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Crown Shape Prediction Model for *Picea ajanensis* and *Abies Nephrolepis* Trees in Young Dark Coniferous Stands

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A simulation model for the age dynamics of young *Abies nephrolepis (Trautv.)* Maxim. and *Picea ajanensis* Fisher trees in dark coniferous stands is proposed. The model equations describe the tree height growth and appearance, and the elongation and inclination angle change of the branches. The model adequately describes the asymmetrical development of tree crowns and can be used to model the stand dynamics.

Key words : *model, crown shape, crown profile, tree, stand, abies, picea*

INTRODUCTION

The study of the processes involved in crown development is of great importance for predicting photosynthetic productivity of single trees and stands, as well as for describing wood quality by its branchiness. The most complete information about structural and crown dynamics of a tree can be obtained by using the functional method. Presently, there are many structural and functional models, which can describe a tree as an integral three-dimensional object, e.g. those presented in (Antonova and Azova 1999, Bryntsev 2001, Martyntsev and tolstopyatenko 1997, Musayev and Arnautova 1999, Gavrikov and Sekretenko 1996, Jaeger 1992, Kurth 1994, Perttunen et al. 1998). However, due to numerous computational difficulties, most of them are hard to apply to the description of tree stand development.

If it is supposed that the crown form is symmetrical relatively to the stem axis, only its profile or generatrix can be described (Li and Jang 1998). In this method, the crown is frequently divided in two parts: upper (over maximal crown diameter level) and lower. The form of the crown parts is depicted by various model equations (Hann 1999, Marshall *et al.* 2003). Sometimes a tree crown is divided into inner and outer (acerose covered) parts, each of them is also depicted by certain equations (Baldwin and Peterson 1997).

Tselniker established empirical models of Picea crown form, basing on the correlation between thickness of annual rings and a number of characteristics of crown elements (Tselniker 1994). After that, analogous model was developed for larch species (Tselniker 1997).

The aim of this work was to develop a model able to describe the age crown dynamics of young dark coniferous trees, particularly of *Abies nephrolepis* and *Picea ajanensis*. Crowns of young *Abies* and *Picea* are usually asymmetrical due to the uneven positioning of the trees in natural stands. Therefore, crown asymmetry should be taken into account in the evaluation of the actual life condition of a tree, its actual photosynthetic production and branch characteristics. Crowns of young coniferous trees usually interpenetrate, which makes modeling difficult. In this case, it is expedient to consider crown development by calculating the branch length only. Thus, the branch elongation model is based on height increment and year of tree development (Deleuze *et al.* 1996). Branch length increases with increasing distance between trees. Our model is based on following two hypotheses: a) the rate of branch elongation decreases according to the growing distance between the top of the tree and the branch base, and b) the rate of branch elonga-

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tion depends on the distance from neighboring trees. The model is developed as a sub-model of the imitational model of young stand growth.

MATERIALS AND METHODS

Empirical data for the development of the model and fitting values of parameters of model equations were obtained by measurement of 27 *Abies nephrolepis* model trees and 25 *Picea ajanensis* trees. These were single or small-grouped trees growing in gaps and open stands without shadowing from higher canopy trees. The trees were not related to sample plots but belonging to the same

Table 1. Characteristics of model trees. H: tree height (cm); A: age of tree (years); $D_{1.3}$: d.b.h. (cm); R_{cr}: crown radius (cm).

