Regional Height Growth Models for Scots Pine in Poland

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Abstract

Background: Site productivity remains a fundamental concern in forestry as a significant driver of resource availability. The site index (SI) reflects the overall impact of all environmental parameters that determine tree height growth and is the most commonly used indirect proxy for forest site productivity estimated using stand age and height. One of the most critical challenges in the site index (SI) concept are local variations in climate, soil, and genotype-environmental interactions that lead to variable height growth patterns among ecoregions and cause inappropriate estimation of site productivity. Developing regional models can solve this problem and allow us to determine forest growth and SI appropriately.

Results: Therefore, the purpose of this study was to develop regional height growth models (RMs) for the Scots pine in Poland. For height growth modelling, we used the growth trajectory data of 855 sample trees, representing the entire range of geographic locations and site conditions of the Scots pine in Poland. Collected growth trajectories were used for the development of the global height growth model (GM) for Poland and RMs for six natural forest regions, which were adopted as the spatial unit for the model regionalisation. Height prediction errors by the global model were found to be significantly larger than those obtained with regional models in all regions. The results showed significant differences between growth trajectories in natural forest regions I, II, and III located in northern Poland compared to stands in natural forest regions IV, V, and VI in southern Poland.

Conclusions: The presented study showed differences in height growth patterns of Scots pines in Poland and revealed that the use of local models could improve the growth prediction and quality of the SI estimation. Developed RMs show better fit statistics and predictive validity than the GM developed for the countrywide scale. Differences in climate and soil conditions which distinguish natural forest regions affect height growth patterns of Scots pine. Therefore, extending this research to models which directly describe the interactions of height growth with site variables, such as climate, soil properties, and topography, can provide additional valuable forest management information.

1. Introduction

Site productivity remains a fundamental concern in forestry as a significant driver of resource availability (Bontemps and Bouriaud, 2014). Appropriate estimation of site productivity is critical for forest management decisions (Skovsgaard and Vanclay, 2008). Additionally, information on site productivity is useful for monitoring and assessing the impact of climate change on forest ecosystems and providing information to support forest management to take effective adaptation measures (Albert and Schmidt, 2010). The site index (SI) reflects the overall impact of all environmental parameters that determine tree height growth (Véga and St-Onge, 2009) and is the most commonly used indirect proxy for forest site productivity estimated using stand age and height (Hägglund and Lundmark, 1977; Johansson, 1999; Raulier et al., 2003; Skovsgaard and Vanclay, 2008, Corral Rivas et al., 2004, Tewari et al., 2007). An appropriate height growth model is needed to determine the SI accurately.

One of the most critical challenges in the SI concept is a local variation of height growth patterns that result from a variety of factors and could cause the under- or over-estimation of the growth potential and productivity of a site (Alvarez-González et al., 2005; Monserud and Rehfeldt, 1990). Species variability caused by sensitivity to environmental factors is the primary reason why a more flexible approach to developing height growth models is recommended to include the impact of local conditions and to accurately reflect height growth variation on a regional scale (Bravo-Oviedo et al., 2008a).

Climate, soil, and genotype-environmental interactions can favour the adaptation of species to local ecological conditions, causing variable height growth patterns for the same species among ecoregions (Alvarez-González et al., 2005; Monserud and Rehfeldt, 1990). In a study conducted in Sweden, Johansson (Tord Johansson, 1995) found significant variation in the height growth curves of forest stands owing to mineral soil type and geographical location. The effect of genetic variability on the height development of trees was reported by (Adams et al., 2006). Genetic variability has also been identified as the primary factor modifying the trajectory of height growth by Buford & Burkhart (1987) (Buford and Burkhart, 1987), who found that the height growth models developed for different provenances differed in their parameters describing the asymptote. Significant differences in height growth patterns can also occur for the same species, even within a given SI class (Monserud, 1984). García (2010) (García, 2010) reported that three sources of height growth development variability could be identified: (a) between sites, (b) within sites, and (c) observation error. Because of the inter-regional variability of growth patterns, regional height growth models (RMs) are derived to improve the predictive ability of the model (Adame et al., 2008; Alvarez-González et al., 2005; Bravo-Oviedo et al., 2008b, 2007; Calama et al., 2003a). Studies on Pinus pinaster in Spain indicated significant differences in growth patterns observed in different areas because of the effect of genotype-environment interaction (Alvarez-González et al., 2005). Research describing regional height growth differences highlights the regional application of the SI concept (Bontemps and Bouriaud, 2013; Calama et al., 2003a; Claessens H., 1999; Karlsson, 2000; Martín-Benito et al., 2008). The role of regional models may be crucial for sustainable forest management, particularly in solving problems that require accurate information on local growing conditions, where climate and soil type lead to inter-regional variation (Bravo-Oviedo et al., 2007).

The Scots pine is one of the most important species in Europe and ranges from the boreal region in Northern and Eastern Europe to the mountains of the Mediterranean in Southeastern Europe (Fig. 1). It is also the most important tree species in Poland, covering approximately 58% of the total forested area of the country (Dyrekcja Generalna Lasów Państwowych, 2018). The Scots pine grows under very variable ecological conditions (Socha, 2012), which could affect the difference in the shape of the growth curves among ecoregions (Johansson, 1995). The effective management of such a considerable forest resource requires a thorough assessment of the productivity of stands at a regional level (Bravo and Montero, 2001) Growth modelling is crucial in assessing the consequences of forest management activities in long term planning in forestry (Gadow and Hui, 1999). The use of inappropriate height growth models may result in erroneous estimation of site productivity. This problem could be solved by the development of RMs, which reflect the difference in growth trajectories resulting from specific growth conditions in a given area. Regional models reflect the impact of regional variability on height growth dynamics resulting from specific climate conditions, soil properties, and differences in local forest management.

In Poland, yield tables with discrete scales are still used in forest management for forest growth and site productivity estimation (Schwappach, 1943; Szymkiewicz, 2001, 1948). The forestry practice reports the incorrect determination of site productivity and incremented volume using yield tables, probably because of the inadequacy of Schwappach's tables from differences in growth conditions, which have changed considerably during the 100 years since the yield tables were developed. Pretzsch et al. (2014) estimated that in Central Europe, site productivity increased by approximately 30–70%. Additionally, the height growth of observed stands differs significantly from that observed 100 years ago (Socha et al., 2020; Socha and Orzeł, 2013) and included in the original tables. Moreover, the tables produce errors by not considering regional growth variability on a countrywide scale.

