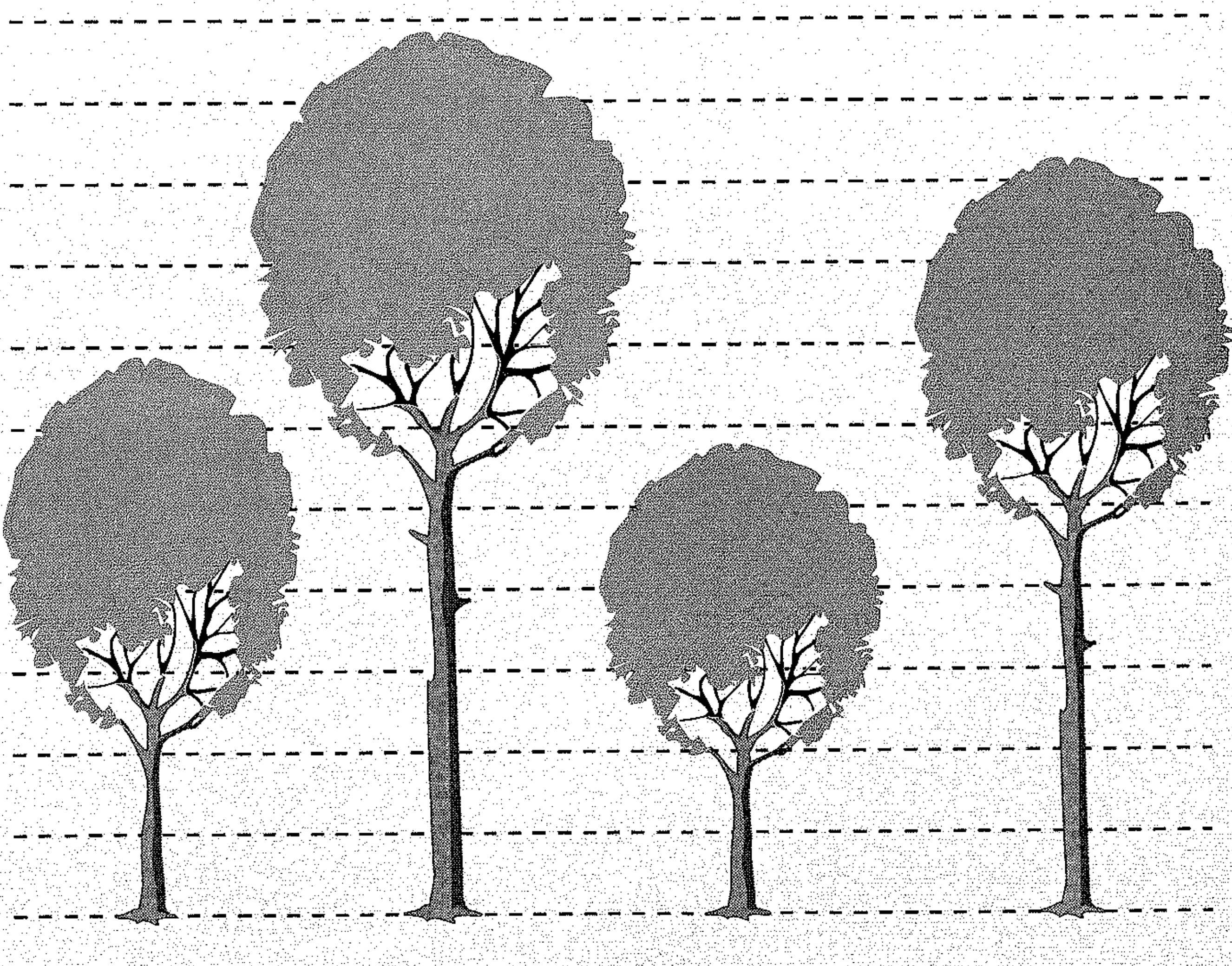
Validation of SILVAH for Tolerant Hardwoods in Ontario



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Ontario Forest Research Institute

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Validation of SILVAH for Tolerant Hardwoods in Ontario

by

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Abstract

Jacek Bankowski, Dan Dey, Murray Woods, Jim Rice, Eric Boysen and Roj Miller. 1995. Validation of SILVAH for tolerant hardwoods in Ontario. Ontario Ministry of Natural Resources, Ontario Forest Research Institute, Sault Ste. Marie, Ontario, Forest Research Information Paper No. 128, 28 p.

SILVAH, a stand growth simulator commonly used in the northeastern United States, has been evaluated by comparing predicted and actual growth of tolerant hardwoods in southern Ontario. The data came from 139 stands, unmanaged or managed (thinned), even-aged or uneven-aged. The data were used to test the accuracy of diameter distribution, basal area, mean quadratic DBH, number of trees per hectare, and stand volume predictions for periods from 5 to 20 years. The accuracy of short-term basal area projections, expressed by modelling efficiency, ranged from 62% to 94%. The reliability of stand density projections was especially low (modelling efficiency from 15% to 88%). Despite underpredicting the number of trees in small DBH classes, SILVAH provided reliable predictions of DBH distribution, especially for uneven-aged, unmanaged stands. Basal area of stands was underestimated by 2% to 6% on the average for 5-year projections (except for low productivity sites). During the same projection period, the error of predicted individual stand basal area ranged from -22% to 25%. Prediction bias increased with longer projection periods. The trend of underestimating stand density and overestimating mean quadratic DBH resulted from low predicted numbers of small DBH trees. Consequently, the basal area of pole and small sawlog timber classes was underestimated (on the average 1% to 28% in 5 years). A few factors contributed to the poor performance of the model: 1) lack of ingrowth data or lack of an automatic ingrowth submodel; 2) incompatibility of model requirements and data sets related to the range of tree sizes in the input list; and 3) inability of the model to account for differences in site productivity.

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

Acknowledgments

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We are especially grateful to Voyteck Zakrzewski for initiating this project and to Michael Ter-Mikaelian and Kadiroo Jayaraman for their valuable suggestions. We acknowledge the efforts of Abby Obenchain and Jim Hayden for their involvement in the preparation of this document. Funding was provided by the Sustainable Forestry Initiative.

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Introduction

This paper presents the results of a validation test of the stand growth simulator SILVAH 4.0—Silviculture of Allegheny Hardwoods (Marquis and Ernst 1992). The test is consistent with methods and data sets used in the validation test of FIBER 3.0 (Bankowski *et al.*1995). Results of this work will be used to select the most suitable stand growth simulators in tolerant hardwoods stands in Ontario. FIBER, SILVAH, TWIGS and FPS are being evaluated.

Description of SILVAH

The SILVAH system is designed for practicing foresters whose primary goal is high-quality sawtimber production, but it includes options and modifications for incorporating wildlife, aesthetics, recreation, and other forest values. This expert system is intended for use in the cherry-maple, beech-birch-maple, and oak-hickory forests in the Allegheny Region of the Northeastern United States, including Pennsylvania, New York, Ohio, West Virginia, Maryland, and New Jersey. See the flow chart (next page) for model input requirements and type of output.

The SILVAH stand growth model was originally developed for the Allegheny hardwoods—a variation of northern hardwood forest in which black cherry is a major component. Growth data used in the development of SILVAH came from 2 major sources. Data on the cherry-maple and beech-birch-maple types were generated from long-term research plots in northwestern Pensylvania (up to 53 years of continuous record). Data on the oak-hickory type in SILVAH came from OAKSIM (Hilt 1985).

Allegheny hardwood species differ greatly in growth rate and tolerance to shade. These differences complicate the determination of the optimum growing space conditions to maintain the maximum yield. Thus, the absolute measures of stand density, such as basal area or numbers of trees per hectare, may not reflect the actual growing-space conditions. Instead, SILVAH uses a relative measure of stand density calculated from the tree area ratio equation calibrated for undisturbed stands (relative density = 100%). The relative stand density (R) equation has the following form (Stout and Nyland 1986):

$$R = \sum_i (\alpha_i N_i + \beta_i \sum_k D_{ik} + \gamma_i \sum_k D_{ik}^2)$$

where,

N_i = number of trees per unit area of i-th species group,
D_{ik} = diameter of k-th tree of the i-th species groups [inch], and
$\alpha_i, \beta_i, \gamma_i$ = coefficients for i = 1,...,3 species group listed in Table 1.

Table 1. Coefficients for the relative stand density equation in SILVAH (Anonymous, 1995).

#	Species group	α	β	γ
1	Black cherry, white ash, yellow poplar	0.33033	0.20426	0.006776
2	Red maple, red oak and others	-0.27142	0.24257	0.015225
3	Sugar maple, American beech, and oaks others than red	-0.027935	0.058959	0.047289

Flow Chart

(Includes information related to growth simulator)

Input:

Regeneration data
- species
- weighted number of seedlings

Overstory data:
Stand table-number of trees in 1" or 2" DBH classes by species and quality class

Site info:
- elevation
- site index
- stand age
- plot size

Treatment specification
- precommercial, combination of pulp, sawlog and commercial, thin harvest, selection cut, or shelterwood
- minimum relative density desired
- distribution of cut
- cutting priority

projection period (various)

Output:

Stand characteristics:
- basal area
- quadratic mean DBH
- q-value
- number of trees per acre
- relative density
- volume

Characteristics by species, size class, quality class, timber class:
- number of trees per acre
- basal area
- volume
- relative density

Text describing stand, management prescriptions, and silvicultural recommendations

SILVAH is a distance-independent, individual-tree growth model. The form of growth and mortality equations differs among relative stand density classes and species, reflecting various species growth patterns. Thus, the model includes sets of equations for each of the 5 species groups:

1. Sugar maple
2. American beech-hemlock
3. Black cherry-yellow poplar
4. Oak species
5. Red maple and others (5a. yellow and black birch — is treated as a separate group in the mortality function).

