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Multivariate mixed-effects models for stand characteristics of hybrid aspen plantations in southern Finland and southern Sweden

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ABSTRACT

Hybrid aspen, a hybrid between the European aspen and North American trembling aspen (*Populus tremula* L. × *P. tremuloides* Michx.), is a promising species because of its fast-growth and its suitability for multi-purpose use. However, models for predicting the age-dependent development of stand characteristics are still missing. The main objectives of this study were therefore to develop the models for predicting stand characteristics of hybrid aspen plantations and to validate the model applicability. The target response variables were stand basal area (BA), basal area-weighted mean diameter (DG) and basal area-weighted mean height (HG). Data were obtained from clonal hybrid aspen trials in southern Finland and southern Sweden. Multivariate mixed-effects modelling was used to estimate the parameters of seemingly unrelated regression for BA, DG, and HG. Model fit provided the following predictor variables: stand age (AGE), the number of trees per hectare (TPH), site index (SI), growing degree-days (GDD5), soil and site type, and thinning treatment. The chosen predictors differed slightly by response variable, but all parameters were highly significant ($P < 0.0001$), and model goodness-of-fit statistics presented high accuracy: RMSE of 2.59 m^2 ha^{-1} for BA, 1.21 cm for DG, 1.05 m for HG in arithmetic scale. The applied simulations illustrated clear differences in the predicted development of stand characteristics when input variables SI, TPH or GDD5 changed. The developed models were assessed to be easily applicable and useful for predicting the stand and tree characteristics of clonal hybrid aspen plantations, especially for the stands with AGE ≤ 30 years and TPH ≤ 2000 trees ha^{-1}.

1. Introduction

Hybrid aspen (*Populus tremula* L. × *P. tremuloides* Michx.) is used as a raw material for pulpwood, plywood, or bioenergy (Liesebach et al., 1999; Beuker, 2000; Hynynen et al., 2004; Rytter and Stener, 2005; Hytönen et al., 2018). Through breeding, outstanding growth characteristics in both tree diameter and height have been obtained (Hynynen et al., 2004; Johnsson, 1953; Lee et al., 2021; Rytter and Stener, 2005; Yu et al., 2001). Hybrid aspen is one of the promising broadleaved species to increase the species diversity in the conifer dominated forests of Northern Europe (Weih et al., 2003). Moreover, hybrid aspen may be useful in sequestrating carbon to mitigate climate change (Hedenus and Azar, 2009; Rytter and Högbom, 2010).

However, there are still insufficient information and methods for assessing the growth potential and optimal management of hybrid aspen stands. There are several types of growth and yield models available based on empirical experiments: whole-stand, size-class, and individual tree models (Lee et al., 2021b; Qin and Cao, 2006; Somers and Nepal, 1994). For modelling the development of stand characteristics of even-aged, single-species plantations, stand-level models have been found to provide high accuracy with easy-to-use predictors (Pienaar and Rheney, 1995; Scolforo et al., 2019). Hence, many studies focused on developing stand-level models for commercially important tree species, commonly managed as even-aged single species stands (Knoebel et al., 1986; Eid, 2001; Næsset, 2002; Siipilehto, 2006, 2011; Scolforo et al., 2019). In the case of hybrid aspen, there is still a lack of applicable growth and yield models although several studies have focused on growth characteristics (Stener and Karlsson, 2004).

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So far, models based on dominant height and site index were developed for hybrid aspen in Sweden and Finland (Johansson, 2013a; Lee et al., 2021a). The basal area-weighted mean diameter (DG), and the basal area-weighted mean height (HG), also known as Lorey's height, have been modelled for major commercial species in northern Europe (Næsset, 2002). Siipilehto et al. (2016) used them to predict stand structure, applying laser-based data. These stand characteristics were applied for estimating diameter distribution and individual tree height for hybrid aspen plantations in Finland (Lee et al., 2021b). However, models predicting the development of these stand characteristics are still missing.