The research adopted the hypothesis that height growth is spatially differentiated. We assumed that height growth patterns are influenced by the variability in site conditions, which can be acknowledged by the development of separate models for natural forest regions, distinguished by environmental conditions. Therefore, the research objective was to analyse the variability of height growth patterns between natural forest regions in Poland and to develop regional models (RM) for the Scots pine in Poland.

2. Materials And Methods

2.1 Collection of the research material

The research material consists of the height growth trajectories of 855 dominant and codominant Scots pines (Table 1). The most substantial part of growth trajectories was collected from the sample plots established within the project "Actual and potential site productivity in Poland for main forest-forming tree species" from 2015–2016. This plot represented the whole variability of growth conditions in Poland for the Scots pine trees. Other tree growth trajectories have been collected in Poland over the last two decades as part of research projects conducted by the Department of Forest Resources Management, University of Agriculture, Krakow, the Forest Research Institute in Sękocin Stary, and the Faculty of Forestry, Warsaw University of Life Sciences. Sample plots represent the area of Poland, with a whole range of geographic distributions and site conditions (Figure 1). The age of the analysed sample trees ranged from 12–175 y, with an average of 76 y and heights ranging from 3.50–36.75 m (Figure 2, Table 1).

Table 1. The number and basic characteristics of growth series for the Scots pine trees, obtained from stem analysis and used for the development of the site index models.

Natural forest region	Number of growth series	Age (years)		Height (m)	
		Min	Max	Min	Max
I	146	20	140	13,2	33,4
II	125	12	175	7,1	36,7
III	174	14	175	8,2	33,8
IV	60	17	112	9,9	33,2
V	39	12	145	3,5	33,1
VI	311	23	141	11	35,6
Total	855				

Natural forest regions (Zielony and Kliczkowska, 2012) were adopted as the regionalisation unit in Poland. Natural forest regions were distinguished by the natural diversity of the country, in particular: variability of climatic and geological conditions, naturally occurring ranges of principal forest-forming tree species, presence and distribution of natural landscapes classes, and distribution of the primary units of potential natural vegetation (Zielony and Kliczkowska, 2012).

2.2. Stem analysis

Stem analysis was used to reconstruct the past height growth of the trees. The trees for stem analysis were selected in the direct neighbourhood of the permanent sample plots established in Scots pine stands. 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). Only trees with typically developed crowns and no visible damage or growth anomalies were selected for SA. After cutting, the total lengths of the trees were measured, and rings were collected for SA. Rings were taken from the base of the felled tree at the height of 0.5 m, and the breast height diameter (DBH) was measured; for trees over 15 m high, subsequent discs were collected at heights of 2.0, 4.0, and successive 2-m intervals to the top of the tree. For trees shorter than 15 m, subsequent discs were collected at heights of 1.5, 2.5, 3.5, and at 1-m intervals further up the tree. The course of growth of the individual trees was reconstructed based on the height of the discs and the number of annual rings. The growth trajectories of all collected trees were visually examined for suppression and release patterns and growth anomalies. As cross-section lengths do not coincide with periodic height growth, the height-age data from the SA were corrected using Carmean's method (Carmean, 1972). The collected growth series for six natural forest regions were used to develop regional height growth models (RMs).

2.3. Models and parameters estimation

The generalised algebraic difference approach (GADA) developed by Cieszewski and Bailey (Cieszewski and Bailey, 2000) allows the use of multiple site parameters and models characterised by polymorphism and variable asymptotes for different sites, equality of the SI and height at base age, and the use of the same function as a height growth and SI model. Therefore, we used the dynamic equation derived by Cieszewski (Cieszewski, 2001) and the GADA approach for the development of the Scots pine SI models. This equation was successfully applied in height growth and SI modelling and was the best for modelling the height growth of primary forest-forming tree species in Denmark (Nord-Larsen, 2006; Nord-Larsen et al., 2009); however, the most appropriate SI modelling for Scots pine in Poland was selected (Cieszewski et al., 2007; Socha et al., 2020; Socha and Orzeł, 2013, 2011).

$$H = H_1 \frac{T^{\beta_1}(T_1^{\beta_1}R+\beta_2)}{T_1^{\beta_1}(T^{\beta_1}R+\beta_2)}, \qquad (1)$$

$$\text{Where:} \quad R = Z_0 + \left(Z_0^2 + \frac{2\beta_2 H_1}{T_1^{\beta_1}} \right)^{0.5};$$

$$Z_0 = H_1 - \beta_3$$

where H is the measured height at age T, H_1 is a site parameter denoting stand height at age T_1, and β_1, β_2, and β_3 are estimated parameters.

An essential property of this equation is that the selection of a base age does not affect predictions, which determines invariance from the base age. Local (site-specific) and global parameters (GP) of SI models were simultaneously fitted using the nested iterative procedure (NIP) that has been described by Cieszewski (Cieszewski et al., 2000), Sharma (Sharma et al., 2011), and Socha (Socha et al., 2017). The NIP starts with the calibration of the global parameters of the equation using the preliminary values of the SI (H_1), determined by the mean height at the base age estimated for the empirical material. In the next iteration, the preliminary values of the global parameters are used as constants, and the site parameters are calculated for every growth trajectory. Next, the global parameters are refitted, using the H_1 estimates for a given trajectory as the constants. NIP is repeated until the model parameters stabilised. Subsequent height observations from the same growth trajectory are significantly correlated, and the assumption of independent errors may be violated. Therefore, the error structured modelling approach with a linear first-order autoregressive error was used in parameter estimation.

Collected growth trajectories were used for the development of a global height growth model (GM) for Poland and RMs for six natural forest regions. Owing to the different number of growth series in individual natural forest regions, the weighted least squares method was used to calculate the global model parameters. Weighting allowed the excessive influence of individual regions with the largest number of growth series on the global model. The ratio of the average number of growth trajectories collected in six analysed regions (N_{avg}) and the number of trees in a given natural forest region (N_{NFR}) was used as the weight (equation 2).

$$\left(H_{obs} - H_{pred}\right)^2 \times \frac{N_{avg}}{N_{NFR}} \qquad (2)$$

The growth trajectories of the individual regional models were directly compared by plotting and graphing the differences between model trajectories.