Abies nephrolepis					Picea ajanensis				
Tree number	H	A	$D_{1.3}$	R_{cr}	Tree number	H	A	$D_{1.3}$	R_{cr}
Group identification									
1	150	23	0.5	75	1	520	41	8	125
2	180	-	0.5	80	2	330	36	5	95
3	340	34	6	125	3	240	-	3	55
4	220	28	2	100	4	300	35	6	100
5	340	35	7	130	5	160	30	0.5	45
6	320	-	8	90	6	550	43	9	130
7	330	35	7	150	7	160	-	0.5	50
8	610	45	10	205	8	260	35	3	85
9	190	27	1	110	9	390	39	5	105
10	350	31	5	105	10	210	30	2	90
11	790	-	13	210	11	140	29	1	55
12	380	37	7	125	12	520	44	8	130
13	430	36	8	75	13	320	37	6	100
14	280	32	4	85	14	170	31	1	70
15	910	45	12	205	15	150	29	1	70
16	360	35	7	135	16	630	44	11	180
17	340	-	6	110	17	130	27	0.5	50
18	600	40	9	175	18	340	-	4	120
19	560	37	8	160	19	290	37	3	90
20	410	37	7	115	20	310	33	4	95
21	640	41	9	120	21	310	38	5	90
22	480	40	8	160	22	660	45	7	175
23	610	39	9	145	23	100	24	0.5	40
24	280	30	6	90	24	90	23	0.5	40
25	360	32	8	95	25	460	45	6	130
26	890	43	15	230					
27	940	44	16	185					
Control group									
1	710	44	10	200	1	440	41	6	130
2	540	38	8	145	2	320	40	5	120
3	510	41	7	150	3	360	38	4	120
4	790	43	11	205	4	480	43	5	155
5	740	41	12	210	5	520	43	7	160
6	380	34	7	140	6	450	39	6	100
7	530	40	7	140	7	350	37	5	110
8	310	34	6	125	8	540	44	8	145
9	650	42	8	160	9	620	45	9	210
10	810	42	13	210	10	400	42	5	150
11	740	38	12	215					

Note: blank fields indicate undefined tree age.

forest type, *Picea*-green moss-fern forest. The trees were therefore characterized by even height increment with no no expressed periods of slow growth. To test the model, 11 *Abies nephrolepis* and 10 *Picea ajanensis* model trees were chosen. The characteristics of the model trees are presented in Table 1.

Each model tree was measured in height, d.b.h., crown length and width of the crown base. The crown base was measured under the lower whorl having at least one living branch. Moreover, the relative distribution of the neighboring trees was measured. Each tree was measured for $N = N_o/10$ branches, N_o being the total number of tree branches. For the branches, we measured the following values: distance between their bases and tree tops, length, inclination angle, age, radial direction (north direction was considered zero), and values of annual increment. Branches which had at least one foliated shoot were considered living.

During the preliminary data analysis, we found the following three dependences in the appearance and elongation of branches. The length of lateral shoots in young branch clusters of tree tops (stem, first-order axis) was in linear correlation with the length of the top shoot. The length of the shoots of the branch top (second-order axis) exponentially decreased with increasing distance between the branch base and tree top, i.e., the lower the branch position in the crown, the shorter the new shoot of its top. The length of new shoots was maximal for the branch of the very treetop. This branch consisted of a single shoot – lateral shoot of top branch cluster. 3) If a crown penetrated a neighboring crown, the rate of shoot shortening on the top of the contacting branches increased. Therefore, it is possible to calculate the length of lateral shoots in the top branch cluster if the height increment of a tree is known. Furthermore, the length of the lower branches can be calculated from the positioning of the neighboring trees.

The appearance of lateral shoots on *Abies* and *Picea* in first-order axis whorls becomes regular from a tree age of 22 years, after which age the whorls are supplemented by 5 axile lateral shoots, symmetrically surrounding the maternal axis. Whorls of younger trees form 2-3, and rarely 4, lateral shoots, and the developing branches can exist for only 5-10 years. Therefore, we designated 22 years as the initial age of the imitated trees and described the tree crown forming during the age of 22-45 years.

In general, the height of young *Abies* trees increased linearly. This temporal height increment is described by the allometric equation:

$$H = r \cdot TA^{s}$$

where H is the tree height (cm), TA the tree age (years), and r and s are the growth rate parameters. From this equation, the length of the young top shoot can be calculated as the difference between the tree height in the current and previous years:

$$LS = r \times TA^{s} - r \times (TA - 1)^{s} \tag{1}$$

where LS is the length of the top shoot (cm).

