

Article

# Site Index Models for Main Forest-Forming Tree Species in Poland

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Received: 4 February 2020; Accepted: 5 March 2020; Published: 8 March 2020



**Abstract:** Site index is the most commonly used measure of potential site productivity, providing key information for forest management practices. It is determined using species-specific site index models that take into account climatic and edaphic factors. To reliably estimate the site index, appropriate models are necessary. In Poland, however, outdated guidelines, i.e., yield tables, are used to determine site classes, which result in the inappropriate estimation of height growth and increments of stands. Therefore, the aim of this study is to develop new site index models for the main forest forming tree species in Poland, in a total of eight species. For the development of site index models, we used growth trajectories of 3052 sample trees, representing the whole range of geographic locations and site conditions. Five dynamic models were selected and parametrized to develop the site index models. The models were evaluated using quantitative measures of goodness of fit (MAE, R<sup>2</sup>, and AIC), the analysis of residuals, and the assessment of how the model reflects the biological phenomena of height growth. Results showed that depending on the species, different models have the highest predictive ability. There are significant differences in results using traditional yield tables and developed site index models. For most of the species, the largest differences characterized either the youngest or the oldest age classes. These differences can be attributed to the changes in growth conditions from the time when yield tables were developed. Growth dynamics of forest stands may also show spatial variability, thus, in future research additional site variables and, regional variability should be taken into account.

**Keywords:** height growth; GADA; site productivity; site index model

## 1. Introduction

Information concerning site productivity remains a fundamental variable in forestry [1–4]. The unbiased estimation of site potential is essential for forest management because it is the main determinant of species-specific decisions, connected with the selection of silvicultural treatments, species composition, and the determination of the allowable cut and rotation periods [3,5,6]. Site productivity is one area of strategic information in forest management, which determines the economic and environmental effects of forest management [6,7] and allows the forecasting of stand growth [2]. The most frequently used and commonly accepted measure of potential site productivity is the site index, determined using species-specific site index models based on the height of the stand at a certain age [1,8–10]. Site index models are the main functions used in the empirical models of tree stand growth [11–13].

In recent years, forest ecosystems in Europe have experienced changes due to both the mean climate variables and the higher risk of extreme weather events [14]. Therefore, for effective long-term planning, forest management has to take into account the impact of climate change on stand growth and site productivity. In general, recent climate changes seem to have had a positive impact on forest productivity, although, this may vary at regional scales [15]. In northern and western Europe, a positive effect on forest growth and wood production is expected [14]. The site index considers the impact of climate conditions, expressing how the climatic and edaphic factors influence site productivity. Therefore, it is frequently used to analyze how environmental changes affect forest ecosystems [16–20]. Climate-sensitive site productivity models provide key information to develop forest management guidelines for adaptation steps and apply mitigation strategies against changing climatic conditions [21]. Site index models also play a crucial role in estimating the dynamics of forest carbon pools. According to the good practice guidance (GPG) of the Intergovernmental Panel on Climate Change (IPCC), the past and future dynamics of forest carbon pools should be calculated using stand volume. Stand volume is most commonly estimated using empirical models, such as EFISCEN [22,23] and CBM-CFS3 [24], which both employ National Forest Inventory data. In calculating both of them, site index models play a crucial role [25].

Appropriate site index models adjusted to local site conditions are necessary for the reliable estimation of the site index. In forestry practice in Poland, a site class is still determined using height growth curves, developed by Schwappach [26] for Scots pine, Norway spruce, European beech, silver fir, and sessile oak, and by Schober [27] for European larch and by Turin [28] for silver birch and black alder. Due to the frequent occurrence of pine stands exceeding the height of Schwappach's first class, Szymkiewicz [28] extrapolated tables for class Ia, however, simple graphical extrapolation raises large doubts in this case [29]. Moreover, Schwappach's tables use the mean Lorey's height to measure the site index. Influenced by the intensity of silvicultural treatment, Lorey's height does not represent site productivity well [30]. Another reason for the inadequacy of Schwappach's tables is because of the significant changes in growth conditions, which have greatly changed during the 100-year period since the development of the tables. Research carried out in Central Europe indicates that these changes have strongly influenced the dynamics of stand growth [19,31–33]. Pretzsch [31] estimated that site productivity increased by about 30%–70%. Most visible changes occur in stands of older age classes. Therefore, height growth and the increments of stands observed currently significantly differ from those included in the original tables, which were observed 100 years ago [34]. Therefore, the use of yield tables can result in the inappropriate estimation of site productivity and stand volume increment estimation. This was an inspiration for Bruchwald et al. to develop new Polish site index models for Scots pine [35,36], Norway spruce [37], black alder [38], and European larch [39]. When developing these models, however, the authors used a function describing a single growth trajectory, which is next extrapolated for different sites [29]. Thus, these models do not appropriately differentiate the height growth rate between different sites in terms of the dependence on stand age. Consequently, for example, for stands of younger age classes, the models can produce unrealistically high site index values [40,41].

For the development of site index models, either dynamic (invariant of a base age) or static (dependent on the base age) equations have been used [42]. The former approach assumes a certain base age, violating the assumptions of regression models, e.g., those of [43,44]. In addition, the choice of a base age strongly affects the final model [45]. This problem was already noticed by Bailey and Clutter [46], who proposed a base-age invariant method of deriving site index models, called the algebraic difference approach (ADA). However, a selection of a parameter of the equation used as the site parameter resulted in site index curves that were anamorphic or polymorphic with single asymptotes. Cieszewski and Bailey [47] solved this problem by developing the generalized algebraic difference approach (GADA), which allows one to use more than one site parameter. Therefore, such models are characterized by both polymorphism and variable asymptotes for different sites [42,48]. The GADA has proven to be an adequate method for site index modeling worldwide [29,42,48–56].

GADA allow for the development of local site-specific site index models, which properly describe local height growth trajectories and enable the reliable assessment of site productivity.