Coefficients of equations differ in each of 4 relative stand density classes. SILVAH recognizes the following relative stand density classes: below 50%, from 50% to 80%, from 80% to 95%, and above 95%. For species groups 1, 2 and 5, the diameter growth equation has the following form:

$$\Delta DBH = \alpha_{ij} + \beta_{ij} D - \gamma_{ij} D^2 - \delta_{ij} R$$

where,

ΔDBH = diameter increment for individual trees,
D = relative tree DBH, D = DBH/mean stand diameter,
R = relative stand density, and
$\alpha_{ij}, \beta_{ij}, \gamma_{ij}, \delta_{ij}$ = coefficients specific for each species group (i = 1,...,3) and relative stand density class (j = 1,...,4).

For black cherry and yellow poplar (species group 3) the equation form is:

$$\Delta DBH = \alpha_j + \beta_j \log_{10} D - \delta_j R$$

where,

coefficients $\alpha_j, \beta_j, \gamma_j$ and δ_j are specific for each relative stand density class.

Growth for the oak species (species group 4) is calculated in basal area increment (ΔBA) and then converted to diameter growth (Hilt 1985):

$$\Delta BA = \alpha(SI^{\beta}) * \exp(\gamma DQ - \delta R) * DBH^2$$

where,

SI = site index,
DQ = quadratic mean DBH,
R = relative stand density,
DBH = diameter at breast height, and
$\alpha, \beta, \gamma, \delta$ = coefficients.

The probability of mortality (PMORT) for an individual tree is determined at the beginning of each 5-year projection with the following function:

$$PMORT = \alpha_{ij} + \frac{\beta_{ij}}{D}$$

where,

PMORT = 5-year mortality rate of each species - DBH class [%],
D = relative tree DBH calculated as DBH/mean stand diameter, and
α_{ij}, β_{ij} = coefficients for species group (i = 1,...,3, 5a) and relative density group(j = 1,...,4).

The mortality function for the red maple and other species (including oak but excluding birches) is:

$$PMORT = \alpha_j + \beta_j \log_{10} D$$

where D is as defined earlier.

Data Description

The data used to validate SILVAH has been previously described by Bankowski *et al.* (1995). A summary of the data sets is shown in Table 2.

Testing Procedures

Trees were grouped into 1" (2.5 cm) DBH classes from 5" to 32" (12.7 to 81.3 cm) for each tree species and quality class (2 quality classes: acceptable growing stock and unacceptable growing stock based on stem quality). Only trees with a DBH larger than 4.5" (11.4 cm) were included in further testing. Data sets were tested separately because of differences in the data-collection method, age structure, and management

Table 2. Description of data sets used for the validation test of SILVAH 4.0.

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[1]	-180	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[2]	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

[1] UA = unevenaged stands.

[2] Measurements for each period were done in various calendar years.

system. Measurements from plots were grouped by stands (plot/systems) and growth of stands was projected by the number of 5-year periods equal to the measured intervals (1 to 4 5-year intervals). For most projections, the information about site quality was not available; thus an average value of site index was selected (e.g., 21.3 m at age 50 for sugar maple). For the Corry Lake and Turkey Lakes projections, however, 2 site index values were evaluated: an average value (21.3 m) and a value derived from stand descriptions (24 m for Corry Lake and 18 m for Turkey Lakes).

Thinning option in managed stands

The objective was to simulate the thinning procedure as close as possible to field conditions. SILVAH does not have a thinning option that allows the removal of trees in each DBH class. Therefore, the removal priority was set up as a selection thinning. The specified relative density area was attained through removing trees until the specified q-factor of the observed diameter distribution was obtained. The actual relative density for each stand was calculated before and after treatment using equations from Stout and Nyland (1986) and coefficients from SILVAH 4.0 software (Anonymous 1995). In addition, for each stand, the field conditions were mimicked using the maximum tree size DBH and uniform type of removal below and above quadratic mean DBH.

Diameter distribution projections

The Kolmogorov-Smirnov Two-Sample Test (Steel and Torrie 1980) was used to examine whether observed and predicted DBH distributions are identical. In the Kolmogorov-Smirnov 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 the stand growth simulation with each data set were examined by comparing the predicted and observed values of stand density (number of trees per hectare), quadratic mean DBH, basal area and volume. Volume tables from SILVAH were used to calculate predicted and "observed" stand volume. To evaluate SILVAH'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 to 24.9 cm)
- Small sawlogs (25 to 40.9 cm)
- Medium sawlogs (41 to 49.9 cm)
- Large sawlogs (≥50 cm)

The observed basal area of each product class was compared to the predicted basal area in each stand. All values were processed in imperial units and then translated to metric units. Residuals values were computed as follows:

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

where,

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

The prediction error was analysed using plots of the residuals (r) vs. predicted values of density, basal area, volume and quadratic mean DBH. Similarly, residuals were plotted vs. basal area for each of the 4 merchantable timber classes.

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 technique used to compare 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,

E_m = modelling efficiency; y_i = observed value; y_i' = predicted value; 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 that 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 and Discussion

Diameter distribution

The trend of underpredicting the number of trees in small DBH classes is illustrated in 2 stands (Figures 1 and 2). This trend may be caused by a lack of trees less than 4.5" (11.4 cm) DBH in the input data sets at the beginning of projection period. The SILVAH model was primarily developed for stands including all trees larger than 1" (2.5 cm) DBH. Therefore, the gap in the input data for 1" to 4.5" (2.5 to 11.4 cm) DBH trees may have resulted in lower numbers of 6" to 8" (15.2 to 20.3 cm) DBH trees by the end of the prediction period.

For both even-aged and uneven-aged managed stands, the Kolmogorov-Smirnov test showed that less than 18% of predicted diameter distributions were statistically ($P<0.05$) different from observed DBH distributions (Table 3). SILVAH provides a reliable prediction of DBH distribution for uneven-aged stands (ARGS, Turkey Lakes and Corry Lake).

Error evaluation for predictions of stand density, basal area, quadratic mean DBH, and stand volume

The variation among data sets, which results from the size of plot/system area, has a significant impact on the magnitude of prediction errors. Figure 3 illustrates the impact of the plot/system area on residuals of basal area predictions. When sample plots are larger, the basal area is predicted more accurately, and variance of basal area residuals are smaller. The species composition (e.g., proportion of sugar maple) does not influence model performance (Figure 4).

The Corry Lake and Turkey Lakes projections with 2 site index options do not show substantial discrepancies in stand volume, basal area, density, and quadratic mean DBH (results are not shown). Thus, site index values in the range of 18.2 to 24.4 m do not have a significant influence on prediction errors. The low model sensitivity to site index values seems to be logical because the percentage of red oak in the study stands was small, and oak is the only species group in SILVAH for which site index is used in the growth equations.

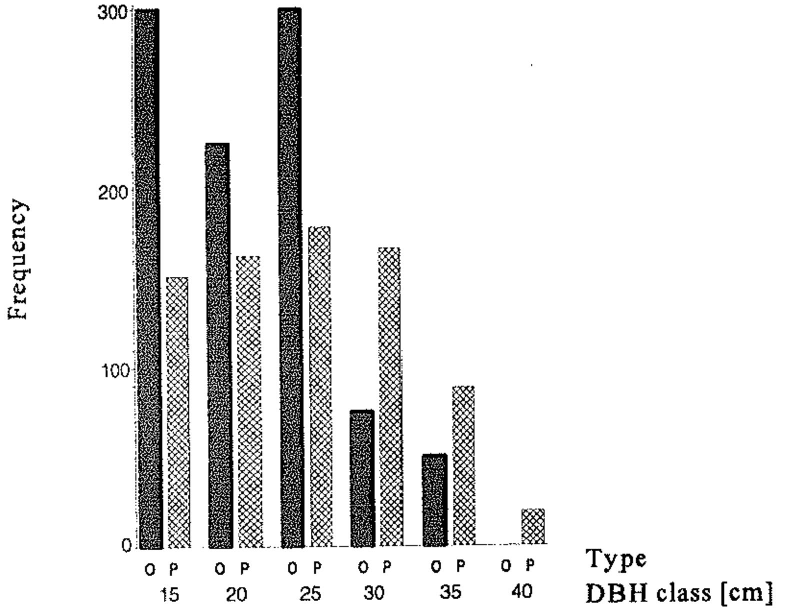

Figure 1. The example of unequal diameter distributions (predicted = "P"; observed = "O") for the stand failing the Kolmogorov-Smirnov Two-Sample Test of equality of distributions ($P<0.05$).