The dependence between the length of the lateral shoot in the young branch cluster and the length of the top shoot is linear:

$$LSM_0 = LS \times f + g \tag{2}$$

where f and g *are* parameters, indicating the rate of decrease in the lateral shoot and the length of the top and the "initial" length of the lateral shoot, respectively.

The dependence of the new shoot length from the distance between the branch base and treetop is given by:

$$LSM_z = \begin{cases} LSM_0 \times \exp(-n \times RW_z), BL < D \\ LSM_0 \times exp(-p \times \exp(-q \times CD) \times RW_z) \\ \qquad BL \geq CD \end{cases} \tag{3}$$

where LSM_z is the length of a new shoot (cm), RW_z the distance between the branch cluster and the top of the first-order axis (cm), BL *the* length of the branch (cm), and CD thedistance to the border limit of the crown contact (m). The coefficient n indicates the speed of shoot length decrease when the tree crowns do not contact, and p and q define changes in the "rate" of shoot shortening if the neighboring trees are present. The values of p and q differ for various combinations of contacting trees. There are four possible variants: a) **Abies** – Abies, b) **Abies** – Picea, c) **Picea** – Abies, d) **Picea** – Picea. Figure 1 shows the pattern of contacting crowns of two neighboring trees.

Dependence of branch inclination angle from its age:

$$\beta(BA) = \beta(0) - \nu \times BA_i \tag{4}$$

where $\beta(BA)$ is the angle of the branch inclination (degrees), $\beta(0)$ the initial angle of the branch

$$CD = \frac{1}{\cos(\gamma)}\sqrt{R_1^2 - \left(\frac{R_1^2 - R_2^2 + D^2}{2D}\right)^2}$$

$$D = \sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2}$$

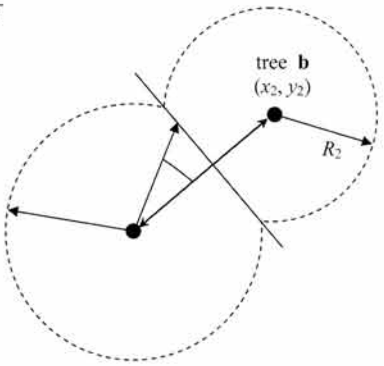

Figure 1. Distance to border of crown contact is in the direction of the branch. Points: tree stems; dash lines: tree crowns; *CL*: contact line; *CD*: distance from tree stem to contact line (m); *D*: distance between trees; R_1, R_2: radii of tree crowns; γ: angle between branch and perpendicular to the contact line; x_1, y_1; x_2, y_2: tree coordinates.

inclination (angle of filial shoot which initiates te branch), *BA* the branch age (years), and ν the rate of branch sagging (degrees/year).

As mentioned above, the young whorl of *Abies* forms at least 5 lateral axile shoots. The average angle between the lateral shoots is 72°, at which point the newly generated whorls turn to various angles around the stem axis. No regular trends were evident in the turning angle, supporting the imitation of crown forming mentioned above in which every new whorl turned to a random angle varying from 0° to 360°.

To test the simulation model, we performed a number of experiments. We imitated the growth of a small tree group (20-30 sample trees) with age interval of 22-45 years. The trees were situated along the virtual sample plot in order, in centers of six-angled cells, as shown in Figure 2. In all, there were 4 possible variants of forest crops, as noted above. The distance between the trees varied between 0.4 and 4 m, with a measuring step of 40 cm. The same intervals were made for empirical data. We observed the development of certain branches growing near the crown base during 20 years. We preferred branches having bases closest to the line connecting neighboring trees. Branches of the crown base were chosen because their structure reflects te most peculiar interrelation between crowns. The top branches exhibited practically no change during the entire range of distances between the neighboring trees (except the smallest ones). We observed the changes of total branch length and length of its acerous covered part. Moreover, we measured the height of the crown base, which can characterize the life duration of branches, in the studied trees. To evaluate the accurateness of this method of branch characteristic forecasting, we conducted analysis of errors, and in particular calculated the value of mean error $E = \Sigma\,(r_m - r_p)/n$, where r_m is the empirical value, r_p the model value, and n the total number of observations.