Site index models constitute an important decision-making tool in forest management. As a result of the inadequacy of existing yield tables, there is a high demand from the State Forests and Forest Management Bureau in Poland to develop new site index and growth models for the main forest-forming tree species. In response to this demand, in the years of 2015–2018, the research project titled “actual and potential productivity of the main forest-forming tree species in Poland,” was implemented, financed by State Forests in Poland. As part of the project, a grid of over 600 permanent research plots was established, a representative for the main forest-forming tree species growing in Polish forests. Trees for stem analysis were located close to the research plots, allowing for retrospective growth reconstruction when felled. In addition, in the frame of the project, over 2400 growth trajectories were gathered from different research projects implemented in Poland in recent years. The collected database constitutes the empirical material used in the presented research. The aim of this research is to develop new dynamic site index models for the main forest-forming tree species in Poland.

## 2. Materials and Methods

The methodology used in this study involved the following steps: (i) the collection of the research material on trees from the projects, (ii) stem analysis, (iii) the selection of models of height growth, (iv) the estimation of models parameters, and (v) evaluation of the models.

### 2.1. Collection of the Research Material

The research material consists of the height growth trajectories of 3052 dominant and codominant trees of the eight main forest-forming tree species in Poland (Table 1), which were collected from the whole territory of Poland (Figure 1). Sampled stands are mainly pure and even-aged. In part sampled stands were artificially planted, however, those are not typical forest plantations and the methods of forest management used in these forests, with the exception of Scots pine, are mainly close to continuous cover forestry. The research uses data from two sources. About 20% of the data were collected from the project titled “actual and potential site productivity in Poland for main forest-forming tree species,” realized in 2015–2017 and financed by the State Forests of Poland. The project established 612 sample plots for eight of the main forest-forming tree species, where stands were selected for each species, representing the whole range of geographic distributions and site conditions. The material collected thus represented the whole variability of Poland’s growth conditions for the forest-forming tree species analyzed. The second data source was the database of individual tree growth trajectories collected in Poland over the last few decades as part of research projects conducted by the main forest research institutions in Poland, namely, the Forest Research Institute in Sękocin Stary, the Faculty of Forestry, Warsaw University of Life Sciences (SGGW), and the Faculty of Forestry, University of Agriculture, Krakow. Both data sets used in the study meet the standards required for site index models development; the sample trees for the height growth reconstruction have been dominant without visible damage and were collected in pure stands of target species.

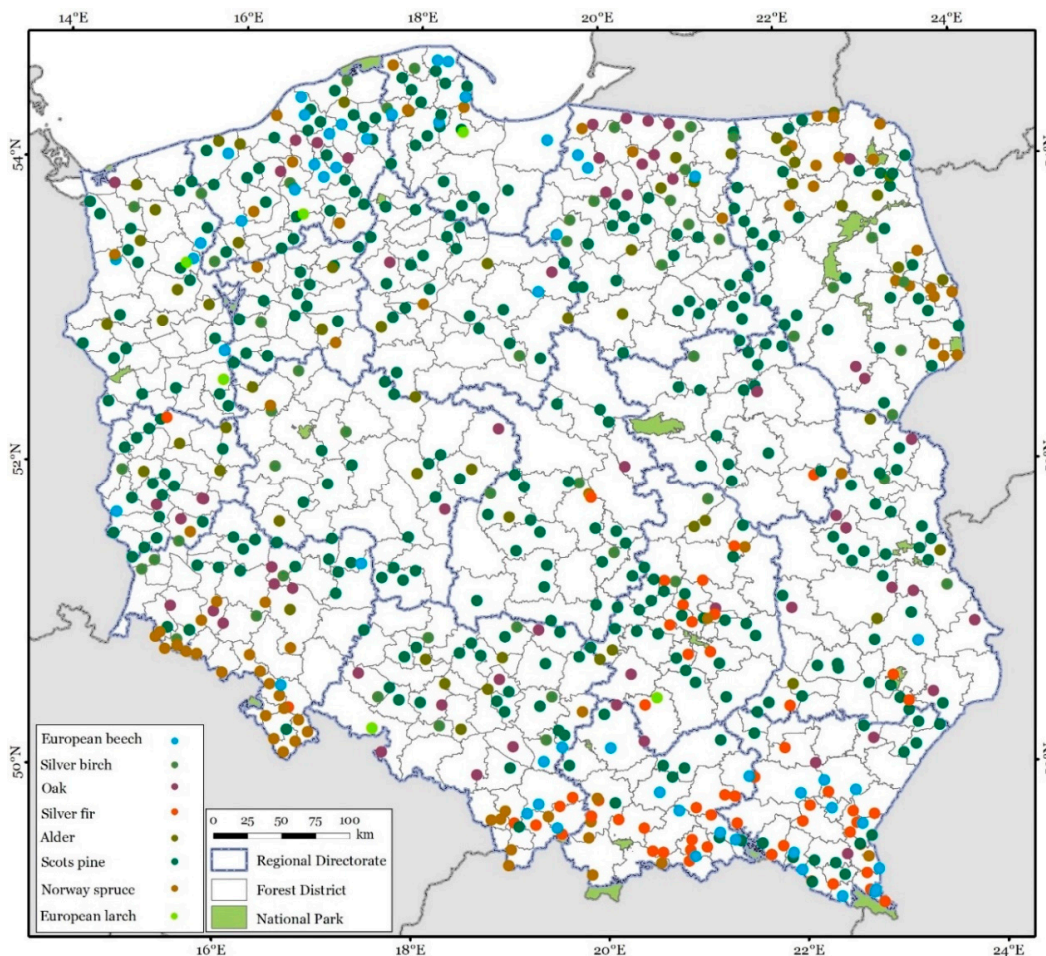
### 2.2. Stem Analysis

Stem analysis used the material of the 3052 trees to reconstruct the past height growth of the trees. The trees for stem analysis were selected in the direct neighborhood of the permanent sample plots established within the research projects. For each plot, one to three trees with a diameter and height close to the top height (TH) defined as the average height of the 100 thickest trees per 1 ha were selected and cut for stem analysis (SA). To reconstruct height growth, only trees with typically developed crowns with no visible damage or growth anomalies were chosen. After cutting, the total lengths of the trees were measured and rings were collected for stem analysis. Rings were taken from the base of the felled tree at a height of 0.5 m, at the diameter at breast height (DBH), and then, for trees over 15 m high, subsequent discs were collected at heights of 2 m, 4 m, and then every 2 m up to the top

of the tree. For trees less than 15 m high, subsequent discs were collected at heights of 1.5, 2.5, 3.5, and every 1 m further up the tree. The course of growth of the individual tree was reconstructed using the height of the discs and the number of annual rings. The growth of the trees was also visually examined for patterns of suppression and release as well as growth anomalies. As cross-section lengths do not coincide with periodic height growth, the height-age data from the stem analysis were corrected using Carmean’s method [57].