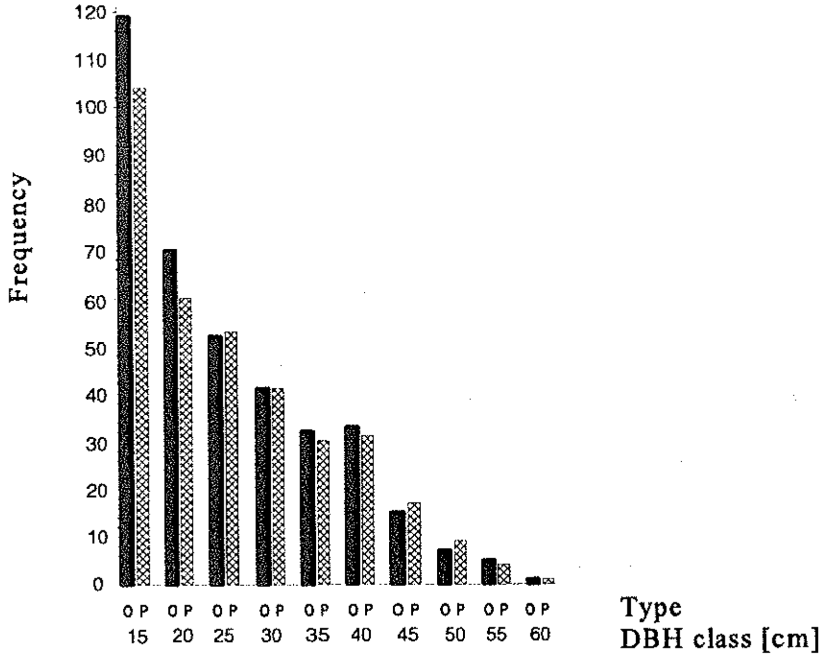

Figure 2. The example of equal diameter distributions (predicted = "P"; observed = "O") for the 5-year projection. The hypothesis of equality of distributions is supported by the Kolmogorov-Smirnov Two-Sample Test ($P<0.05$).

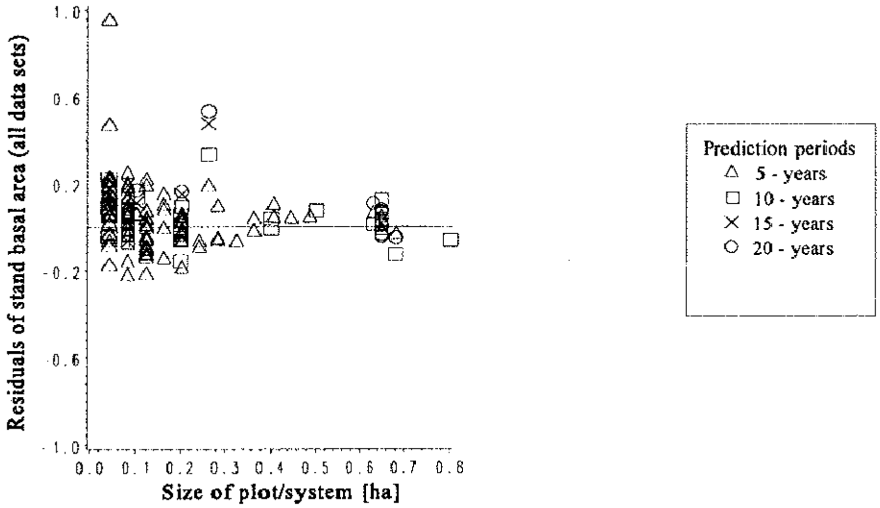

Figure 3. Relationship between residuals of stand basal area and size of plot/system. Data from all data sets and all available prediction periods was included. Residual equals "0" means the perfect fit.

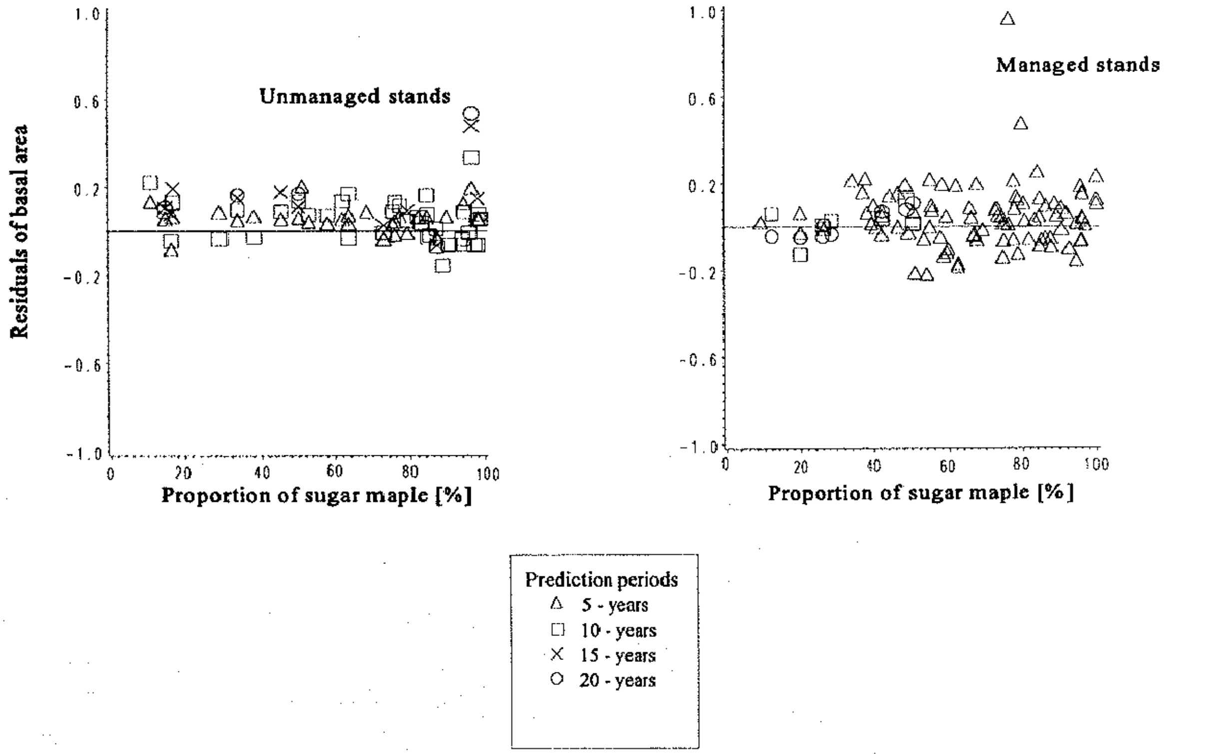

Figure 4. Residuals of stand basal area in relation to proportion of sugar maple (by basal area) for unmanaged and managed stands. The residuals for all data sets are plotted.

Table 3. 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
ARGS	5	10	0
	10	10	0
Turkey Lakes	5	13	0
	10	13	0
Beckwith Plots	5	20	3
	10	16	3
	15	11	2
	20	4	1
Corry Lake Woodlot	5	4	0
	10	8	0
	20	8	0
Algonquin Polar Plots	5	88	19

I. Uneven-aged, unmanaged stands

The modelling efficiency for 5-year basal area predictions for the Turkey Lakes stands is approximately 30% higher than in the ARGS data set (Table 6). In longer predictions (10 year), the modelling efficiency decreases significantly for both data sets. For both data sets that represent uneven-aged, unmanaged stands (ARGS and Turkey Lakes), the 5- and 10-year predictions for quadratic mean DBH are overestimated (Table 4, Figure 5). Stand density estimates are significantly less than the observed number of trees ($P<0.05$) (Table 5, Figure 6). The stand basal area projections for Turkey Lakes are unbiased (Table 6, Figure 7). SILVAH significantly ($P<0.05$) underestimated basal area for the ARGS stands.

Several factors may be influencing the performance of SILVAH in predicting basal area. SILVAH estimates of the number of trees in smaller DBH classes are less than the observed density, and projections of the number of trees in larger DBH classes are higher than observed values. The lower number of trees estimated in the small DBH classes may be the result of a lack of regeneration and ingrowth data; insufficient input (SILVAH considers all trees above 1" (2.5 cm), while only trees above 4.5" (11.4 cm) were used in this test); or a result of overestimations of mortality or DBH increment.

To test the sensitivity of the model to input requirements, stands from Turkey Lake with trees larger than 2" (5 cm) DBH (original data set included measurements above 2" (5 cm)) and regeneration data (fictional) were used for growth projections. Comparison of predicted and observed number of trees in the lower DBH classes showed smaller differences when input trees $\geq$ 1" (2.5 cm) DBH were considered. However, the overall influence on stand density (observed vs. predicted) was insignificant.

The expected error for a single stand prediction (absolute error) is 1% to 9% in 5-year predictions and 2% to 14% in 10-year predictions for unmanaged, uneven-aged conditions (Table 8).

II. Even-aged, unmanaged stands

For the Beckwith stands, the modelling efficiency decreases from a range of 88% to 94% in 5-year projections to a range of 78% to 79% for 20-year estimates (Table 8). SILVAH underestimates (up to 7%) all stand characteristics in the 5-year simulation with the Beckwith data. Model biases ranged from 6% to 29% in 20-year predictions. Average errors (bias) of stand density, basal area and stand volume are statistically significant (Tables 5, 6 and 7 and Figures 6, 7 and 8). Projections of quadratic mean DBH are unbiased (except the 20-year projections), and the absolute error has lower values than other stand characteristics (Table 4, Figure 5). Absolute error for all stand characteristics ranges from 1% to 11% for all prediction periods (Table 8).