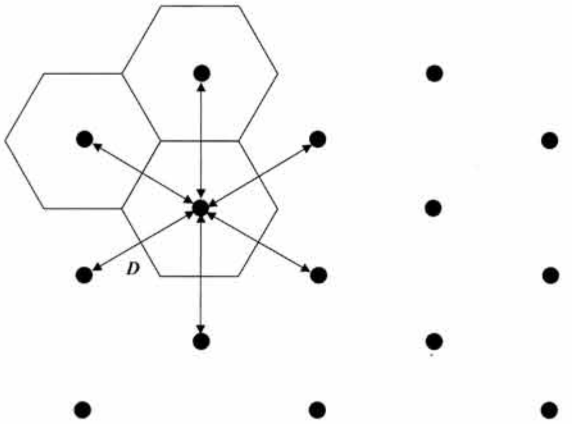

Figure 2. Scheme of tree allocation. D: distance between neighboring trees.

RESULTS AND DISCUSSION

The height increment of young *Abies nephrolepis* and *Picea ajanensis* trees is shown in Figure 3. *Abies nephrolepis* trees were characterized by higher annual increment and by 45 years they were 1-1.5 m higher. The interrelation between the length of lateral shoots in the new branch cluster and the length of the top shoot is presented in Figure 4. Based on the parameters of equation (2), we can conclude that model line must cross the axis of ordinates through the zero point. However, the lateral shoots still cannot develop if the top shoot length equals zero. The linear model is probably applicable under only a small variability

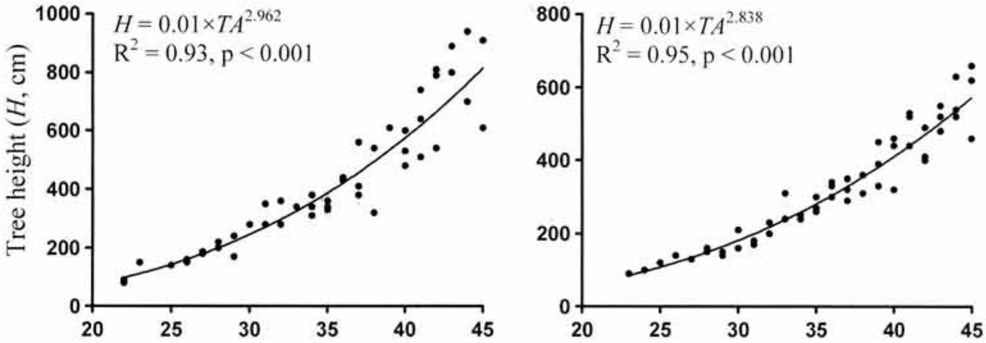

Figure 3. Height increment of *Abies nephrolepis* (a) and *Picea ajanensis* (b). Points: empirical data; line: model (equation 1).

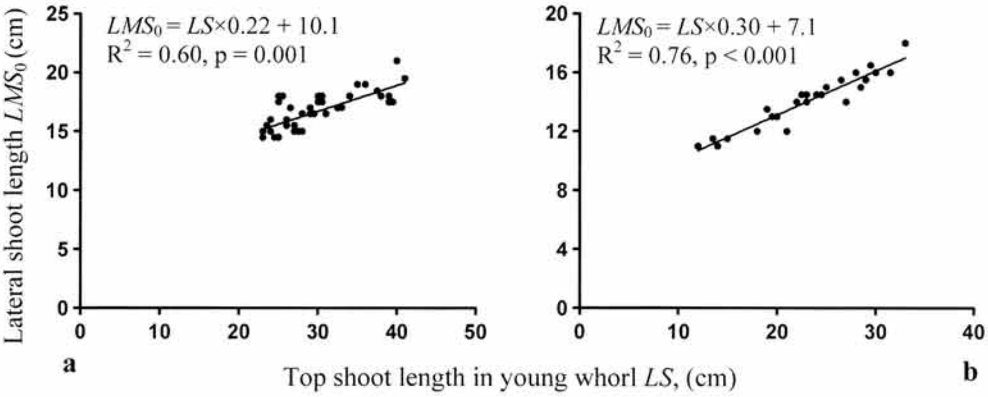

Figure 4. Dependence between length of top and lateral shoots in young branch cluster on first order axis; a: *Abies nephrolepis*; b: *Picea ajanensis*. Dashes: empirical data; line: model (equation 2).