**Table 1.** The number and basic characteristics of growth series for the analyzed species, obtained from stem analysis and used for the development of the site index models.

Species	Number of Growth Series	Age (Years)		Height (m)	
		Min	Max	Min	Max
Scots pine ( <i>Pinus sylvestris</i> )	988	12	175	7.07	36.75
European beech ( <i>Fagus sylvatica</i> )	327	60	180	15.79	33.56
Black alder ( <i>Alnus glutinosa</i> )	448	7	120	5.15	31.4
European larch ( <i>Larix decidua</i> )	227	20	170	16.38	38.55
Silver birch ( <i>Betula pendula</i> )	99	20	105	10.46	33.46
Oak ( <i>Quercus</i> sp.)	317	18	145	9.5	32.91
Norway spruce ( <i>Picea abies</i> )	419	10	154	1.27	41.57
Silver fir ( <i>Abies alba</i> )	227	20	215	1.7	36.16
3052					



**Figure 1.** The location of sample plots for the analyses of the forest-forming tree species in Poland. From these plots, stem analysis data used for model development were collected.

2.3. Models

Over the years, researchers have used various mathematical functions to describe the growth of stands. Kiviste et al. [58] documented 74 different mathematical models for this purpose. Recently, several new solutions have been proposed to model the growth of various forest-forming species [29,42,48,50,56,59–62]. New growth functions have been used to develop site index models for different countries, such as Sweden [63], Finland [64], Spain [59,65,66], the USA [67,68], Turkey [61], and Poland [35,36,41,42,69].

To reliably estimate the site index, a model should have the following desirable attributes [47,50,70]:

1. Polymorphism, allowing the model to take into account different site-specific growth patterns, depending on site conditions;
2. Variable asymptotes for different sites;
3. Equality of the site index and the height at base age;
4. The possibility of using the same function as both a height growth model and a site index model.

The GADA method, which enables one to use one or two site-specific parameters representing the site’s quality, provides dynamic site index models that meet these criteria [47,59].

In the present study, we selected five dynamic models with symbols from M1 to M5 for further analysis (Table 2). All of these models meet the most criteria above and have been successfully applied to site index modeling, which makes them potential candidates for reliable site index models. Model M1, derived by Cieszewski [48], was applied in site index modeling in Denmark [71] and Poland [69,72]. Model M2 from the base function of Chapman–Richards, was developed by Krumland and Eng [73] and was used as one of the candidate functions for development site index models for Norway spruce and Scots pine by Sharma [60]. GADA formulation of the model M3 was developed by Cieszewski [74] based on the Bertalanffy–Richards function. Models M4 [60] and model M5 are the growth models that have frequently been tested in many studies concerning site index modeling [60,61,75]. In the case of the model, M5 GADA is equivalent to ADA [76].

**Table 2.** The dynamic generalized algebraic difference approach (GADA) formulations with base equations used to model dominant height growth.

Model No.	Base Model Forms	Parameter Related to Site and Solution for theoretical Variable X	Dynamic GADA Formulation and Reference
M1	$H = \frac{a_1 S^{a_2}}{(1 + e^{a_3 - a_4 H - a_5 H S})}$	$S = X_0$ $R = Z_0 + \left( Z_0^2 + \frac{2b_2 H_1}{T_1^{b_1}} \right)$ $Z_0 = H_1 - b_3$	$H_1 = H_0 t_1^{b_1} \left( \frac{t_0^{b_1} R + b_2}{t_1^{b_1} R + b_2} \right)$ Cieszewski [48]
M2	$H = a_1 [1 - \exp(-a_2 t)]^{a_3}$	$a_1 = X$ $X_0 = H_0 / (1 - \exp(-b_2 t_0))^{b_3}$	$H_1 = H_0 \left( \frac{1 - \exp(-b_2 t_0)}{1 - \exp(-b_2 t_1)} \right)^{b_3}$ Krumland and Eng [73]
M3	$H = a_1 [1 - \exp(-a_2 t)]^{a_3}$	$a_1 = \exp(X)$ $a_3 = b_2 + b_3 / X$ $X_0 = \frac{1}{2} \ln Y_0 - b_2 L_0 + \sqrt{(\ln Y_0 - b_2 L_0)^2 - 4b_3 L_0}$ with $L_0 = \ln 1 - \exp(-b_1 t_0)$	$H_1 = H_0 \left( \frac{1 - \exp(-b_1 t_1)}{1 - \exp(-b_1 t_0)} \right)^{(b_2 + \frac{b_3}{X_0})}$ Cieszewski [74]
M4	$H = \frac{t^2}{a_1 + a_2 t + a_3 t^2}$	$a_2 = X$ $X_0 = \frac{t_0}{H_0} - \frac{b_1}{t_0} - b_2 t_0$	$H_1 = \frac{t_1^2}{b_1 + X_0 t_1 + b_2 t_1^2}$ Sharma et al. [60]
M5	$H = a_1 \exp(-a_2 t^{-a_3})$	$a_2 = X$ $X_0 = -\ln\left(\frac{Y_0}{a_1}\right) t_0^{a_3}$	$H_1 = b_0 \left( \frac{H_0}{b_0} \right)^{\left( \frac{t_1}{t_0} \right)^{b_2}}$ Anta et al. [76]

$a_1, a_2, a_3, a_4, a_5$  are parameters in base models;  $b_1, b_2, b_3$  are parameters in dynamic models;  $S$  is the parameter related to site;  $H_0$  and  $H_1$  are heights (in m) at age  $t_0$  and  $t_1$  (in years), respectively;  $X_0$  is the solution of  $X$  for initial height and age.

#### 2.4. Parameter Estimation

What distinguishes the selected equations is that the choice of the base age does not affect the estimates of the model parameters [47,48,50]. Local (site-specific) and global parameters (GPs) of site index models were simultaneously fitted using the iterative nested procedure (INP) that has been described by Cieszewski [77], Sharma [60], and Socha [69].