III. Uneven-aged, managed stands

For 5-year projections, the modelling efficiency for the Corry Lake simulations, represented by large sample plots, is higher (40% to 94%) than for the Algonquin Polar Plots (21% to 73%). This difference is attributed to variation in geographical location of the data sets and variation in sample plot size between the 2 studies.

Trends in the 5-year projections of stand density, quadratic mean DBH, and basal area for Corry Lake and Algonquin Polar Plot stands that were thinned are comparable to those for unmanaged stands (Tables 4, 5, 6 and 7; Figures 5, 6, 7 and 8). Projections of stand density and basal area are underestimated, and quadratic mean DBH is overestimated. The biases in Algonquin Polar Plot stand density, basal area, and quadratic mean DBH projections are statistically significant ($P<0.05$). The range of error for all stand characteristics is larger than in unmanaged stands (from 25% to 84% for all predictions). The lower performance in managed stands may be related more to the smaller size of sample plots in the Algonquin Polar Plots than to the thinning simulation.

The longer (10- to 20-year) predictions for Corry Lake show a small bias (under-estimate) from 4% to 7% in stand basal area. This error results from a large under-estimation in stand density (13% to 25%).

Table 4. Error statistics of quadratic mean DBH predictions.

Data set	Prediction period	N	Average error	Range of error (min;max)	Absolute error	Modelling efficiency
ARGS	5	10	-0.004	-0.03;0.01	0.01	0.92
	10	10	-0.003	-0.04;0.04	0.02	0.74
Turkey Lakes	5	13	-0.05[1]	-0.06;-0.02	0.05	0.60
	10	13	-0.081	-0.12;-0.04	0.08	0.08
Beckwith Plots	5	20	-0.002	-0.14;0.05	0.02	0.93
	10	16	-0.003	-0.15;0.09	0.03	0.89
	15	11	0.001	-0.20;0.09	0.03	0.73
	20	4	0.06	0.02;0.13	0.01	0.79
Corry Lake Woodlot	5	4	-0.02	-0.06;0.00	0.01	0.75
	10	8	-0.051	-0.12;-0.02	0.05	0.12
	20	8	-0.101	-0.15;-0.04	0.10	-1.21
Algonquin Polar Plots	5	88	-0.051	-0.25;0.07	0.05	0.21

[1] This value is statistically significant (Wilcoxon Rank Test $P<0.05$).

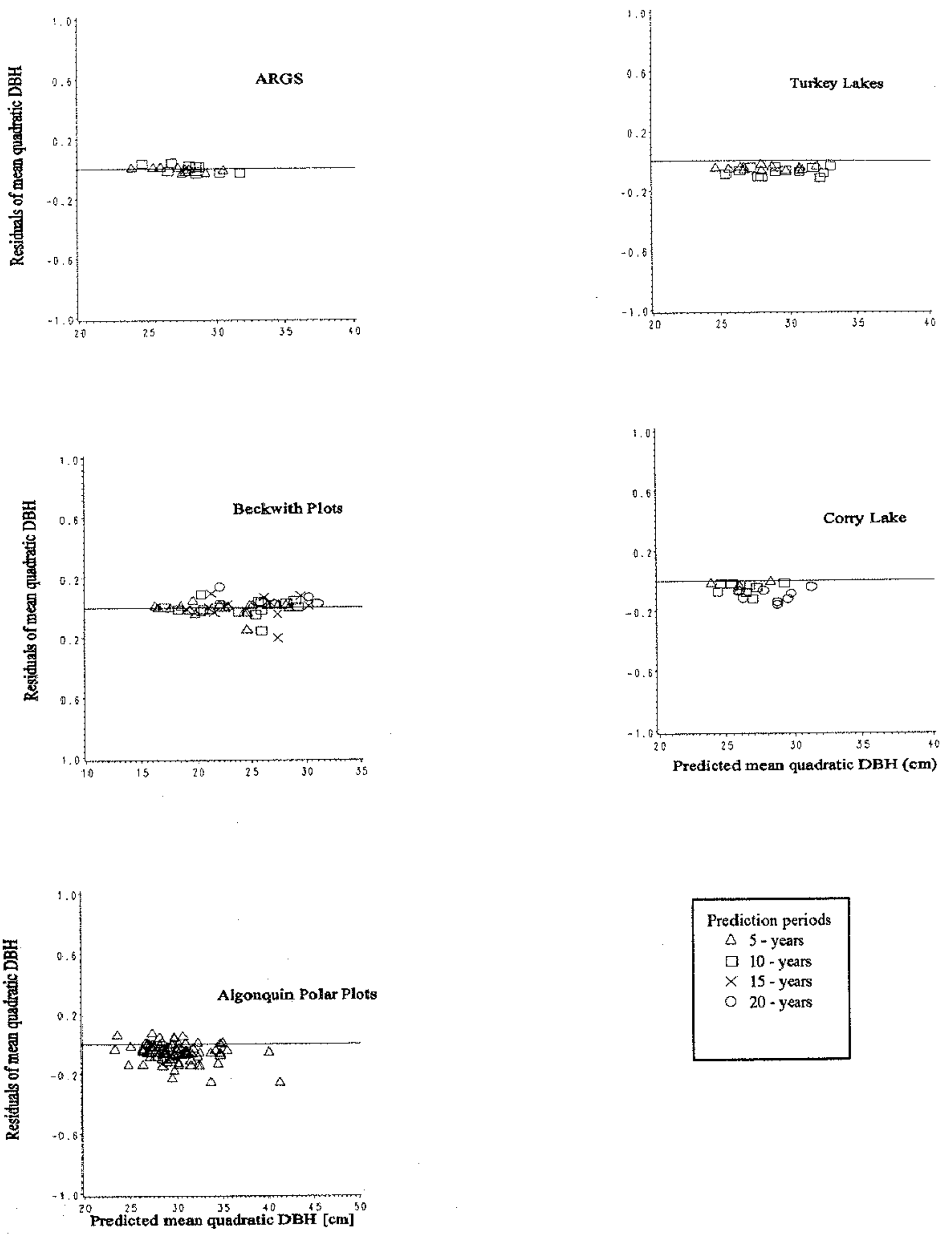

Figure 5. Residuals of quadratic mean DBH for the 5 data sets and all available prediction periods.

Table 5. Error statistics of stand density predictions.

Data set	Prediction period	N	Average error	Range of error (min;max)	Absolute error	Modelling efficiency
ARGS	5	10	0.06[1]	0.02;0.11	0.06	0.69
	10	10	0.10[1]	-0.10;0.21	0.11	-0.29
Turkey Lakes	5	13	0.09[1]	-0.02;0.23	0.09	0.15
	10	13	0.10[1]	-0.26;0.28	0.14	-0.81
Beckwith Plots	5	20	0.07[1]	-0.06;0.24	0.08	0.88
	10	16	0.09[1]	-0.11;0.35	0.09	0.78
	15	11	0.14	-0.11;0.68	0.11	0.55
	20	4	0.09	-0.03;0.15	0.02	0.88
Corry Lake Woodlot	5	4	0.07	-0.02;0.19	0.04	0.40
	10	8	0.13	-0.10;0.30	0.16	0.43
	20	8	0.25	0.04;0.57	0.25	-3.87
Algonquin Polar Plots	5	88	0.17[1]	-0.13;0.84	0.15	0.36

[1] This value is statistically significant (Wilcoxon Rank Test $P<0.05$).