To develop such models, a different approach from the ordinary least squares (OLS) estimator is required. This is because the OLS estimator is optimal and unbiased for uncorrelated variables and is applied to separate model fitting for each response variable, respectively. In the case where the desired response variables correlate with each other in a stand, like stand basal area (BA), DG, and HG, seemingly unrelated regression (SUR) approach is more appropriate for model fitting (Zellner, 1962; Borders, 1989; LeMay, 1990; Siipilehto, 2011; Mehtätalo and Lappi, 2020). For example, Siipilehto (2006) showed that the mathematical relationship between BA, the number of trees per hectare (TPH) and quadratic mean dbh (DQ) can be written as $BA = q \times TPH \times DQ^2$, in which $q = \pi/200^2$. Thus, the linearized form is given via a log-transformation as $\ln(BA) = \ln(q) + \ln(TPH) + 2 \times \ln(DQ)$. Naturally, DQ is highly correlated with DG used in this study. To deal with hierarchical data (e.g., repeated measurements), a mixed-effect model should be used. When combining models for several correlated variables with hierarchical data, the most appropriate method is the SUR approach with mixed-effects as a modelling technique for final outputs (Goldstein, 1995; Siipilehto et al., 2007), also called multivariate mixed-effects modelling (Mehtätalo and Lappi, 2020).

The objectives of this study were 1) to develop the multivariate mixed-effect models for BA, DG, and HG of hybrid aspen, 2) to simulate the development of hybrid aspen stands by combining models for stand characteristics with prior models of diameter distribution and tree height curves, and 3) to test the validity and reliability of model combination by examining the consistency among model performance and considering if the simulation results are logical and realistic for practical forestry.

2. Materials and methods

2.1. Data source

2.1.1. Finnish experiments

The first data source (Luke 1) consisted of measurement data from a hybrid aspen spacing trial series in southern Finland (Table 1, Fig. 1, Lee et al., 2021a). Depending on the experimental sites, some mechanical site preparation was performed before the plantations were established. Repeated measurements were conducted 3–8 times at an interval of 1–3 years depending on experiment and/or stand age. Three observations were excluded from the modelling due to the storm damage.

The second data source (Luke 2) was data from a breeding trial series with hybrid aspen clones (Table 1, Fig. 1). Only one measurement at the age of 12 years was applicable because it included both dbh and height. On some of the agricultural sites chemical weed control was carried out one year before planting. In general, soil preparation was carried out before planting, but with various methods at different sites. At all sites the trees were protected by 60 to 90 cm Tubex tubes. Most of the sites were fenced against moose and deer except for those in Keuruu and Punkaharju, that were planted on sites for which the risk for damage by moose was low. There is no information about weed control after the establishment of the trials. The trials have a randomised complete block design, but plot size, number of trees per plot and number of blocks vary between trials.

Table 1
Summary statistics of hybrid aspen modelling dataset from southern Finland and southern Sweden.