Parameter estimation was carried out in R using the NLS procedure and suitably defined model form (R, 2008).

2.4 Comparision of country scale and regional growth trajectories

In order to analyse the differences between global-country scale and regional height growth patterns, we developed a global height growth model for Scots pine in Poland and regional models for individual natural forest regions. Using the site parameter estimated for individual SA trees, we calculated the growth trajectories of every individual tree according to the global height growth model and regional model, appropriate for the region from which the given tree originates. Next, we calculated the residuals between observed and model growth trajectories for the global and regional model. We assumed that if the given regional model does not differ from the global model, the residuals of the compared models should not differ significantly. In order to check the significance of differences in the global and regional model residuals, we used the t-test for dependent samples.

3. Results

All developed models showed good fit and explain (in most cases) over 99% (adjusted R^2) of the height growth variation (Table 2). The prediction errors of all developed regional models were relatively low, with root mean square error (RMSE) varying from 0.64–0.74 m (Table 3). For each natural forest region, the regional models provided better accuracy compared to the global model for RMSE and mean absolute error (MAE). The highest mean error was observed when predicting the height growth in the II natural forest region with the global model (ME = -0.14 m). For all other natural forest regions, the systematic errors were lower than 0.05 m for global and regional models.

Table 2
Parameters estimation results of the global and regional site index models.

Model / region	No of cases	b1	b2	b3	R^2
GM / I-VI	855	1.364	5855	30.51	0.9909
RM / I	146	1.281	8813	32.68	0.9914
RM / II	125	1.503	2582	39.75	0.9951
RM / III	174	1.326	9706	26.72	0.9891
RM / IV	60	1.408	7520	22.52	0.9929
RM / V	39	1.418	2157	37.24	0.9939
RM / VI	311	1.46	10090	15.14	0.9920

Table 3
Assessment of the height growth prediction accuracy of individual trees from six natural forest regions in Poland using the global (GM) and the regional models (RM).

Region	GM	RM	GM	RM	GM	RM
	RMSE (m)		MAE (m)		ME (m)	
I	0.715	0.669	0.5088	0.4894	-0.0223	-0.014
II	0.8553	0.6558	0.6459	0.4899	-0.1416	-0.0134
III	0.7583	0.7448	0.5483	0.5391	-0.0085	-0.004
IV	0.7427	0.7216	0.5465	0.5368	0.025	-0.0046
V	0.6653	0.6393	0.4724	0.4534	-0.0305	-0.0073
VI	0.8055	0.7166	0.6081	0.545	0.0472	-0.0024
RMSE – root mean square error, MAE – Mean absolute error, ME – mean error						

Growth trajectories of models developed for individual regions were directly compared using the height at base age 100 y as the reference level (Fig. 3). We found significant differences between growth trajectories in natural forest regions I, II, and III, located in northern of Poland compared to stands in natural forest regions IV, V, VI, from southern Poland. Top heights values estimated from the regional model for natural forest regions I–III are lower under the age of 100 and higher over 100 years of age, signalling growth asymptotes from southern to northern Poland and differences in height growth dynamics. The growth of stands in south and southeastern Poland (regions IV–VI) is decelerating faster.

In contrast, Scots pines from stands located in natural forest regions I–III show more persistent height growth. We compared the growth curves using the age of 40 instead of the standard base age of 100 to better illustrate the differences in height growth of Scots pines from the analysed regions. In this case, the differences described above are even more pronounced (Fig. 4).

Differences between the model trajectories for the GM developed for Poland and regional models developed for natural forest regions with base ages of 100 and 40 are presented in Fig. 5 and Fig. 6, respectively. The biggest top height differences are observed between model trajectories from natural forest regions I and VI (Fig. 5, Fig. 6).

The results of one-sided Student's t-test for dependent samples showed statistically significant ($\alpha = 0.05$) differences between the average residuals of the global and regional models in natural forest regions II, IV, V, and VI (Table 4). In natural forest regions I and III, there are no significant differences between the average residuals of the global and regional models.

Table 4
Comparison of residuals between observed and model growth trajectories calculated for individual trees from global and regional models using the t-test for dependent samples.

Residual	Region	Mean (m)	No of cases	Mean difference (m)	Standard deviation (m)	t	df	p
RM	**I**	-0.014208	2287	0.001535	0.195732	0.374943	2286	0.71
GM		-0.015742						
RM	**II**	-0.003401	1696	0.14563	0.59202	11.73029	2273	0.01>
GM		-0.149031						
RM	**III**	-0.003928	2775	-0.002371	0.114756	-1.08862	2774	0.28
GM		-0.001556						
RM	**IV**	-0.004638	906	-0.022628	0.221025	-3.08157	905	0.01>
GM		0.01799						
RM	**V**	-0.007767	560	0.029879	0.156985	4.50402	559	0.01>
GM		-0.037646						
RM	**VI**	-0.003235	4770	-0.051074	0.432923	-8.14797	4769	0.01>
GM		0.047839						

The distributions of residuals versus predicted values for global and regional models are different (Fig. 7). Residuals for regional models are characterised by homoscedasticity and showed no correlation with the predicted top heights in all analysed regions (Fig. 7). The use of the global model to predict height growth results in systematic errors, particularly in regions II and VI (Fig. 7), where the residuals of growth prediction for individual trees using the global model are correlated with predicted values, indicating the inappropriateness of the general model. Moreover, height prediction errors by the global model are significantly larger than those obtained with regional models in all regions (Table 3). This indicates an increase in the accuracy of growth modelling using regional models that are better suited to local growing conditions.

4. Discussion

In this study, we analysed the differences in the height growth dynamics of Scots pines in natural forest regions in Poland and showed that the height growth is spatially differentiated. The most relevant differences in growth patterns are observed in the north-south gradient. The shape of the growth trajectory for stands located in natural forest regions from the north and northwestern Poland (I–III) differs for younger and older trees. In these natural forest regions, the stands also reach higher absolute heights compared to those of southern regions. Our results show that the use of the generalised model in Poland produces errors in the determination of site productivity.

Spatial variation in growth patterns was previously reported; these variations have usually been interpreted as the result of variability in climate, geology, soil type, geographical location, and genotype (Adams et al., 2006; Buford and Burkhart, 1987; Tord Johansson, 1995).