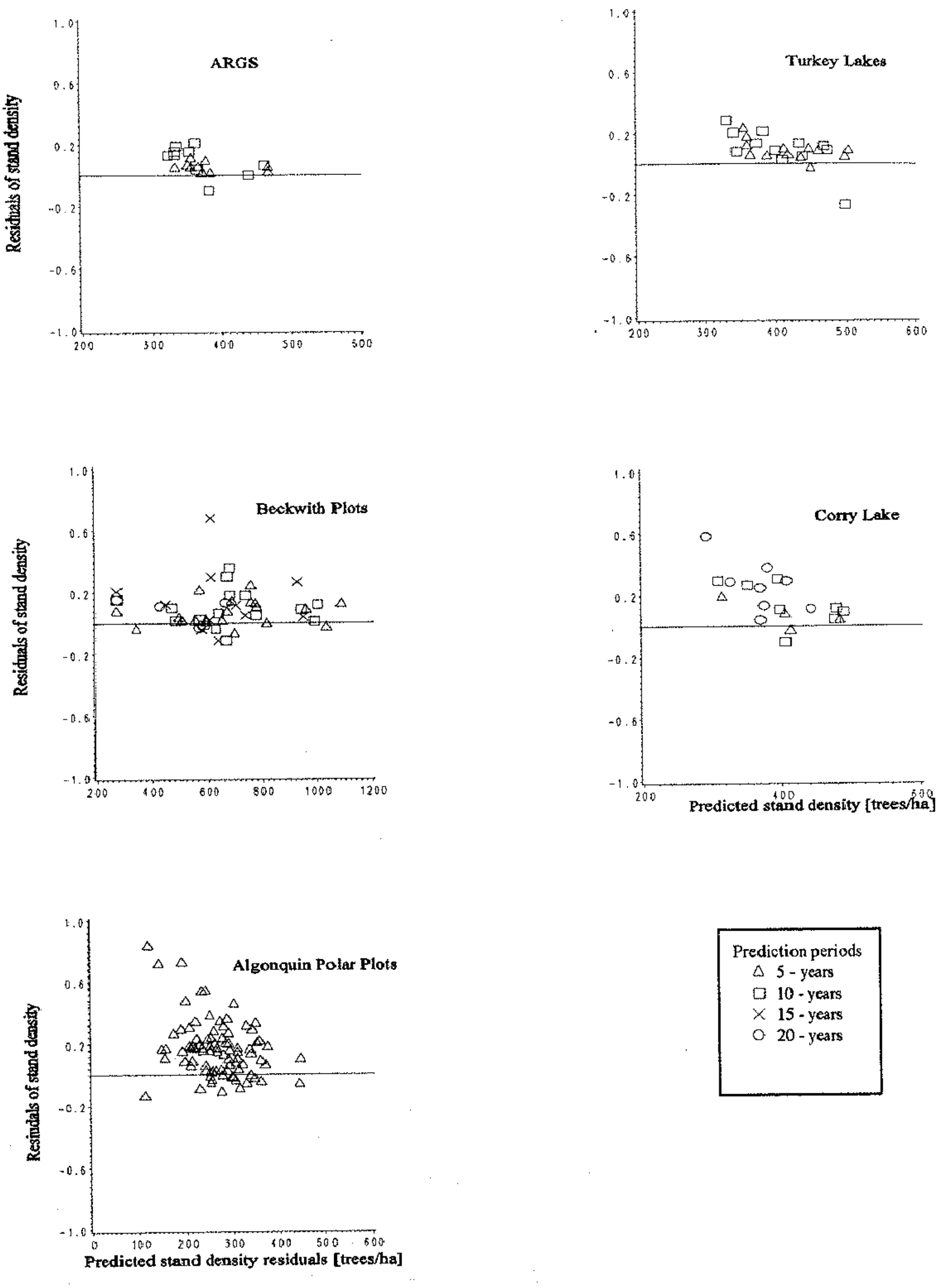

Figure 6. Residuals of stand density for the 5 data sets and all available prediction periods.

Table 6. Error statistics of basal area predictions.

Data set	Prediction period	N	Average error	Range of error (min;max)	Absolute error	Modelling efficiency
ARGS	5	10	0.05[1]	0.03;0.07	0.05	0.62
	10	10	0.09[1]	-0.03;0.16	0.10	-0.29
Turkey Lakes	5	13	-0.004	-0.10;0.07	0.03	0.92
	10	13	-0.02	-0.15;0.08	0.05	0.74
Beckwith Plots	5	20	0.06[1]	-0.08;0.20	0.08	0.94
	10	16	0.08	-0.07;0.33	0.08	0.81
	15	11	0.13[1]	-0.06;0.48	0.10	0.72
	20	4	0.24	0.10;0.53	0.06	0.79
Corry Lake Woodlot	5	4	0.02	-0.03;0.07	0.02	0.94
	10	8	0.02	-0.13;0.12	0.05	0.78
	20	8	0.01	-0.05;0.11	0.05	0.78
Algonquin Polar Plots	5	88	0.04[1]	-0.22;0.25	0.08	0.73

[1] This value is statistically significant (Wilcoxon Rank Test $P<0.05$).

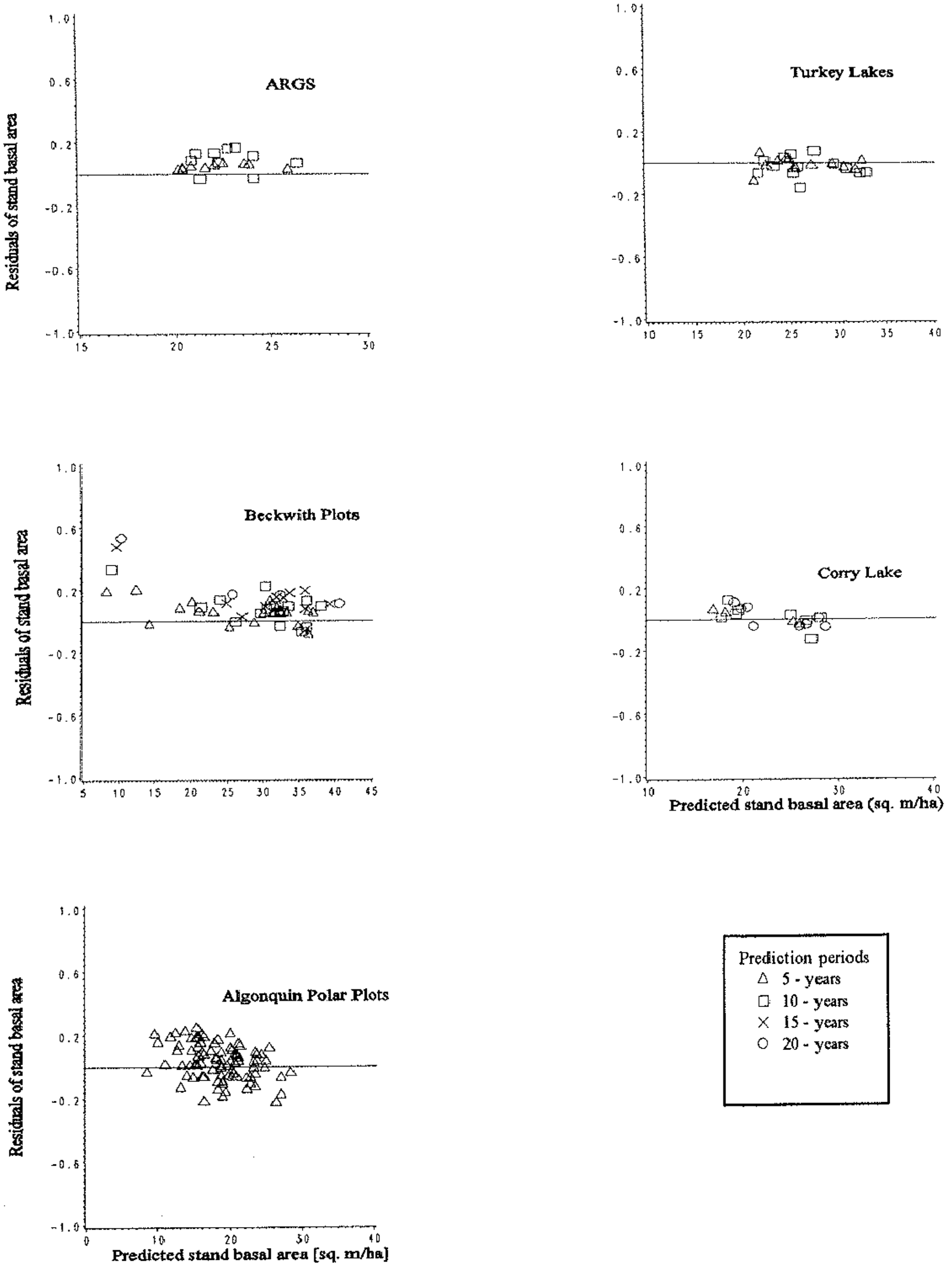

Figure 7. Residuals of stand basal area for the 5 data sets and all available prediction periods.

Table 7. Error statistics of stand volume predictions.

Data set	Prediction period	N	Average error	Range of error (min;max)	Absolute error	Modelling efficiency
ARGS	5	10	0.05[1]	0.02;0.08	0.05	0.77
	10	10	0.09[1]	-0.03;0.16	0.10	0.06
Turkey Lakes	5	13	-0.03	-0.13;0.03	0.04	0.93
	10	13	-0.06	-0.20;0.04	0.07	0.71
Beckwith Plots	5	20	0.06[1]	-0.25;0.25	0.09	0.91
	10	16	0.07	-0.22;0.43	0.10	0.82
	15	11	0.12	-0.14;0.59	0.09	0.76
	20	4	0.29	0.13;0.66	0.06	0.76
Corry Lake Woodlot	5	4	-0.06	-0.12;-0.02	0.03	0.88
	10	8	-0.06	-0.16;0.04	0.07	0.76
	20	8	-0.13	-0.21;-0.02	0.13	-0.01
Algonquin Polar Plots	5	88	0.02	-0.25;0.30	0.10	0.72

[1] This value is statistically significant (Wilcoxon Rank Test $P<0.05$).