Variable	Luke 1, Finland	Luke 2, Finland	Skogforsk, Sweden
Dataset structure			
No. of stands	4	16	14
No. of plots	48	69	21
No. of measurements by stand	3–8	1	4–10
No. of observations	291	69	189
Stand characteristics			
Stand age (AGE, years)	12.2 ± 4.6 (5–20)	12	13.7 ± 4.9 (5–29)
Stand density (TPH, trees ha^{-1})	931.6 ± 423.8 (300–1600)	947.5 ± 200.1 (644–1600)	926.7 ± 382.0 (366–2417)
Basal area (BA, m^2 ha^{-1})	10.8 ± 9.0 (0.1–35.7)	6.4 ± 2.6 (2.1–12.8)	18.2 ± 8.5 (1.3–41.1)
Diameter, basal area-weighted mean (DG, cm)	12.0 ± 5.7 (2.1–26.8)	10.2 ± 1.3 (6.9–13.2)	17.3 ± 5.9 (4.1–33.4)
Height, basal area-weighted mean (HG, m)	13.6 ± 6.6 (3.6–27.6)	10.8 ± 2.0 (6.6–15.8)	17.8 ± 5.8 (5.1–33.0)
Dominant height (HDOM, m)	15.1 ± 6.8 (4.0–29.8)	12.4 ± 2.2 (8.1–18.3)	18.7 ± 6.8 (4.7–35.5)
Cumulative mortality at last measurement (trees ha^{-1})	22.3 ± 63.7 (0–410)	–	42.9 ± 60.4 (0–229)
Management			
Initial planting density (trees ha^{-1})	400–1600	1000–1667	1100–2500
Year of establishment	1997–1999	1998–2002	1986–1997
Clone information	E10476, E10467, E10490 [a]	65 clones in total	4–107 clones by site [b]
Plot size (m^2)	1000	1250–9900	400–19200
No. of thinning	0	0	0–3
Thinning intensity	–	–	Weak, Moderate, Strong [b]
Site characteristics			
Location	Southern Finland	Southern Finland	Southern Sweden
Latitude	N 60°10′–60°39′	N 60°12′–62°13′	N 55°36′–59°08′
Longitude	E 23°55′–26°07′	E 23°29′–29°20′	E 13°00′–15°57′
Growing degree-days above 5 °C (GDD5, °C·days)	1411.5 ± 6.6 (1397.5–1418.8)	1353.1 ± 53.9 (1256.5–1437.1)	1593.2 ± 68.9 (1460.2–1651.8)
Site type with no. of stands	Former agricultural land (Field) 2, Forest site (OMT[c]) 2	Former agricultural land (Field) 12, Forest site (OMT[c]) 1, Forest site (MT[c]) 1	Former agricultural land (Field) 14
Soil information with no. of stands	Clay 1, Clayey mold 1, Moraine 2	Clay 3, Clayey mold 3, Coarse silt 7, Moraine 3	Clayey moraine 9, Coarse silt 2, Fine sandy moraine 1, Heavy clayey moraine 1, Moraine 1
Site index[d] (SI, m)	25.4 ± 2.8 (16.6–29.8)	20.4 ± 3.6 (13.4–30.3)	26.8 ± 2.3 (22.5–31.7)

a: Detailed clone information was provided in Lee et al., 2021.
b: The clone information and thinning treatment were described in detail by Rytter and Stener (2014).
c: OMT is Oxalis-Myrtillus (a herb-rich heath forest) site type and MT is Myrtillus (a mesic heath forest) site type (Cajander, 1949).
d: Site index was computed based on Lee et al., 2021 with a base age of 20 years.

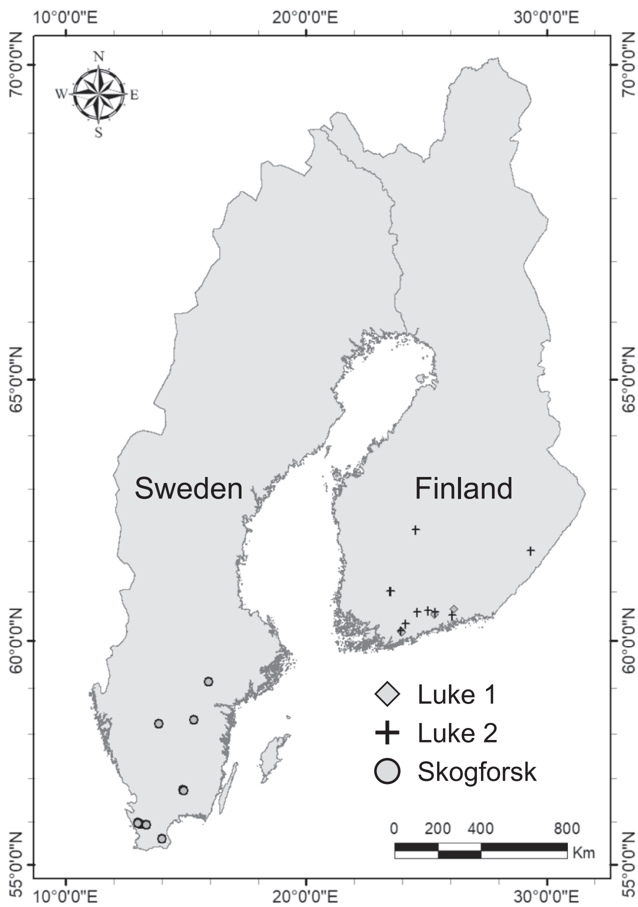

Fig. 1. Location map of hybrid aspen trials from Luke in Finland and from Skogforsk in Sweden.