Therefore, we compared the country scale with regional model height growth trajectories and found significant differences between height growth patterns of trees from natural forest regions located in northern and southern Poland. This may be because natural forest regions in northern Poland have deep podsolic, brown podsolic, and brown glacial soils, whereas natural forest regions V and VI feature upland soils with less depth. The depth and physical properties of soil and the sand and clay contents lead to varying soil fertility and productivity (Brandl et al., 2018; Seynave et al., 2005). Additionally, the availability of water is strongly correlated with the growth of stands and has an impact on the productivity of sites (Nathalie Breda, Roland Huc, André Granier, 2006). A linear increase in net primary production with increased water availability was observed at dry sites (Loik et al., 2004). The amount of annual precipitation in Poland changes from south to north and, with soil fertility and depth, can explain the difference in height growth variability between the northern and southern regions.

We found that growth trajectories for individual models vary with age. The growth of stands in southern and southeastern Poland is slowing at a more rapid rate, whereas northern and northeastern stands have more persistent rapid height growth. Intensive growth in the youngest age classes in regions IV, V, and VI can be explained as the impact of soil depth. In the youngest age classes, when soil depth is not a limiting factor, the impacts of climate and other factors are more important for growth dynamics, but with the transition to older age classes and increased interspecific competition, soil depth likely begins to limit the growth dynamic. An evident slowdown of growth dynamics in oldest age classes in natural forest regions IV, V, and VI may be the result of a combination of shallower and less fertile podsolic and brown podsolic soils and low annual rainfall. In regions, I, II, and III, geological and climatic conditions are more favourable for Scots pines and likely result in a larger height increment in the older stands.

The significant height growth differences in different regions indicate that the use of one generalised height growth model for the entire country may result in the inappropriate estimation of site productivity and have direct forest management consequences. The importance of regional models may increase because the projections of climate change in Poland predict accentuated differences in site conditions between the northwest and southeast regions (Kundzewicz et al., 2017). The obtained results concerning the spatial variability of the height growth dynamics of Scots pines should be considered when making forest management decisions concerning the rotation age or intensity of silvicultural treatments.

The amount of carbon stored in forests is greater than in any other terrestrial ecosystem (Barrio Anta and Diéguez-Aranda, 2005), and tree growth data play a major role in carbon sequestration and biomass production calculations (Bowman et al., 2013). Several conversion methods have been developed for different types of forest to obtain reliable estimates (A. Isaev, G. Korvodin, D. Zamolodchikov and Pryaznikov, 1995; Fang and Wang, 2001; Schroeder et al., 1997). However, our results show that not considering specific regional growth conditions and the resulting differentiated growth patterns by using only global models for these calculations may result in an over- or under-estimation of regional height growth, biomass production, and carbon sequestration. Many studies on the estimation of biomass production and carbon sequestration emphasise that the regional approach is promising (Bravo-Oviedo et al., 2010; Woodbury et al., 1998); therefore, the use of models developed on a regional scale shows particular importance for effective forest management.

With the development of geographical information systems and technologies, tools such as the mapping SI are increasingly common (Latta et al., 2011). Many problems regarding the stability of forest stands and disturbance of forests in Europe concern relatively small areas. Many studies found that SI mapping and analyses, (particularly on a small scale) provide information for a more dynamic assessment of forest growth and should be an important component of regional planning and management (Coops et al., 2010, 2007). Therefore the use of advanced forestry solutions focused on smaller areas, regional growth models, and the analysis of local trends have great potential for the fast detection of problems and for the precise formulation of answers to stand instability and forests disturbances.

We used the height growth trajectories of dominant and codominant Scots pines collected using the unified methodology to develop a regional model; however, collection methods and data processing in different regions should be carefully executed. Differences in methodology or data sources can lead to significant inconsistencies between growth models that are not based on ecological or biological causes (Calama et al., 2003b). The growth patterns of a given species in different ecological or geographical conditions are significant and should be determined before developing local models for small areas. The differences in local model predictions may not be large enough in small geographical regions to justify the development costs (Calama et al., 2003b). In this situation, smaller regions with low climatic and geomorphological variability should be grouped together to develop a single model for larger areas.

5. Conclusions

The presented study showed regional differences in height growth patterns of Scots pines in Poland. Developed RMs show better fit statistics and predictive validity than the global model developed for the countrywide scale. Differences in climate and soil conditions which distinguish natural forest regions affect height growth patterns of Scots pine. Therefore, extending this research to models which directly describe the interactions of height growth with site variables, such as climate, soil properties, and topography, can provide additional valuable forest management information.

Declarations

Ethics approval and consent to participate: Not applicable

Consent for publication: Not applicable

Availability of data and material: The datasets used and/or analysed during the current study are available

from the corresponding author on reasonable request.

Competing interests: The authors declare that they have no competing interests

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Authors' contributions:

Conceived and designed the study: JS. Collected data: JS. Analysed the data: JS, LTC, DC. Wrote the paper: JS, LTC, SZ, DC, PH. All authors read and approved the final manuscript.