The INP starts by calculating the GPs of Function (1), using the height measured in base age for each of the growth trajectories of the individual trees. Next, for each growth trajectory, the GPs are assumed as constants, and the site-specific parameter (SI) is estimated. The SI values fitted for a given tree then become the “observed” values and the GPs are re-estimated. This procedure was repeated here until the GPs were stabilized.

To fit the models, we wrote a devoted R script [77]. As the data represent a time series, the models used a first-order autocorrelation error structure. We did so to deal with possibly autocorrelated residuals from the models, a problem often encountered in models fitted to data representing successive (and thus often correlated) observations in time, especially when all the possible time intervals are used. Such autocorrelation can adversely affect the estimates of model parameters and their standard errors [78].

To compare the fitted models with the corresponding growth trajectories from yield tables [26,28], we plotted height growth curves for a range of site indices.

#### 2.5. Model Evaluation

To select the best models, we used three tools, namely, (i) graphical methods to compare residuals with the corresponding fitted values, (ii) statistics of the goodness-of-fit, and (iii) the evaluation of a model’s suitability to represent biological realism [70]. Such a procedure has been frequently used to compare and evaluate models [45,55,60,61,66]. To assess biological realism, we analyzed the trajectories and age of culmination of height increment. According to the general rules of growth [30], we assumed that the height increment of stands growing on the weakest site conditions should not exceed the increment in more fertile sites. Besides, we assumed that as the site productivity decreases, the age of culmination of height increment should increase.

In the first step, to evaluate the quality of the fit, the procedure analyzes three statistics, namely, the mean absolute error (MAE, Equation (1)), coefficient of determination ( $R^2_{adj}$ , Equation (2)), and the Akaike information criterion (AIC, Equation (3)):

$$MAE = \sum_{i=1}^n \frac{|h_i - \hat{h}_i|}{n} \quad (1)$$

$$R^2_{adj} = 1 - \frac{\sum_{i=1}^n (h_i - \hat{h}_i)^2}{\sum_{i=1}^n (h_i - \bar{h}_i)^2} \left( \frac{n-1}{n-p} \right) \quad (2)$$

$$AIC = 2 \log L + 2p \quad (3)$$

where  $h_i$ ,  $\bar{h}_i$ ,  $\hat{h}_i$  are the measured, mean, and predicted values of the heights, respectively,  $n$  is the total number of observations used to fit the model,  $p$  is the number of parameters in the model, and  $L$  is the residual sum of squares.

In the second step, we analyzed plots of model residuals, which allow for assessing the model’s fit across the range of the data. In the last step of the procedure, we analyzed whether each model had the desired biological properties.

### 3. Results

The five individual growth functions for the eight forest-forming species yielded 40 site index models (Table 3). Due to the properties of the differential equations, they were also height growth models. Table 3 summarizes parameter estimates and goodness-of-fit statistics of these candidate

models. Figure 2 shows the model fit to growth series and Figure 3 shows the residuals against the predicted values. As emphasized earlier, to select the best model, we cannot use just one particular statistical measure, but instead, have to make a compromise between the statistical aspects and biological realism of the model. In the case of models with similar statistics of the goodness-of-fit, the model, which meets the criteria of biological realism was recommended.

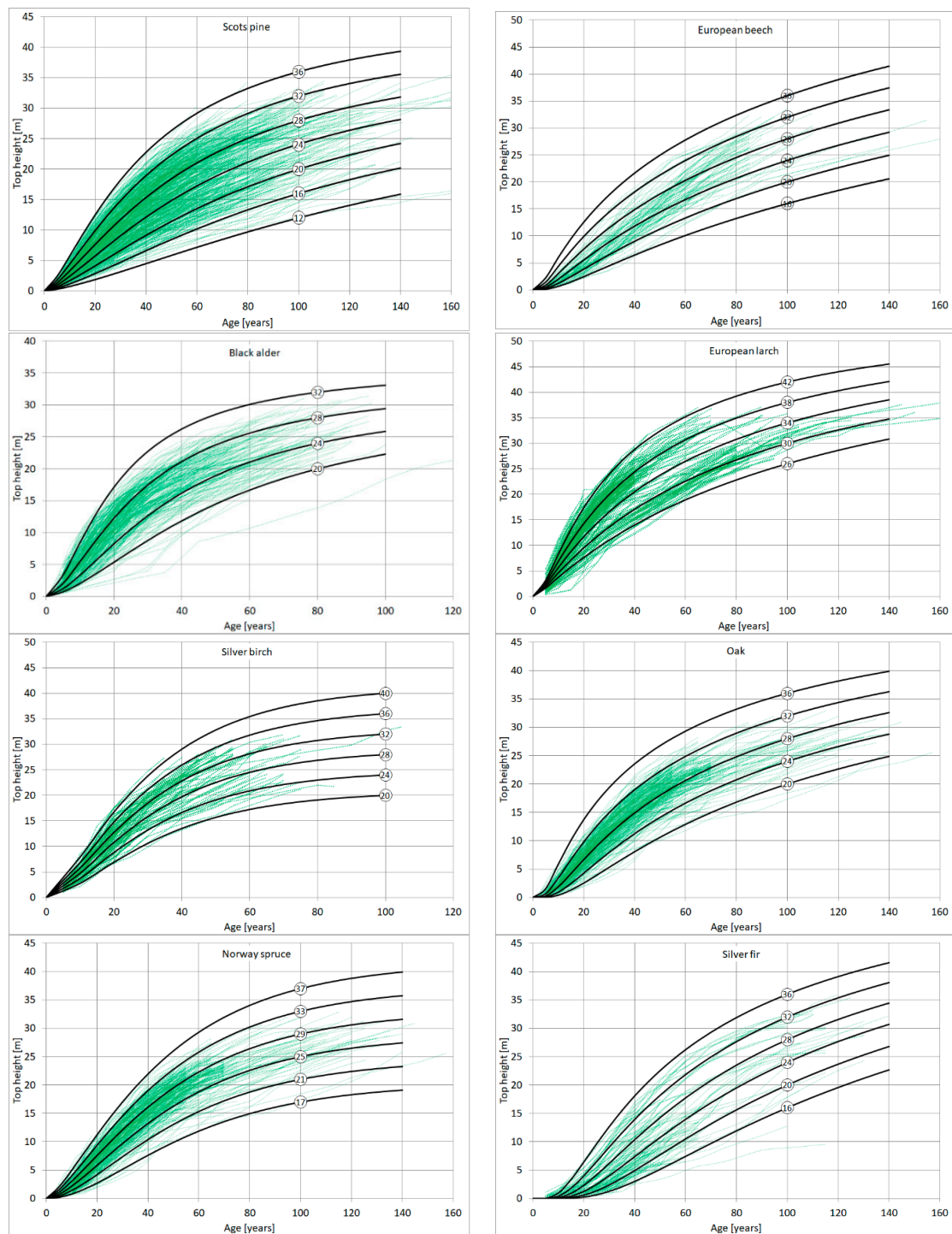
**Table 3.** Parameter estimates and goodness-of-fit statistics for the individual site functions and species. R<sup>2</sup>: Coefficient of determination. AIC: Akaike information criterion. MAE: Mean absolute error.