2.1.2. Swedish experiments

The third data source was from Skogforsk in Sweden (Table 1, Fig. 1, Rytter and Stener, 2005, 2014; Fahlvik et al., 2021) where the trials were originally established for genetic testing of hybrid aspen clones. The experiments were treated once with herbicides before planting and fenced to prevent browsing. Neither fertilization nor mechanical treatment such as ploughing was conducted as a site preparation. In contrast to the Finnish trials, the Swedish trial series was thinned, where tree selection for thinning was based on tree health, quality, growth, and spacing. At each site, the experiment was separated into three plots with different thinning intensity. At each site, thinning treatments (weak, standard or strong) were established in a randomised block design (Rytter and Stener, 2014). At the latest measurement occasion included in the present study, the experimental plots had been thinned one to three times depending on the treatment applied and the age of the experiment.

2.1.3. Data integration and additional variable retrieval

The Finnish and Swedish data were combined to develop a common stand-level model of hybrid aspen for clonal plantations in both countries. The stand age (AGE) and TPH were available based on the inventoried data from each measurement instance. AGE was calculated as the number of growing seasons since the planting of the experiments without considering seedling age (usually one year). The dependent variables of BA, DG, and HG were calculated from plot-level data of each measurement. Site index (SI) was estimated for each trial based on dominant height (the average height of one hundred thickest trees per hectare) through the model developed by Lee et al., 2021a. The dominant heights measured near the base age of 20 years were used among all the observations since measurements were not always made exactly at age 20, and the density-free site index model was applied in the clone trials which was not used for modelling in Lee et al., 2021a. The used site type categories were former agricultural land or forest land (OMT or MT) according to the classification by Cajander (1949) (Table 1). Five categories for soil type were applied: moraine, fine sand, clayey moraine, clay, and mold.

Thinning was characterized using several variables. Time after last thinning in year (Talty) was calculated and transformed into different dummy variables; Talty5−, code 1 if thinned within five years or code 0 if not; Talty5+, code 1 if thinned five or more years ago or code 0 if not. Additional thinning variables characterized if the plot was thinned (*thinned*) with an interaction term of Talty by calculating *Thinned*/(Talty + 10) for continuous and nonlinear thinning effect. An evident distinction in latitude was detected between the countries; the Swedish experiments were located more southly than the Finnish ones (Fig. 1). Latitude and temperatures sum were considered to explain the differences in location amongst data sources. To obtain the annual temperature sum (growing degree-days, GDD5) for every site, open-source geoweb service ClimateDT was used with 5 °C threshold based on average monthly temperature (Institute of Biosciences and Bioresources, 2022). The annual GDD5 was averaged from 1991 to 2020 to obtain a more conservative GDD5 throughout the years the trials were growing and the final GDD5 was used as a predictor.

2.2. Modelling approach and statistical analysis

A multiplicative model structure was assumed for response variable Y, linearized using logarithmic transformation (e.g., Eid, 2001; Siipilehto, 2011). The models in general form (Eq. (1)) and linearized form (Eq. (2)) were as follows:

$$Y = b_0 X_1^{b_1} X_2^{b_2} \cdots X_n^{b_n} e \quad (1)$$

$$\ln Y = \ln b_0 + b_1 \ln X_1 + b_2 \ln X_2 + \cdots + b_n \ln X_n + \ln e \quad (2)$$

Where Y is the response variable, $b_0 - b_n$ are the model parameters, $X_1 - X_n$ are the predictor variables, ln is the natural logarithm, and e is a base of natural logarithm, or Euler's number, approximately equal to 2.71828.