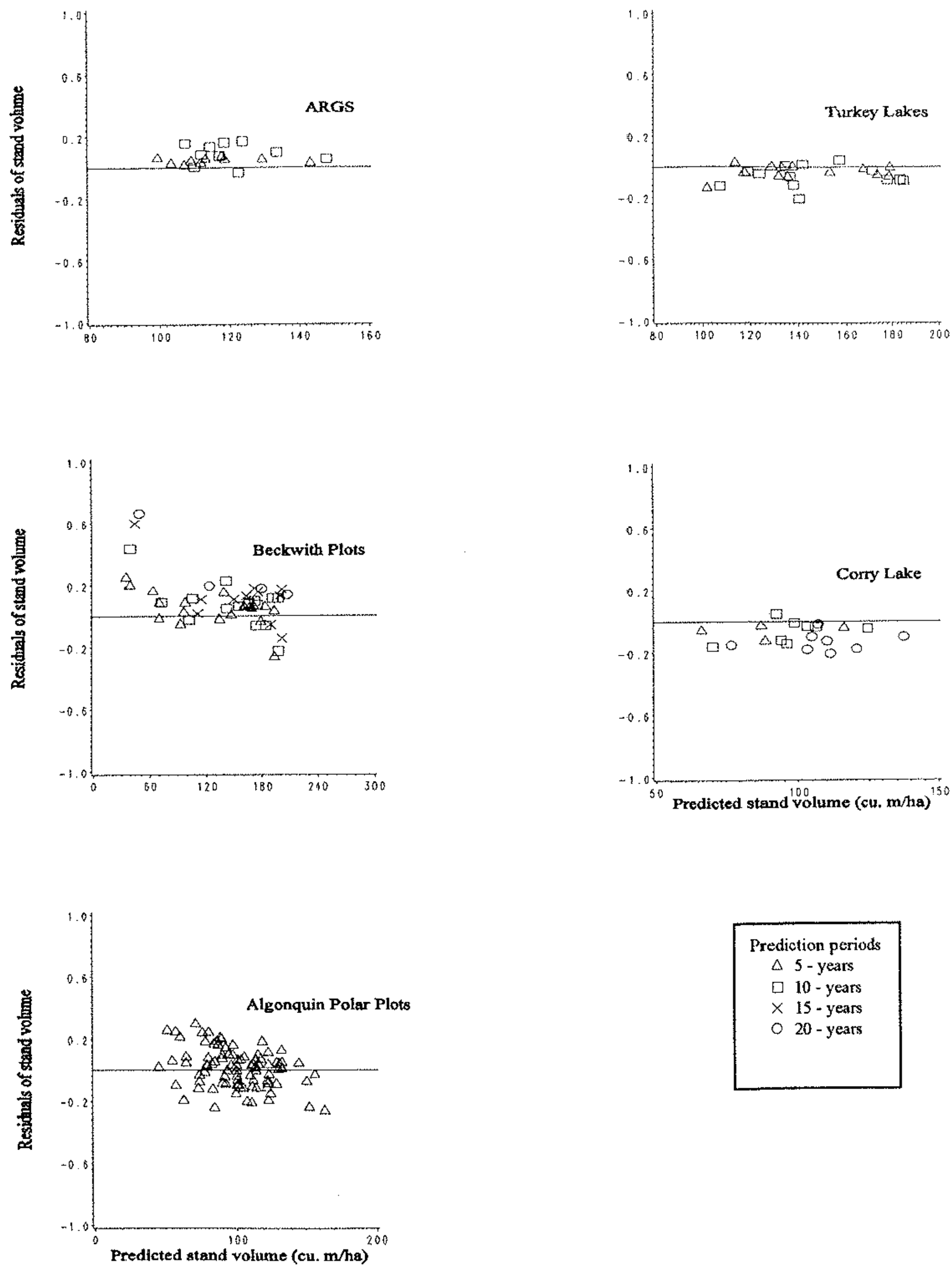

Figure 8. Residuals of stand volume for the 5 data sets and all available prediction periods.

Table 8. Summary of error statistics for stand volume, basal area, stand density, and quadratic mean DBH predictions. Data are 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	-0.05;0.06	-0.13;0.23	0.01;0.09	0.15;0.93
	10	23	-0.06;0.10	-0.26;0.28	0.02;0.14	-0.81;0.74
Unmanaged/ even-aged	5	20	0.00;0.07	-0.25;0.25	0.02;0.09	0.88;0.94
	10	16	0.00;0.09	-0.22;0.43	0.03;0.10	0.78;0.89
	15	11	0.08;0.14	-0.20;0.59	0.03;0.11	0.55;0.76
	20	4	0.06;0.29	-0.03;0.66	0.01;0.06	0.78;0.79
Managed/ uneven-aged	5	92	-0.06;0.17	-0.25;0.84	0.01;0.15	0.21;0.94
	10	8	-0.06;0.13	-0.16;0.30	0.05;0.16	0.12;0.78
	20	8	-0.13;0.25	-0.21;0.57	0.05;0.25	-3.87;0.78

Error evaluation for basal area predictions by merchantable timber classes

SILVAH does not provide reliable projections of basal area in merchantable timber classes (Tables 9 to 12; Figures 9 to 12). In a few instances, the model failed to predict the presence of poles and small sawlogs. Also, for medium and large sawlogs, SILVAH was not able to provide 5-year basal area projections for 14% to 17% of stands.

On average, SILVAH underestimates the pole and small sawlog basal area in 5-year projections. Tables 9 and 10 illustrate the larger biases in basal area of pole class (6% to 28%) as compared to small sawlogs (1% to 13%).

Biases increase with longer projections, especially in the pole class. Basal area projections of the large timber classes are overestimated for all periods. Over-estimations for Corry Lake are especially large, which may be related to an inaccurate estimate of mortality.

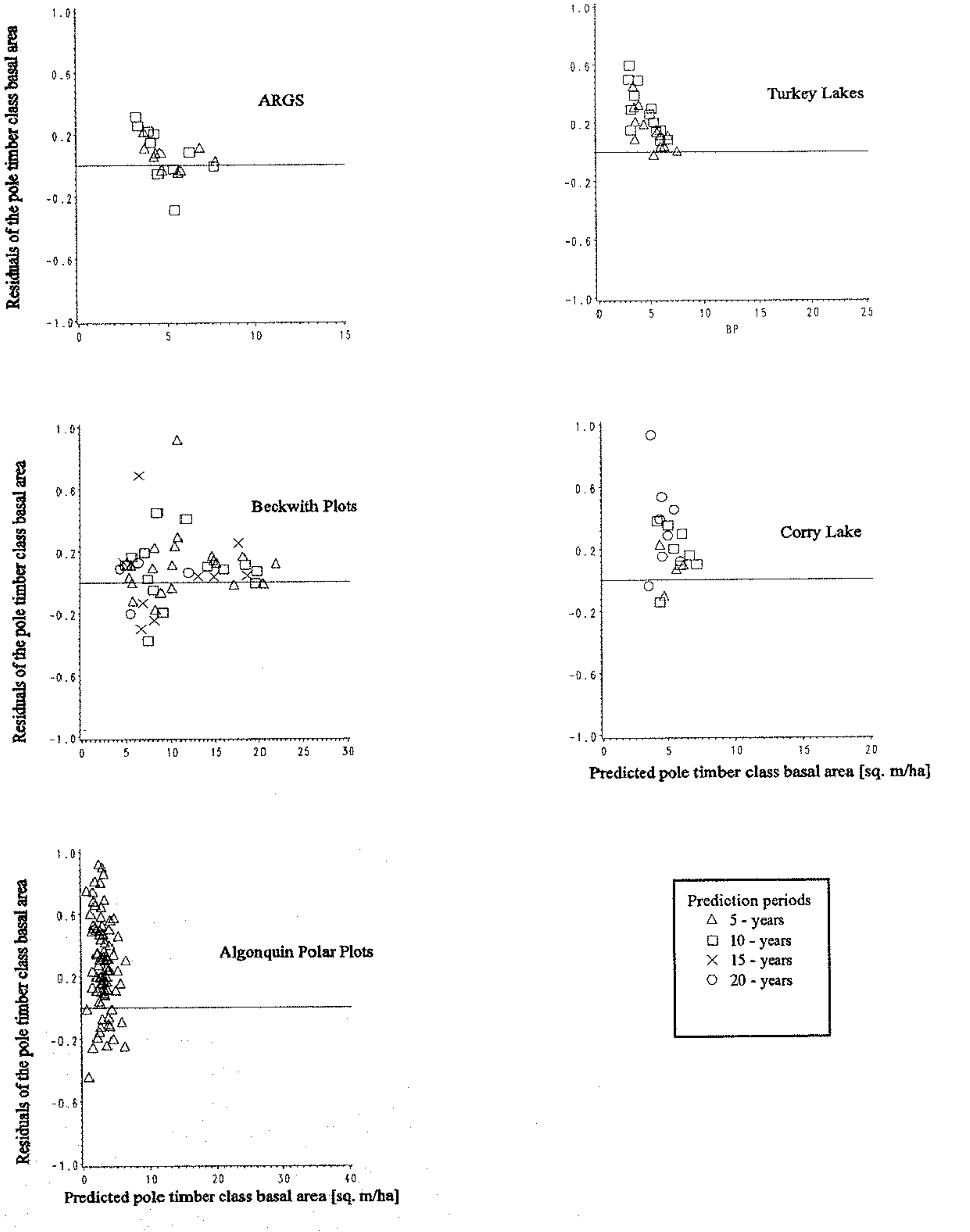

Figure 9. Residuals of the pole timber class basal area for the 5 data sets and all available prediction periods.

Table 9. Error statistics of basal area predictions for poles (10 to 24.9 cm).