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Figures

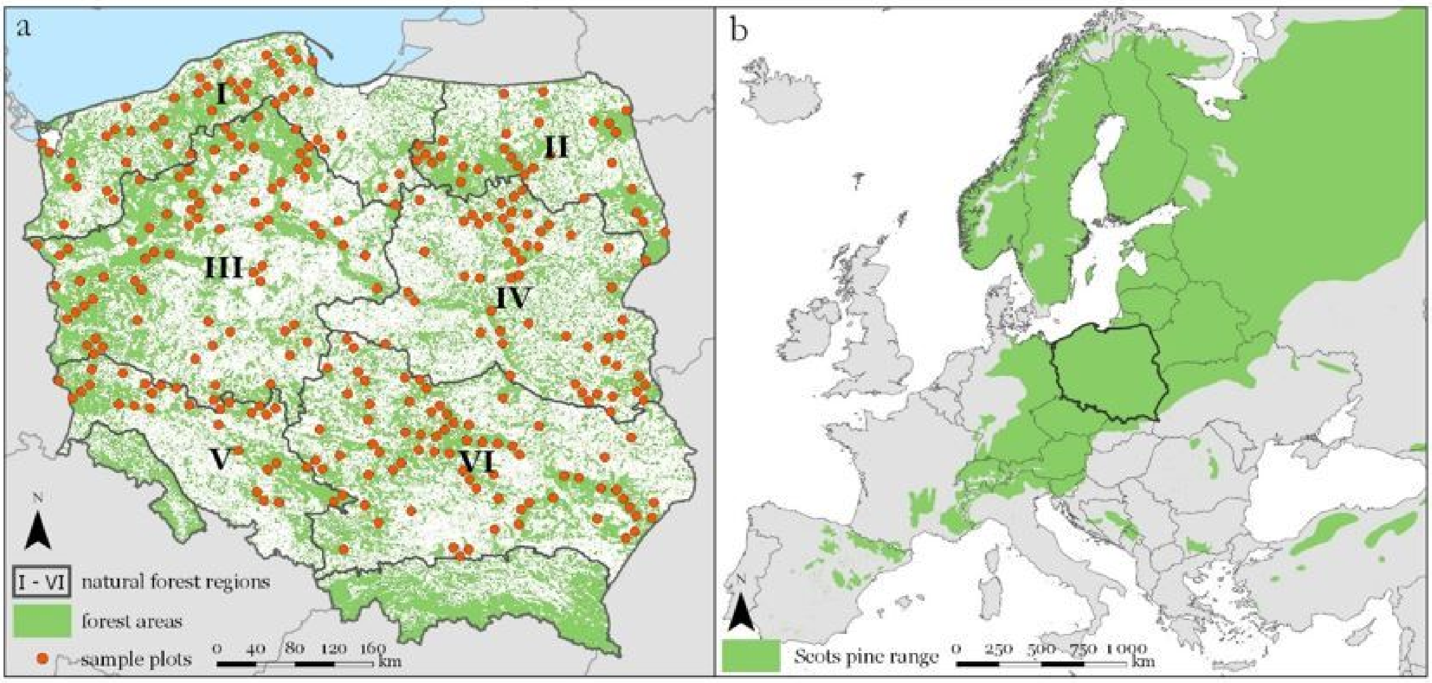

Figure 1

Natural forest regions in Poland with locations from which stem analysis data were collected (a); range of Scots pine distribution in Europe (b). Note: The designations employed and the presentation of the material on this map do not imply the expression of any opinion whatsoever on the part of Research Square concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delimitation of its frontiers or boundaries. This map has been provided by the authors.

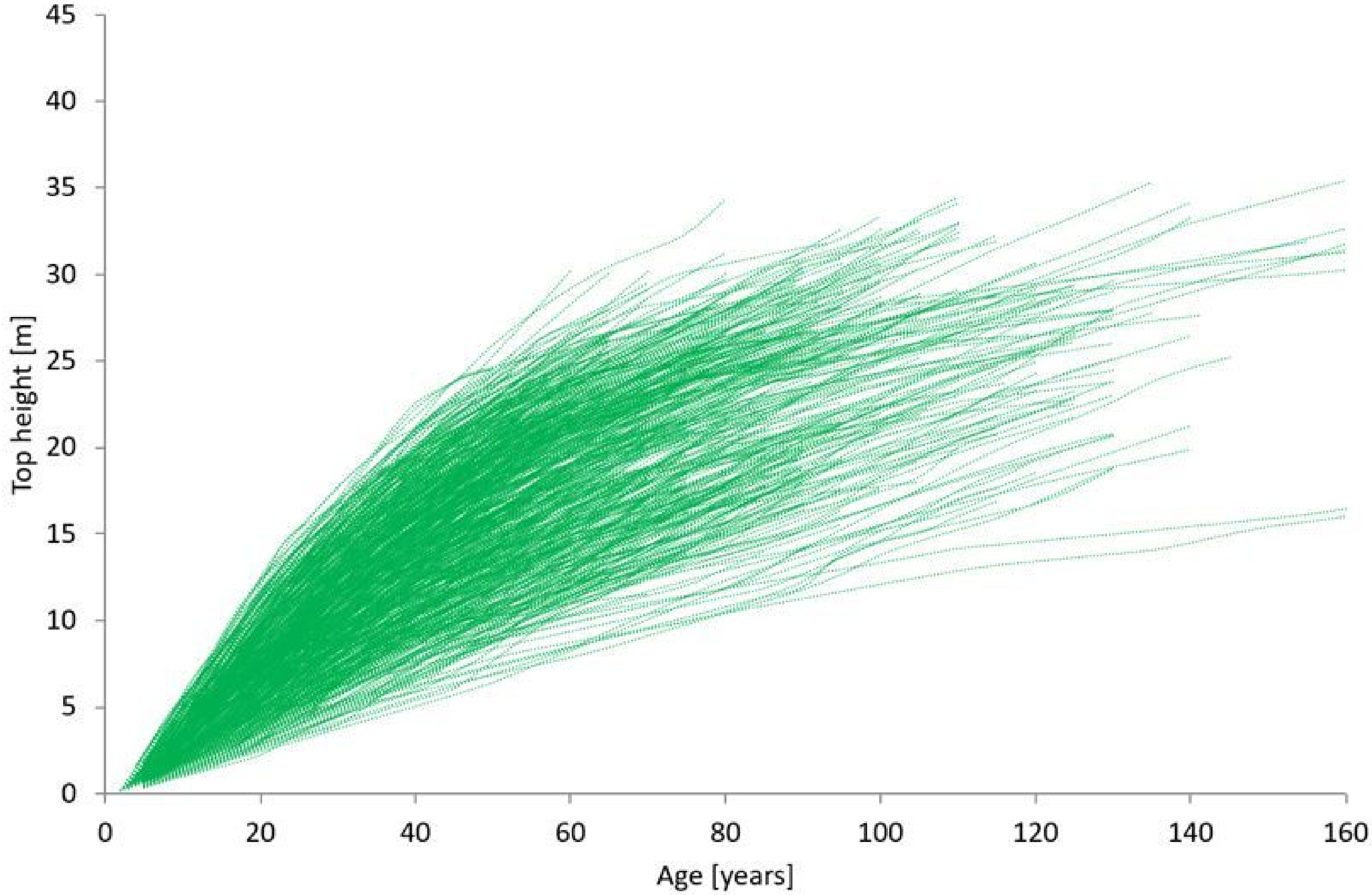

Figure 2

Growth trajectories obtained by stem analysis of 855 Scots pine trees used for the development of the global and regional height growth models