Species	Function	Parameters	Estimate	R <sup>2</sup> <sub>adj</sub>	AIC	MAE	
Scots pine	M1	b1	1.366	0.989	35324	0.6	
		b2	5802.862				
		b3	30.581				
	M2	b2	0.017	0.986	39205	0.65	
		b3	1.236				
	M3	b1	0.020	0.988	36937	0.61	
		b2	0.860				
	M4	b3	8.425	0.989	35608	0.61	
		b1	10.848				
	M5	b2	0.019	0.988	36518	0.64	
		b0	101.255				
	European beech	M1	b1	1.366	0.987	8604	0.677
			b2	5802.952			
			b3	30.581			
		M2	b2	0.015	0.987	8730	0.684
b3			1.675				
M3		b1	0.017	0.988	8561	0.672	
		b2	1.243				
M4		b3	7.797	0.986	8895	0.707	
		b1	47.661				
M5		b2	0.013	0.987	8797	0.697	
		b0	206.947				
Black alder		M1	b1	1.565	0.985	28359	0.728
			b2	1644.059			
			b3	29.161			
		M2	b2	0.035	0.981	30673	0.83
	b3		1.472				
	M3	b1	0.039	0.983	29327	0.77	
		b2	0.159				
	M4	b3	31.764	0.984	28803	0.74	
		b1	9.244				
	M5	b2	0.025	0.983	36518	0.645	
		b0	101.255				
	European larch	M1	b1	1.328	0.984	8783	0.843
			b2	625.507			
			b3	43.486			
		M2	b2	0.017	0.978	9661	1.044
b3			1.084				
M3		b1	0.023	0.982	9075	0.897	
		b2	0.346				
			b3	21.046			

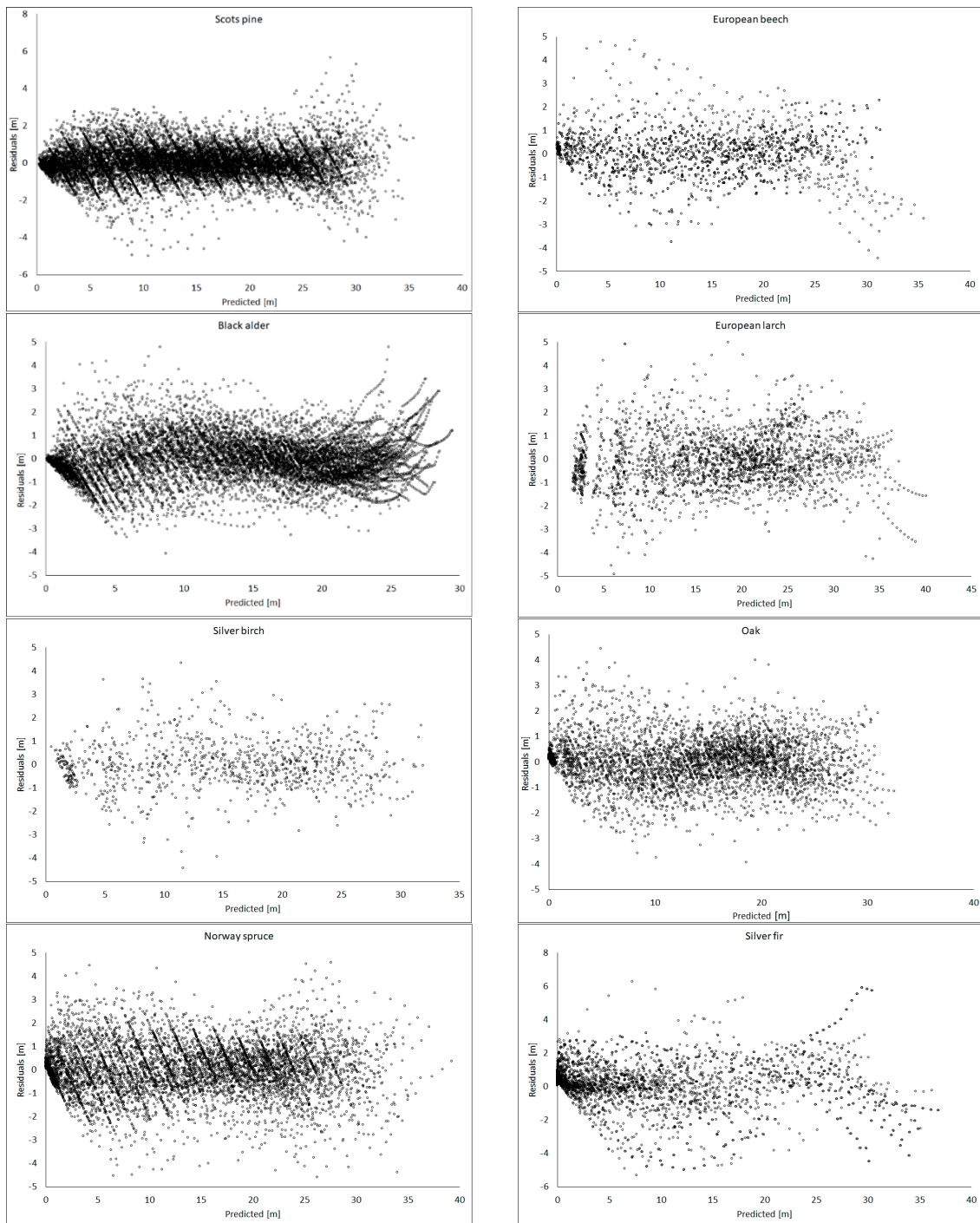
Table 3. Cont.