Data set	Prediction period	N	Average error	Range of error (min;max)	Absolute error	Modelling efficiency
ARGS	5	10	0.06	-0.04;021	0.08	0.87
	10	10	0.08	-0.28;0.31	0.16	0.48
Turkey Lakes	5	13	0.15[1]	-0.02;0.45	0.15	0.53
	10	13	0.01[1]	-0.18;0.15	0.29	-0.11
Beckwith Plots	5	20	0.11	-0.17;0.91	0.15	0.78
	10	15(1)[2]	0.08	-0.37;0.44	0.16	0.88[3]
	15	11(1)	0.06	-0.30;0.68	0.20	0.863
	20	4	0.02	-0.20;0.12	0.12	0.93
Corry Lake Woodlot	5	4	0.07	-0.10;0.22	0.12	0.50
	10	8	0.17	-0.14;0.37	0.21	0.06
	20	8	0.35	-0.04;0.93	0.36	-1.19
Algonquin Polar Plots	5	84(4)	0.28[1]	-0.44;0.92	0.34	0.393

[1] This value is statistically significant (Wilcoxon Rank Test $P<0.05$).

[2] The number in parentheses represents the number of stands excluded from calculations due to missing predicted or observed values.

[3] Missing values of residuals are excluded from calculations.

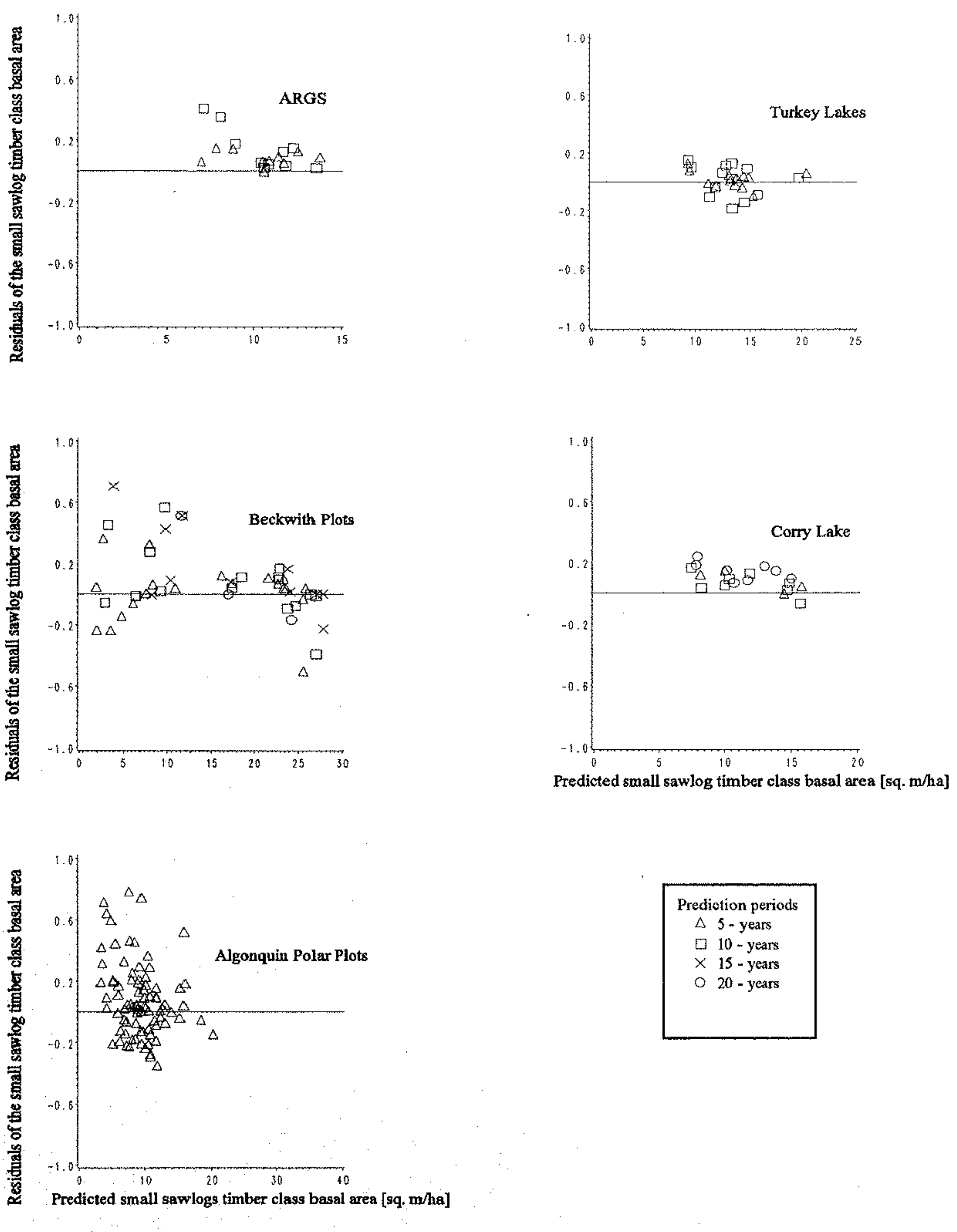

Figure 10. Residuals of the small sawlog timber class basal area for the 5 data sets and all available prediction periods.

Table 10. Error statistics of basal area predictions for small sawlogs (25 to 40.9 cm).

Data set	Prediction period	N	Average error	Range of error (min;max)	Absolute error	Modelling efficiency
ARGS	5	10	0.08[1]	-0.01;0.14	0.08	0.80
	10	10	-0.09[1]	0.02;0.40	0.14	-0.27
Turkey Lakes	5	13	0.02	-0.09;0.12	0.05	0.92
	10	13	-0.21	-0.67;0.33	0.10	0.73
Beckwith Plots	5	20	0.01	-0.50;0.36	0.13	0.88
	10	16	0.07	-0.39;0.56	0.15	0.81
	15	11	0.15	-0.22;0.70	0.20	0.80
	20	3(1)[2]	0.11	-0.17;0.51	0.22	-7.863
Corry Lake Woodlot	5	4	0.07	-0.01;0.14	0.08	0.88
	10	8	0.06[1]	-0.07;0.16	0.08	0.87
	20	8	0.14[1]	0.06;0.23	0.14	0.60
Algonquin Polar Plots	5	85(3)	0.13	-0.35;0.78	0.19	0.673

[1] This value is statistically significant (Wilcoxon Rank Test P<0.05).

[2] The number in parentheses represents the number of stands excluded from calculations due to missing predicted or observed values.

[3] Missing values of residuals are excluded from calculations.

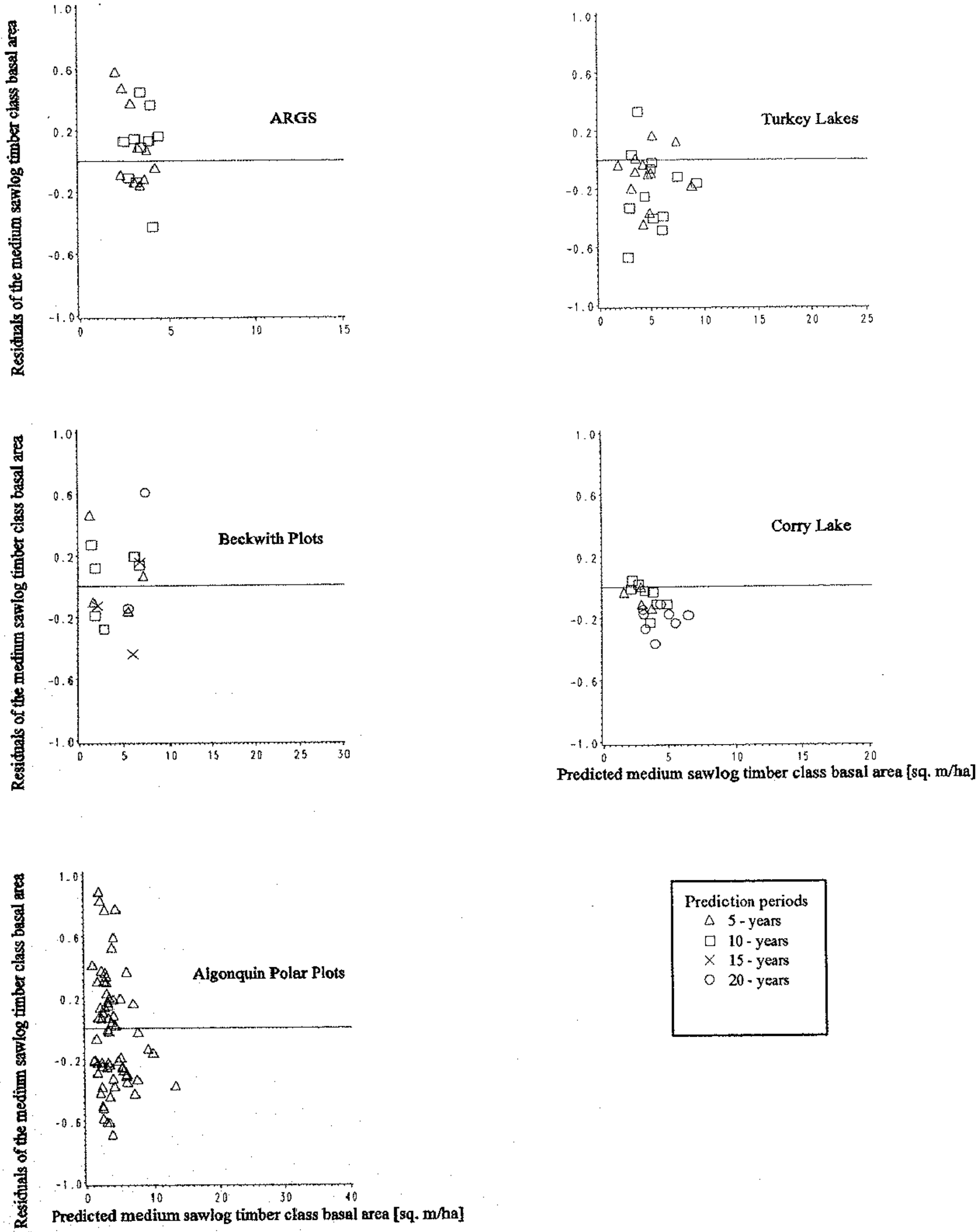

Figure 11. Residuals of the medium sawlog timber class basal area for the 5 data sets and all available prediction periods.