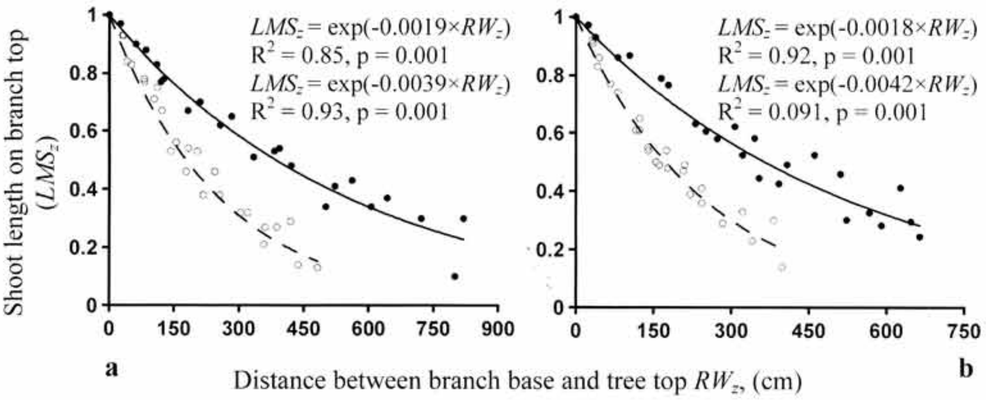

Figure 5. Change of rate of shoots shortening on second order axes; a: *Abies nephrolepis*; b: *Picea ajanensis*. Length of shoot LMS_z (equation 3) is approximated to one. Points: undisturbed growth; circles: neighboring trees are within 2 meters; line: model.

of height increment of the trees.

The relative shortening of the new shoots of a branch with increasing distance between the branch base and tree top is presented in Figure 5. The rate of length decrease of the *Abies* shoots was somewhat higher than that of *Picea*, resulting in the crown base of single-growing *Picea* trees to be wider than that of *Abies trees*. The dependence of the branch angle on its age is presented in Figure 6. The accuracy of the forecasted angle decreased with increasing branch age. Depending on the conditions, branches of the same age exhibit various basal diameters, which this influences the branch flexibility.

The parameters of the model equations (1)-(4) are presented in Table 2. They were correlated with the empirical data by using software developed by V.V. Sukhanov.

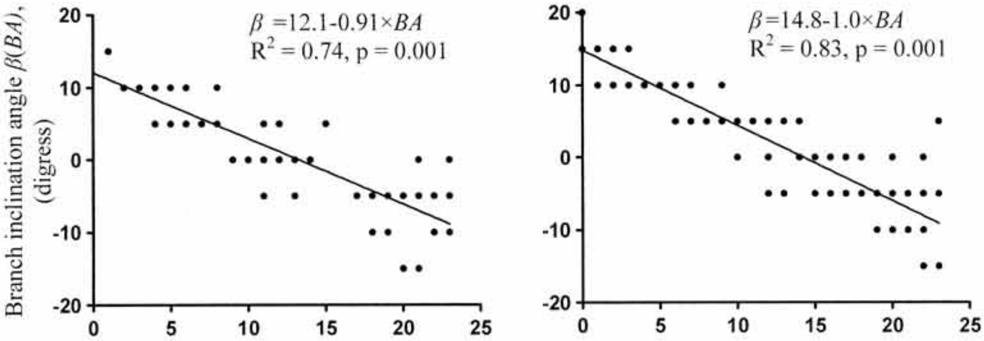

Figure 6. Dependence of inclination angle of branch β from age of the branch *BA*; a: *Abies nephrolepis*; b: *Picea ajanensis*. Dots: empirical data; line: model (equation 4).

Table 2. Parameters of model equations (1)-(4) for *Picea ajanensis* and *Abies nephrolepis*.