Species	Function	Parameters	Estimate	R <sup>2</sup> <sub>adj</sub>	AIC	MAE	
	M4	b1	4.639	0.983	8948	0.878	
		b2	0.018				
	M5	b0	78.357	0.983	8879	0.848	
		b2	0.514				
Silver birch	M1	b1	1.366	0.984	3007	0.744	
		b2	5802.952				
		b3	30.581				
	M2	b2	0.036	0.983	3079	0.777	
		b3	1.580				
	M3	b1	0.038	0.983	3042	0.768	
		b2	1.120				
			b3	12.810			
			b1	11.337			
	M4	b2	0.023	0.984	2999	0.731	
		b0	101,255				
	M5	b2	0,436	0.984	3172	0.845	
Oak	M1	b1	1.664	0.987	12376	0.691	
		b2	7635.281				
		b3	30.359				
	M2	b2	0.022	0.984	13253	0.776	
		b3	1.591				
	M3	b1	0.025	0.986	12632	0.708	
		b2	0.699				
			b3	18.602			
			b1	27.831			
	M4	b2	0.022	0.986	12632	0.708	
		b0	60.331				
	M5	b2	0.654	0.986	12511	0.697	
Norway spruce	M1	b1	1.833	0.986	19814	0.775	
		b2	6121.850				
		b3	40.956				
	M2	b2	0.016	0.977	23053	1.009	
		b3	1.606				
	M3	b1	0.025	0.985	20405	0.828	
		b2	0.770				
			b3	24.012			
			b1	31.549			
	M4	b2	0.014	0.979	22498	0.96	
		b0	86.625				
	M5	b2	0.642	0.986	20024	0.8	
Silver fir	M1	b1	1.833	0.976	12075	0.992	
		b2	6121.850				
		b3	40.956				
	M2	b2	0.007	0.959	13629	1.285	
		b3	1.478				
	M3	b1	0.017	0.975	12018	0.993	
		b2	1.439				
			b3	6.830			
			b1	66.678			
	M4	b2	0.011	0.959	13614	1.285	
		b0	63.533				
	M5	b2	0.867	0.978	11596	0.916	





**Figure 2.** Site-specific height growth curves representing the developed site index models, along with the observed height growth trajectories obtained from stem analysis. The numbers in circles show the corresponding values of the site index.



**Figure 3.** Residual versus predicted values from the selected site index models for the analyzed tree species studied.

Hence, the below analyses used quantitative measures of the goodness-of-fit (MAE,  $R^2$ , and AIC), the analysis of residuals, and the evaluation of how the model reflects the biological phenomena of height growth as criteria.

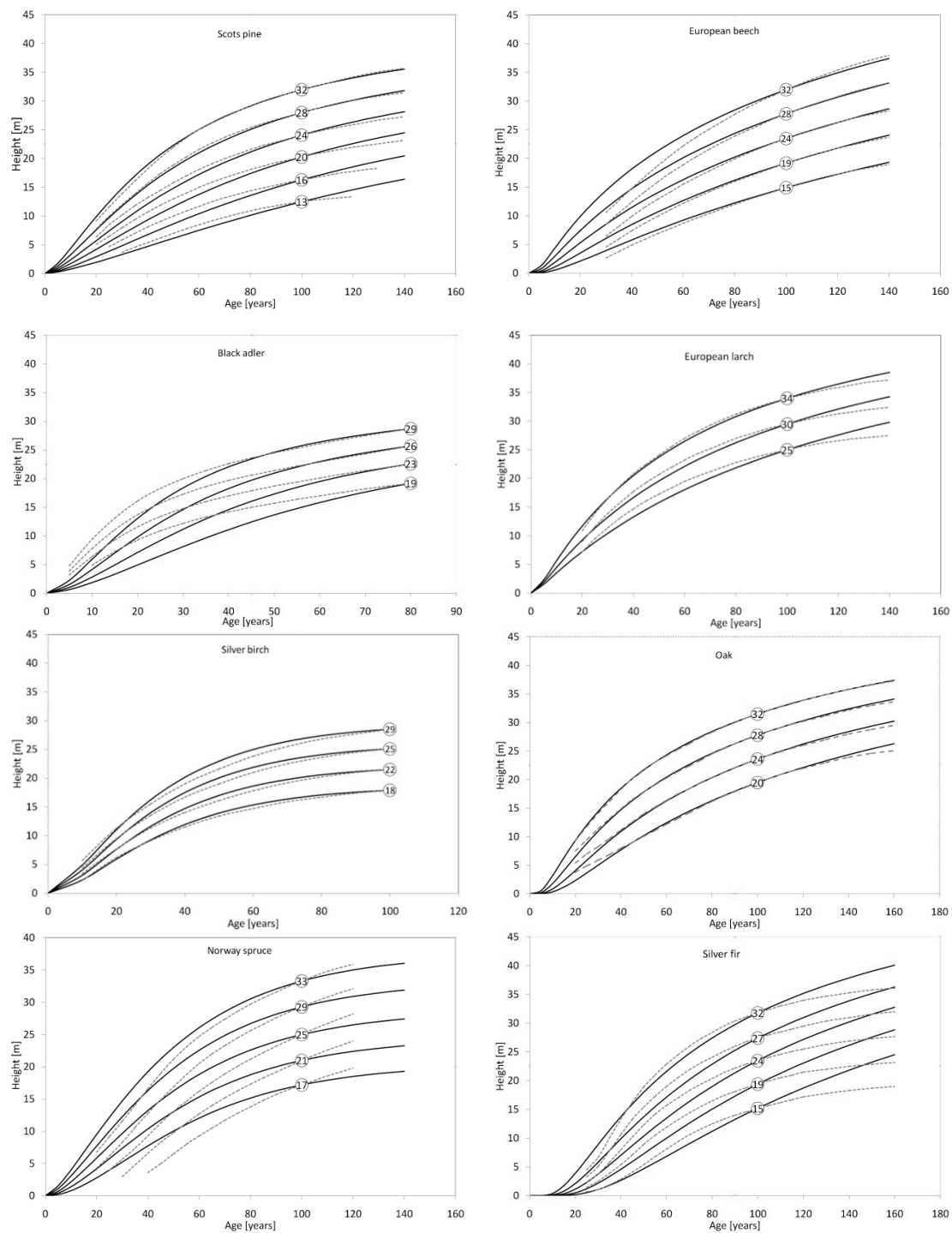
The evaluation of fit statistics and the graphical analysis for model M1 indicates that this function had the best predictive ability as compared to the other models studied for Scots pine (Figure 2) and most of the analyzed species (Table 3). The European beech models, built based on functions M1, M3, and M5, had comparable fitting statistics, but after analysis of the residuals of models, we found systematic errors of model M3 in the dependence on stand age. Therefore models M1 and M5 (Figure 2)