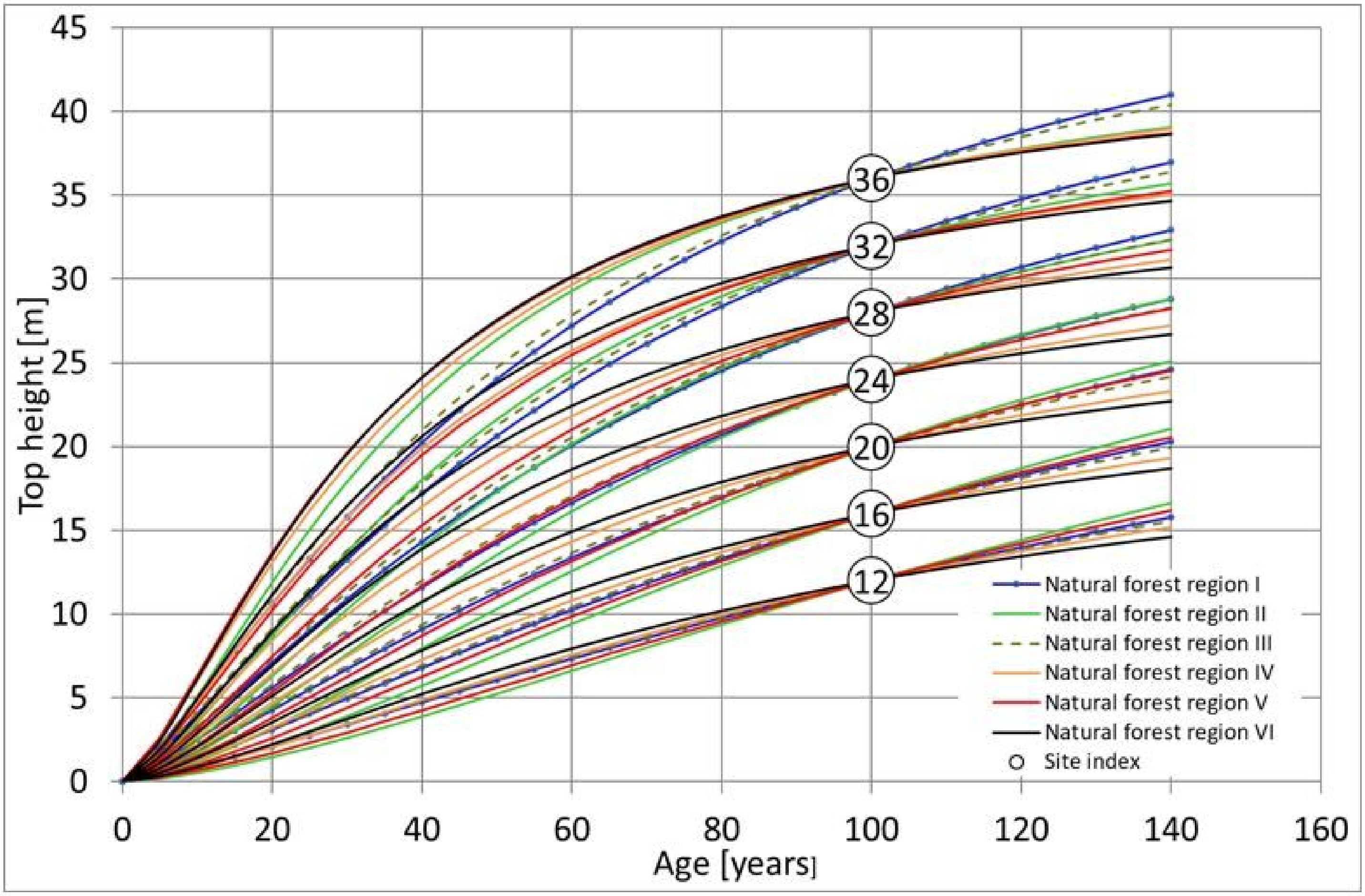

Figure 3

Top height estimated from site index models for Scots pines in six natural forest regions (base age 100 y).