Table 11. Error statistics of basal area predictions for medium sawlogs (41 to 49.9 cm).

Data set	Prediction period	N	Average error	Range of error (min;max)	Absolute error	Modelling efficiency
ARGS	5	10	0.10	-0.15;0.58	0.21	0.25
	10	10	0.08	-0.42;0.44	0.21	0.26
Turkey Lakes	5	12(1)[2]	-0.10	-0.44;0.16	0.14	0.73[3]
	10	12(1)	-0.21	-0.67;0.33	0.25	0.27[3]
Beckwith Plots	5	4(1)	0.06	-0.16;0.46	0.19	0.94[3]
	10	6(2)	0.04	-0.28;0.27	0.20	0.92[3]
	15	3(1)	-0.14	-0.44;0.15	0.24	0.56[3]
	20	2(1)	0.23	-0.14;0.60	0.37	0.20[3]
Corry Lake Woodlot	5	4	-0.07	-0.14;-0.01	0.07	0.74
	10	8	-0.06	-0.23;0.04	0.07	0.67
	20	8	-0.21[1]	-0.36;-0.11	0.21	0.06
Algonquin Polar Plots	5	67(17)	-0.03	-0.68;0.88	0.31	0.47[3]

[1] This value is statistically significant (Wilcoxon Rank Test P<0.05).
[2] The number in parentheses represents the number of stands excluded from calculations due to missing predicted or observed values.
[3] Missing values of residuals are excluded from calculations.

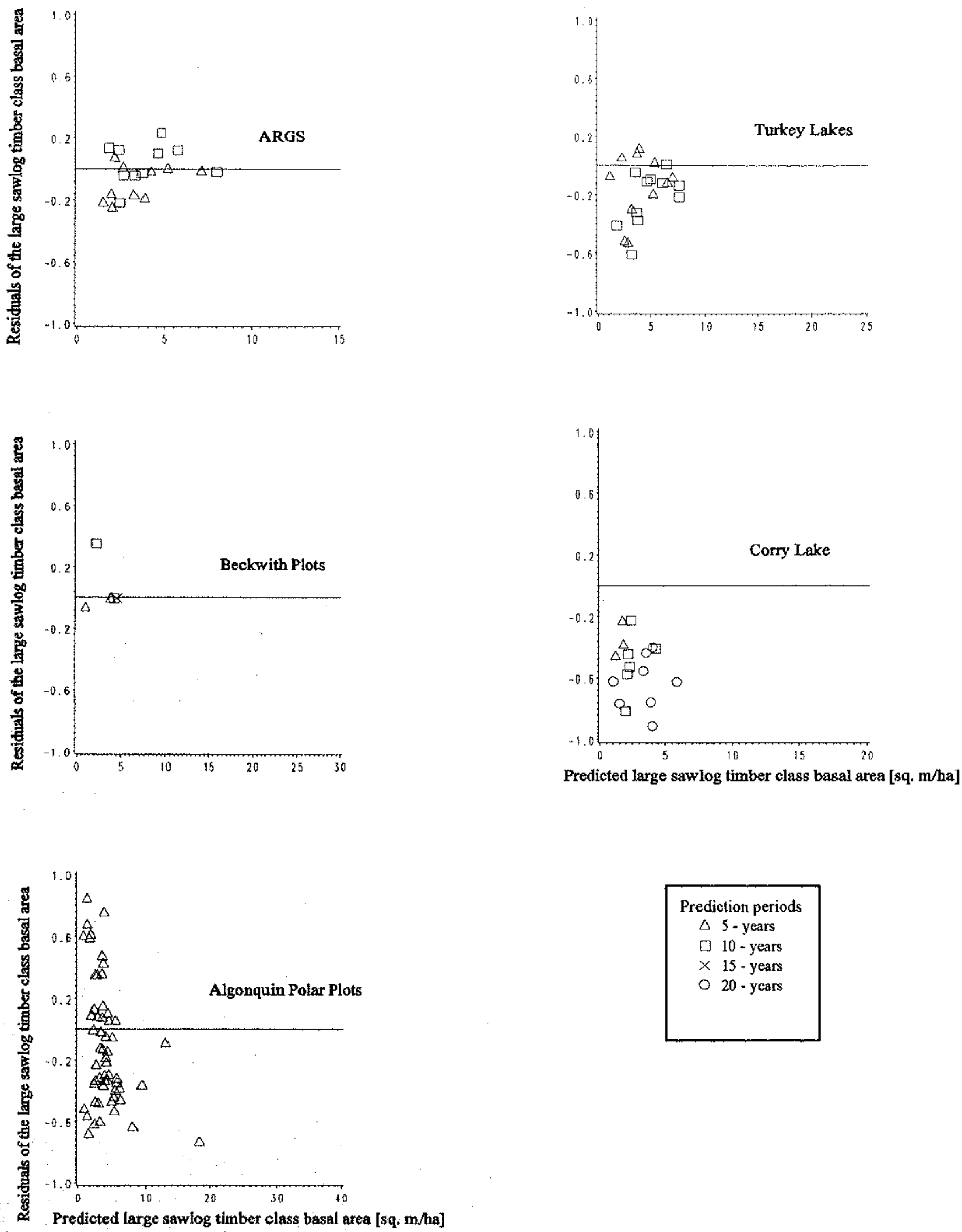

Figure 12. Residuals of the large sawlog timber class basal area for the 5 data sets and all available prediction periods.

Table 12. Error statistics of basal area predictions for large sawlogs (≥50 cm).

Data set	Prediction period	N	Average error	Range of error (min; max)	Absolute error	Modelling efficiency
ARGS	5	10	-0.09	-0.24;0.08	0.11	0.95
	10	10	0.04	-0.21;0.23	0.11	0.93
Turkey Lakes	5	11(2)[2]	-0.14	-0.52;0.12	0.17	0.823
	10	11(2)	-0.22	-0.61;0.01	0.20	0.703
Beckwith Plots	5	2	-0.03	-0.06;-0.01	0.03	0.99
	10	2(1)	0.17	-0.01;0.35	0.17	-0.023
	15	1(3)	-0.01	-0.01	0.01	-
	20	0	-	-	-	-
Corry Lake Woodlot	5	3(1)	-0.35	-0.45;-0.22	0.35	-2.713
	10	6(2)	-0.50[1]	-0.82;-0.22	0.50	-2.333
	20	8	-0.631	-0.91;-0.40	0.63	-7.66
Algonquin Polar Plots	5	57(13)	-0.10	-0.73;0.84	0.35	-0.703

[1] This value is statistically significant (Wilcoxon Rank Test P<0.05).

[2] The number in parentheses represents the number of stands excluded from calculations due to missing predicted or observed values.

[3] Missing values of residuals are excluded from calculations.

Summary

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

- The accuracy of 5-year basal area projections, expressed by modelling efficiency, ranges from 62% to 94%.
- Basal area is underestimated on average from 2% to 6% for 5-year projections (except for the Turkey Lakes data set).
- Range of error for basal area projections in a 5-year period is from -22% to 25% for all data sets.
- Stand volume predictions are similar to basal area projections (except for Corry Lake stands).
- SILVAH underestimates stand density for all stands and slightly overestimates quadratic mean DBH for uneven-aged stands.
- Low values of predicted stand density result from underpredicting the number of trees in small DBH classes. This deficiency may be caused by the following factors: lack of regeneration/ingrowth data, unrealistic tree mortality model, or overestimation of diameter increment.
- The overestimates in the number of trees and basal area for larger DBH classes may be a result of a lower mortality rate in these classes.
- The poor performance of the model may be related to the lack of trees from 1" to 4.5" (2.5 to 11.4 cm)DBH in the input tree list. SILVAH was originally calibrated for stands with measurements of all trees larger than 1" (2.5 cm) DBH, and therefore coefficients of relative stand density and growth equations used may not be accurate.
- SILVAH does not provide reliable projections of basal area in merchantable timber classes.
- The model does not include a site index variable in the growth and mortality equations, except for the oak species.
- Growth projections of stands from larger plots (> 0.3 ha in size) have smaller residuals.

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