proved to be best suited to the empirical data among all of the other analyzed models. For black alder, model M1 had the best predictive ability in terms of the results of residual distribution and biological realism compared to the other models. Models M1 and M4, tested for European larch, showed a good fit for statistics with small differences between models, however, considering the plot of residuals, we propose the application of model M4 for site index determination for this species. Among all the equations tested for silver birch, models M1 M4 and M5 were characterized by good fitting statistics but after a detailed analysis of growth trajectories and plots of residuals, we recommend model M1 here. For oak, we recommend model M5, which provided the best results for the distribution of residuals. Goodness-of-fit statistics showed that model M1 for Norway spruce had the best predictive ability as compared to model M3, however, based on analysis of residuals we recommend model M3. For silver fir, the model built based on model M5 had the best fitting statistics as compared to the other models tested for silver fir, and was also well-fitted across the range of data.

Residual plots were used as one of the criteria of the model evaluation. For the models chosen, the most appropriate plots of residuals are presented in Figure 3. None of the models showed any apparent trends and structures across the range of predicted values, which indicates that the site index curves for the recommended models well represent the observed height age patterns across the range of site conditions.

High values of the adjusted (by the number of parameters in the model) coefficients of determination ( $R^2_{adj}$ ) indicate that selected models accounted for at least 97.5% of the total variation in the data (Table 3), which represents a very good fit in every single case. Here, mean absolute errors ranged between 0.60 m (Scots pine) and 0.91 m (silver fir).

Growth curves obtained from the developed site index models were compared directly with the growth curves from the yield tables (Figure 4). For Scots pine, the curves were similar, with the largest differences observed in the old and young age classes, especially for less productive sites. The models differed more significantly for European beech and black alder in the youngest age classes. The yield tables showed that black alder's stands reach nearly half of the total height in the first 15 years of life, after which their growth slows down, while the site index model developed in this study shows a fast growth rate up to 40 years. Large differences in growth trajectories were observed for Norway spruce and silver fir. For the former, the results show that the height growth of younger stands is considerably faster than what is found according to yield tables. For the latter, there were differences particularly in the oldest age classes, where the obtained model, in contrast, to yield tables, did not show the strong inhibition of height increase. Differences in height growth trajectories for European larch were rather small, with the larger height increment from developed models than in yield tables for the oldest stands. Growth curves from yield tables and the developed models provided similar trajectories for oak and silver birch.



**Figure 4.** Height growth curves from the selected site index models (solid lines) against those obtained from yield tables (dotted lines). The numbers in circles show the corresponding values of the site index.

#### 4. Discussion

We developed site index models using dynamic functions derived from the GADA method, which meet the crucial requirement of polymorphism and variable asymptotes. This enables the good representation of empirical data, from both statistical and biological perspectives. To assess biological behavior, we analyzed height increment curves. We found the higher height increment in weaker site conditions, which was observed in the case of some models in the stands of older age classes,

as incompatible with generally known growth rules [30]. We also assumed that as the site productivity decreases, the age of culmination of height increment should increase.

All the selected models had the desired properties of a good site index model. Compared to the methods still used in Polish forestry practice, such as yield tables, our models provide better predictive ability, which was also reported by many other studies that applied the GADA methodology, for instance [47].

It is important to note that yield tables were developed at the end of the nineteenth century and the beginning of the twentieth century. Each yield table value represents information obtained on the basis of only one age and site class, while each point of the curve of the developed models is the result of information from the entire range of empirical data. The purpose of modeling is to generalize the information contained in the measurement data and to compensate for random errors. The use of mathematical models developed by the simultaneous estimation of their parameters on the basis of all observations from all height growth trajectories collected for individual species is, statistically speaking, much more effective than tables containing the results of the individual adjustment of growth curves for individual site classes [79]. These attributes are one of the probable reasons for the differences between site index curves from yield tables and the newly developed dynamic site index curves.

The height growth trajectories obtained by the dynamic site index models have different courses from those of the yield tables. For most species, the two types of models showed the largest differences for either the youngest or the oldest age classes. For Scots pine, we observed some differences in both old and young age classes, especially for less productive sites (Figure 4), most likely due to the fact that yield tables poorly represent data within this range [80].

For European beech, the largest differences were observed in the youngest age classes, which is likely a consequence of the use of the longer regeneration periods for natural stands, which have been used in the past. A common current approach in the practice of beech forest management uses shorter regeneration periods, which could explain the observed changes.

The two types of models provided different results for black alder as well. The site index curves suggested a slower height growth speed in the youngest age classes than that resulting from the yield tables. This overestimation by yield tables may result from their use of data for coppice alder stands, which most probably present very intensive growth in the initial period of growth.

The differences we observed for European larch were similar to those observed for Scots pine, with less productive sites being poorly represented in the data and the oldest age classes being either underestimated or overestimated by yield tables.

Site index curves from yield tables and the developed model's curves for oak and silver birch have almost the same course, demonstrating the possibility of the use of yield tables for site index estimation for this species. The large differences observed for Norway spruce probably have resulted from using different regeneration methods in the past (such as the shelterwood system) and a long regeneration period. The guidelines for the forest silviculture of this species have changed quite significantly during the twentieth century. In particular, its regeneration period was shortened, which is a key factor affecting the growth dynamics of this species, particularly for trees up to 60–80 years in age. In comparison to the height growth trajectories obtained from the developed model for Norway spruce, the site index curves from yield tables showed large errors in determining site productivity.