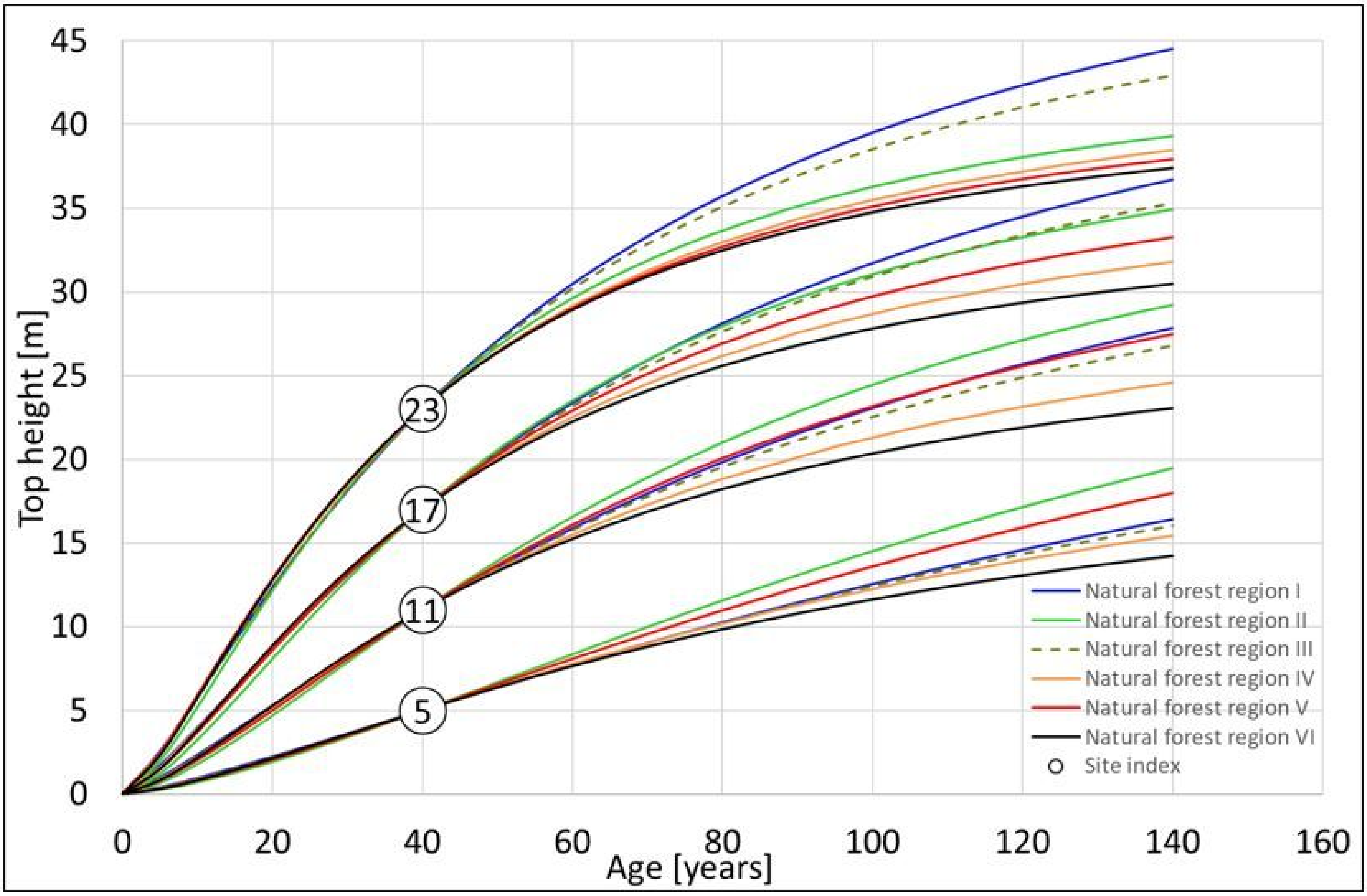

Figure 4

Top height estimated from site index models for Scots pines in six natural forest regions (base age 40 y).

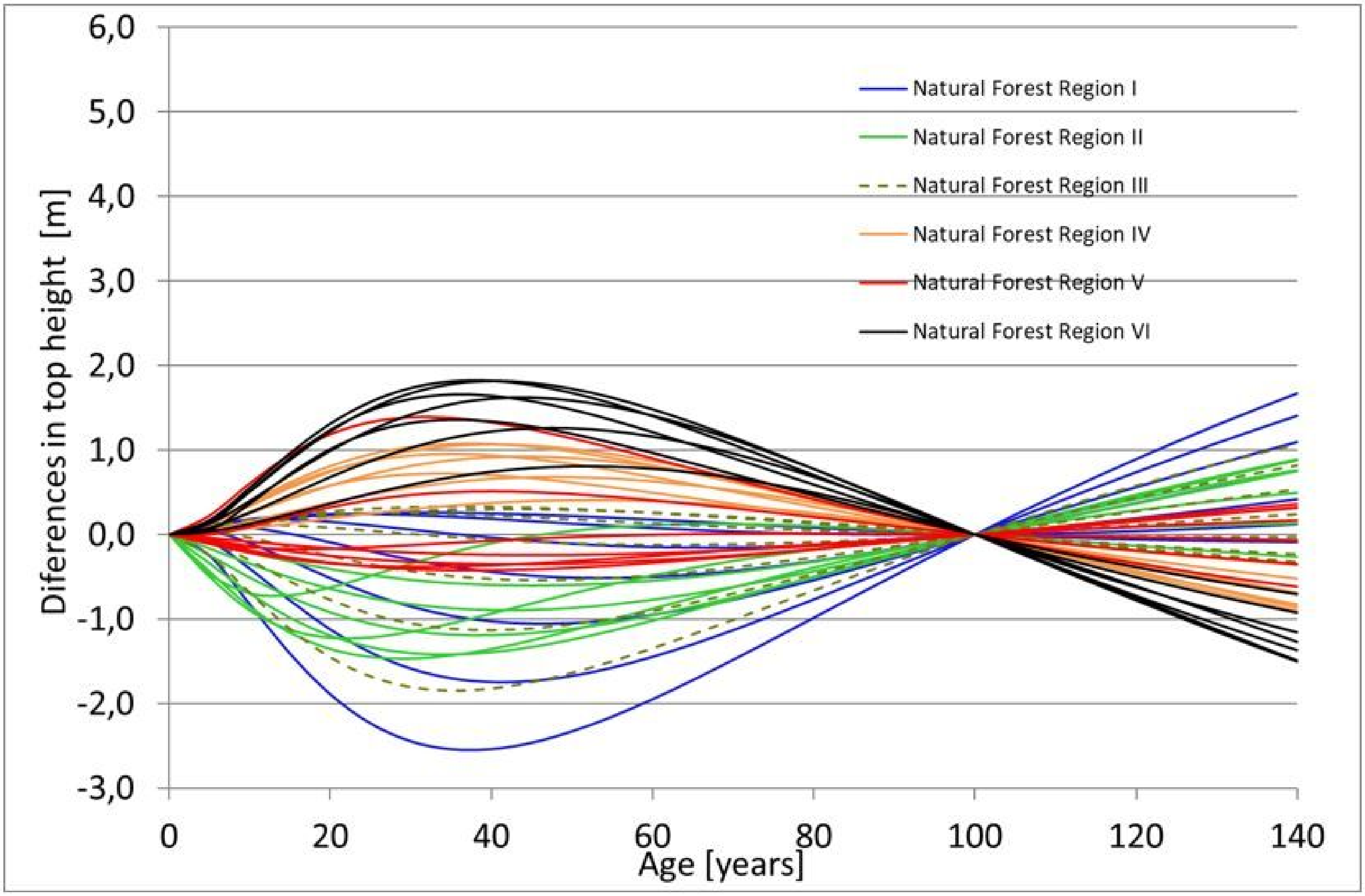

Figure 5

Differences between the model trajectories for the global height growth model developed for Scots pines in Poland and for natural forest regions (base age 100 y). Lines with the same colour depict values for the following SI: 12, 16, 20, 24, 28, 32, and 36.