Model	Parameter	Abies nephrolepis		Picea ajanensis	
		Value	error	value	error
1	r	0.010	0.004	0.012	0.005
	s	2.9	0.2	2.83	0.02
2	*f*	0.22	0.02	0.30	0.02
	g	10.1	0.7	7.1	0.5
3	n	0.00177	0.00006	0.00183	0.00006
	p (P-P)	0.0074	0.0007	0.0093	0.0005
	q (P-P)	0.71	0.04	0.83	0.05
	p (P-A)	0.0098	0.0009	0.0074	0.0008
	q (P-A)	0.85	0.07	0.72	0.06
5	ν	0.91	0.08	1.04	0.05
	$\beta(0)$	12	1	14.8	0.7

P-P – Picea-Picea interrelation, P-A – Picea-Abies interrelation.

After imitation of the crown development, we obtained data on the quantity, length and spatial distribution of the branches. These data enabled an evaluation of the crown form and the measurement of a number of its characteristics, including value, effective value (Li 1998), length, and average basal diameter. A sample of tree crown, obtained with the model, is shown in Figure 7.

The obtained results are presented in Figure 8. It is noteworthy that the sequences of empirical data were initiated at inter-tree spacings of 80-100 cm. At close spacings, the branches withered and even disappeared so quickly that such data are very difficult to register.

The model accurately reflects the changes in total branch length with increasing inter-tree distance. At small spacings between the contacting trees (150-200 cm), all four variants were noted by a minor deviation of the model curve from a number of empirical data: the model slightly underestimated the branch length. This deviation is valuable for the *Abies-Abies* interrelation. This

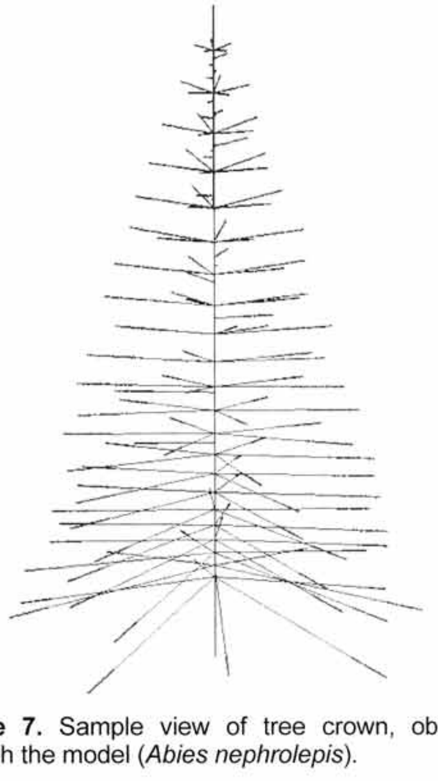

Figure 7. Sample view of tree crown, obtained through the model (*Abies nephrolepis*).