Analyzing growth trends for fir in the oldest age classes showed significant differences. The comparison of the curves suggests that, currently, stands of the oldest age classes do not show as significant slowdown as yield tables may suggest, which is consistent with the biology of this species. The current knowledge indicates that, in favorable conditions, silver firs can grow for 200 years [81].

In general, the results indicate that for most forest-forming tree species, the currently used yield tables provide different height growth curves than those actually observed. On the one hand, this observation might be due to the small amount of data used to construct yield tables for the youngest and oldest age classes, as well as the less productive sites, which are relatively rare. On the other hand,

site indices for young stands are commonly considered to be very variable, because early growth is irregular and determined not only by site conditions but also by other factors [82]. Two of the key roles in this variation are the regeneration period and the regeneration method, the former likely being a reason for the differences between the growth curves fitted for Norway spruce and European beech, while the latter for black alder.

Another important factor affecting growth curves is the selection of trees. It is known that not all trees in the top layer of the stand belong to this layer throughout their entire life. As such a change in the canopy position of a tree is quite probable [83], models based on the data from stem analysis can sometimes overestimate growth rates [10]. We used the verification procedure to assess the growth curve of the individual growth series against the background of more trees living in the given area. This allowed us to limit the probability of choosing trees whose growth curves significantly differ from the growth curves of other trees growing in similar site conditions.

Most likely, the differences in growth curves obtained using dynamic site index modeling and yield tables, the latter obtained using data older than 100 years, were due to the changes in growth conditions over this time. As shown by the latest research, these were changes mainly in nitrogen deposition and the climatic parameters [31,84], as well as an increase in carbon dioxide concentration [85]. Changing site conditions over time [31] undoubtedly constitutes a disadvantage of the site index concept [3], as they lead to a negative correlation between stand age and the site index [21,60,69]. This problem is sometimes solved by the inclusion of a stand age as one of the variables when modeling site productivity [33,86].

Site index, which is traditionally used to determine current growth conditions, has increasingly used in new research areas, such as mapping the site index from remote sensing data, simulating productivity changes, and analyzing the CO<sub>2</sub> sequestration of forest ecosystems [25,87]. Such analyses and tools provide valuable data to develop improved management practices in terms of mitigation and adaptation strategies for climate change. The appropriate prediction of site productivity is also key to developing effective strategies of CO<sub>2</sub> sequestration [25]. Such activities should form the basis of modern forest management, which would take into account the need to adapt forest ecosystems to the effects of climate change. In this research, we have observed differences in the growth dynamics and site requirements of the main forest-forming species. This knowledge may be key in many areas of forest management, especially in the context of maintaining the sustainability of forests in the face of climate and environmental changes.

What is important from the perspective of forest management is that Poland is geologically and climatically diverse, particularly along the northeastern and southwestern gradients. Thus, the growth dynamics of forest stands may show spatial variability. If this variability is significant, future research should focus on dynamic site index models that take into account additional site variables. This thought is not new, however, as various authors have pointed out that when analyzing the site index, regional variability should be taken into account [3,56,71]. Therefore, future research should focus on the development of regional site index models, which would help foresters to estimate the potential productivity of forest sites. Although the development of such regional models requires extensive research material, the recent research suggests that for building them, not only the results of stem analysis may be used, but also other data sources. Data from permanent plots that are part of the large-scale National Forest Inventory and data from aerial laser scanning have also successfully been used for site index modeling [60,69].

## 5. Conclusions

We have developed new site index models for eight of the main forest-forming tree species in Poland, namely Scots pine, European beech, black alder, European larch, silver birch, oak, Norway spruce, and silver fir, using over 3000 data series describing the trajectories of tree height growth. Selected for each species, the best dynamic forms of the growth function allow for a good fitting of the models to the empirical data, as evidenced by the explanation of about 98% variation in height

growth, which was crucial for the elimination of systematic errors. The main purpose of the developed models is the determination of site productivity. Thanks to the properties of the functions used for the development of the models, however, they can also be used as models describing the height growth of the stands. This research is the response to demands from the State Forests in Poland, Forest Management Bureau and other stakeholders to develop new yield tables (growth models) for the main forest-forming tree species in Poland. The presented research is the first stage in the construction of new empirical growth models/yield tables. The site index models presented in this research will be one of the functions of the developed growth models.

**Author Contributions:** Conceptualization, J.S.; Methodology, J.S.; Validation, J.S., L.T.-C.; Formal Analysis, J.S.; Investigation, J.S. and L.T.-C.; Resources, J.S.; Data Curation, J.S., S.O.; Writing—Original Draft Preparation, J.S., L.T.-C., E.G., S.O.; Writing—Review & Editing, J.S. and L.T.-C.; Visualization, J.S. and L.T.-C.; Funding Acquisition, J.S. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was supported by the project I-MAESTRO. Project Innovative forest MANagEmEnt STRategies for a Resilient biOeconomy under climate change and disturbances (I-MAESTRO) is supported under the umbrella of ForestValue ERA-NET Cofund by the National Science Centre, Poland and French Ministry of Agriculture, Agrifood, and Forestry; French Ministry of Higher Education, Research and Innovation, German Federal Ministry of Food and Agriculture (BMEL) via Agency for Renewable Resources (FNR), Slovenian Ministry of Education, Science and Sport (MIZS). ForestValue has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement N° 773324. Data collection was supported by the project “Actual and potential site productivity in Poland for the main forest forming tree species”, financed by the General Direction of State Forests [agreement no. ER-2717-11/14, 15th April 2014].

**Acknowledgments:** We would like to thank the Forest Management and Geodesy Bureau from Sekocin Stary for cooperation in implementing the project “Actual and potential site productivity in Poland for the main forest forming tree species”, particular for help in collecting the height growth data. We thank Professor Arkadiusz Bruchwald for sharing stem analysis data for different tree species collected within his research projects. We also thank three anonymous reviewers and the scientific editor who provided valuable comments on earlier versions of the manuscript.

**Conflicts of Interest:** The authors declare no conflicts of interest.

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