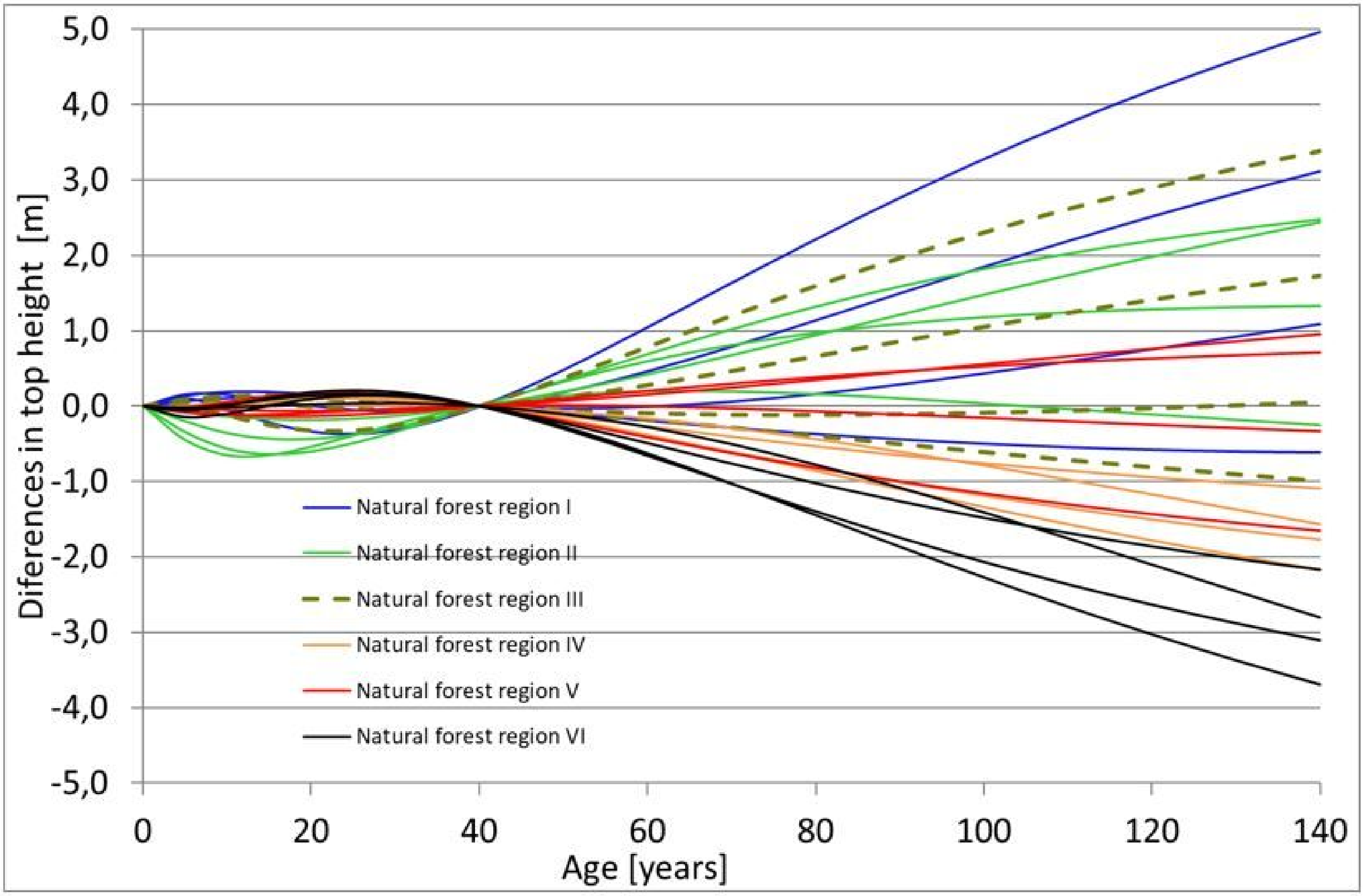

Figure 6

Differences between the model trajectories for the global height growth model developed for Poland and site index models for Scots pines in natural forest regions (base age 40 y). Lines with the same colour depict values for the following SI: 12, 16, 20, 24, 28, 32, and 36.

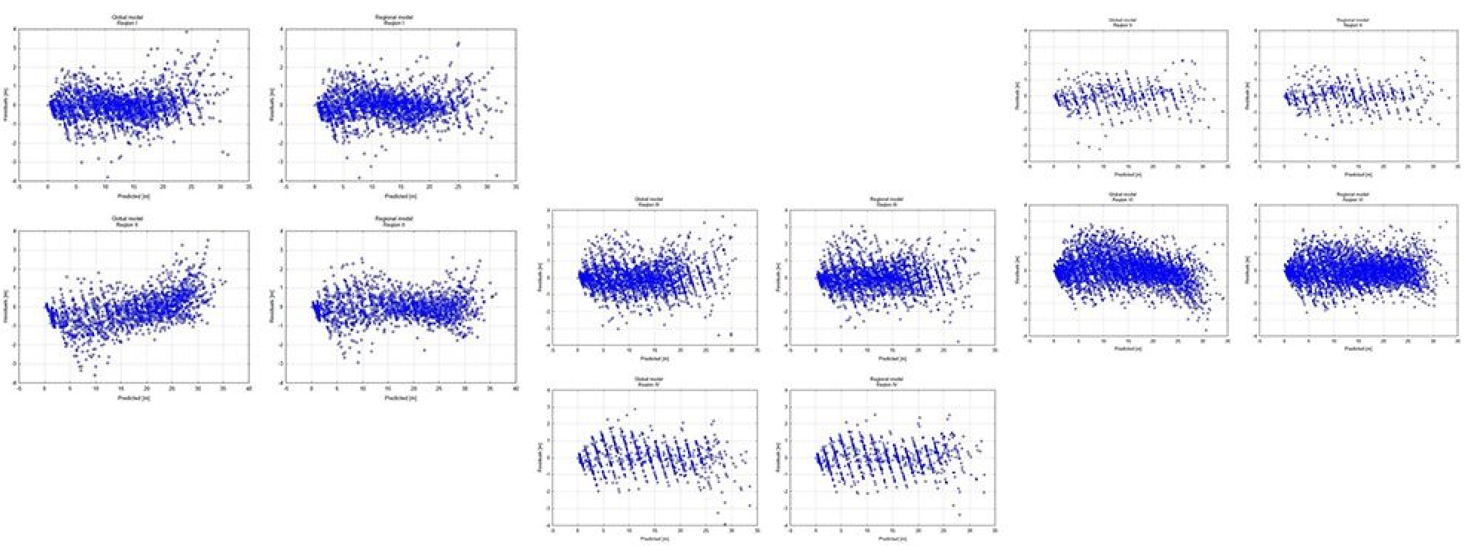

Figure 7

Residual versus fitted values for the global (left) and regional (right) site index models for Scots pines in Poland.