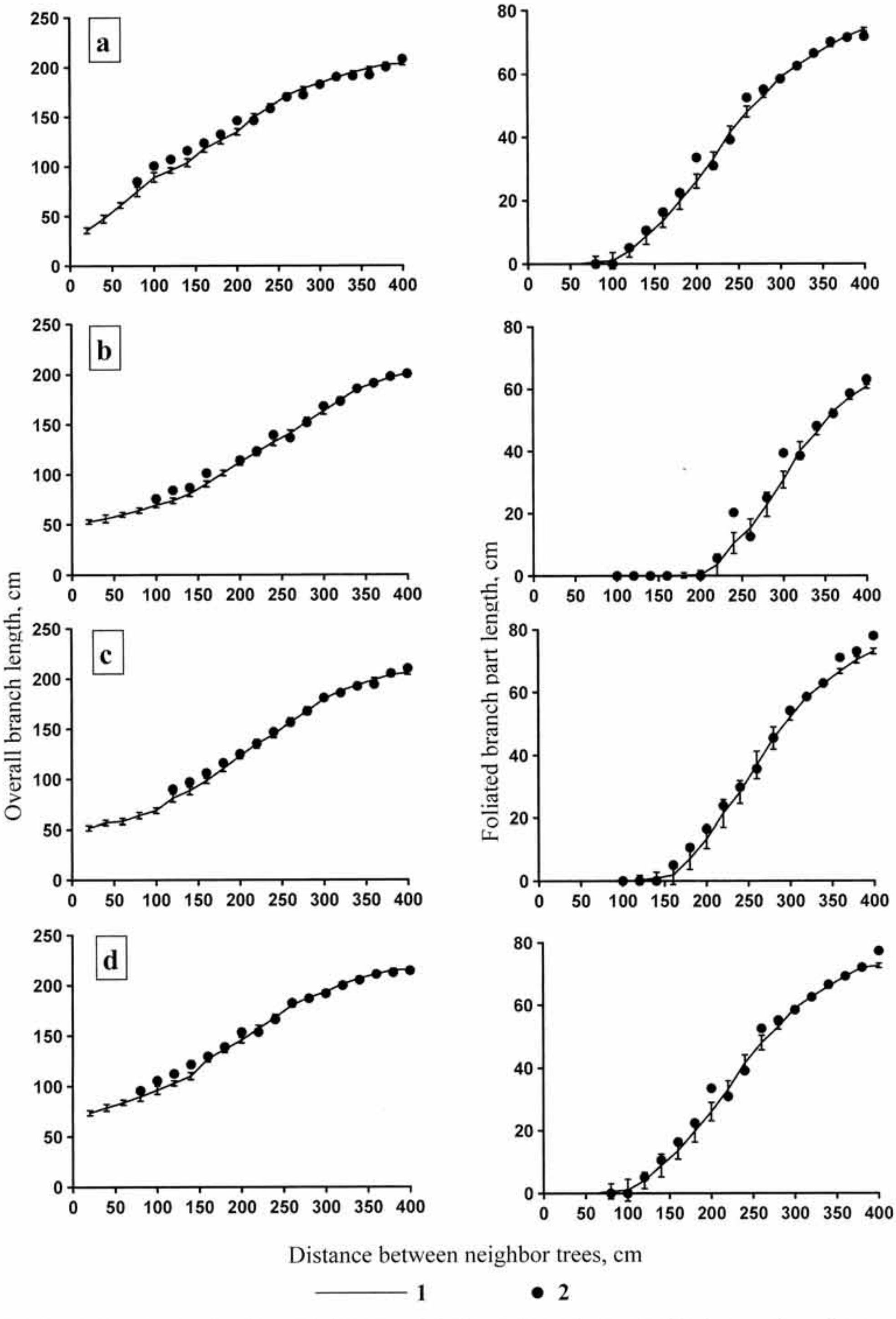

Figure 8. Change in overall length and length of foliated branch part with increasing distance between neighboring trees; a: Abies-Abies; b: Abies-Picea; c: Picea-Picea; d: Picea-Abies. Age of branch: 20 years; 1: model (95% confidence interval is shown for points); 2: empirical data.

indicates that for the natural situation of crown contact, the increment of secondary axes decreases with a slight delay, resulting in the summarized branch length appearing to be longer. This model deficiency will required consideration further development of the model.

The model accurately depicted the length of the acerous parts of the branch in all cases. *E* did not substantially differ from zero, confirming that the branch length and length of the photosintetically active part of the branch may be predicted with confidence. The possession of any information about all tree branches enables the thickness of the living part of the crown to be estimated along its entire length. Furthermore, if we accept that the acerous density is homogeneous all along the crown, the distribution of needles along the stem can also be estimated. Thus, we can obtain a coarse approximation of the needle distribution.

CONCLUSION

The model suggested in this paper adequately predicts the asymmetrical development of young *Abies* tree crowns and provides information about crown form, crown and length, as well as about the quantity, length and spatial distribution of the tree branches. Having obtained data on the volume and form of the crown, it is possible to consider such meaningful characteristics as acerous mass and vertical distribution of the needles. The model is comparatively simple and does not require any special computing resources, thereby simplifying the modeling of stand growth.

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