To develop the model for the several stand characteristics (BA, DG, and HG) simultaneously, SUR approach was applied with mixed-effect as multivariate mixed-effects models (Mehtätalo and Lappi, 2020). In the process of modeling, the separate mixed-effects models were firstly fitted to find the best performing model structures for each dependent variable. Thereafter, several candidates of the separate models were compared with multivariate mixed-effects models to check model improvement and significance. Model fitting was executed via the *lme* function of the *nlme* package in R statistical software (R Core Team, 2019). Considering the hierarchical design at each experimental site and the longitudinal correlation among repeated measurements, both experiment and plot could be considered as random effects in a nested structure (i.e., random = ~1|experiment/plot in R syntax). However, instead of a nested structure, if we exclude experiment and reidentified each plot independently as a random effect (namely, plotID), more significant dummy variables were found regarding site and soil characteristics (i.e., random = ~1| plotID in R syntax). In addition, the latter option would provide easier calibration of the models, i.e., best linear unbiased prediction (BLUP) estimation. The candidate predictors examined in this study were AGE, SI, TPH, GDD5, latitude, thinning effect, site type, and soil type. The cumulative dead trees at plot-level was 22.3–43.9 trees ha^{-1} (ca. 2–4 per plot) on average by data source during the measurements (Table 1), and thus, mortality was not handled due to the lack of observations regarding self-thinned stem numbers (also see Fig. A1 of Lee et al., 2021a). The clone effect was not considered in this study due to randomly, diverse mixtures depending on plot design, so the model was developed for general purpose in any clonal hybrid aspen plantations.

A small range of constants such as 0.1–0.5 was checked in dependent variables to make the models unbiased and predict logically. It was because in the modeling data there were observations very close to zero (especially in BA) causing bias without an additional constant term even though all observations were non-zero values. With preliminary results, a constant 0.1 was added to the BA model as a response variable. Linearization of the model typically homogenize the original heteroscedastic residual error (Eid, 2001; Siipilehto, 2011). Non-transformed models were not fitted in our study. Because of the multiplicative relationship between the predictor variables, only the log-transformed stand characteristics provide linearized residual errors between the modelled characteristics (response variables) such as BA, TPH, DG (e.g., Siipilehto, 2006). However, here this was not the case but instead, highly decreasing variance was found with respect to increasing stand age. To transform back to arithmetic scale from logarithmic scale, the bias correction term was added to the predicted value following Mehtätalo and Lappi (2020). To do so, correction term includes variance of random plot (v_{plotID}) and residual variance (v_{ε}) as ($v_{plotID} + v_{\varepsilon}$)/2. In addition, the residual variance was formulated to be the power function of stand age: $v_{\varepsilon} = std(\varepsilon)^2 \times AGE^{2P}$, where v_{ε} is the residual variance, std(ε) is the standard deviation of the residuals ε, and P is the estimated power for the variance function (Appendices A, B and C). The variance function in relation to AGE was based on separately fitted models giving the estimates for power P to each model. Thereafter, the originally estimated weights from separate fitting were associated to variable AGE^P to be used as a fixed weight in the multivariate model (Mehtätalo and Lappi, 2020).

During the model development fit statistics such AIC, BIC, −2log-likelihood, and residual figures were checked to find the best model formulation. To test the models, the residuals of logarithmic and arithmetic scale were displayed in scatterplots based on only fixed-effect parameters. Overall metrics of residuals were provided with root mean square error (RMSE), mean absolute error (MAE), and mean absolute percentage error (MAPE). All the residuals, not only over the predicted values, but also over independent variables, were carefully examined through the *whiskers* function of the *lmfor* package (Mehtätalo and Kansanen, 2022) for adding vertical lines onto residual plots to show 95% confidence intervals for individual observations in the classes of the variable on the x-axis, which is useful to analyze the homogeneity of residuals (Appendix A).

2.3. Simulation and validity

After developing the models and checking the performance, extended model applications through simulation were tested to assess the practicability in cooperation with other prior developed models of hybrid aspen. The prior models applied in this process were diameter distribution and tree height prediction developed by Lee et al., 2021b. To recover diameter distribution via the 2-parameter Weibull function, the predicted BA and DG with input TPH were used. In individual tree height estimation, the BA, DG, and HG, predicted based on input AGE, TPH, and tree dbh, were used with the previously developed Näslund's model (Lee et al., 2021b). In our simulation, we applied Model 1 of Näslund's function in Lee et al., 2021b because it was considered as more conservative and stable than Model 2 against a wide range of stand conditions (Appendix B).

When the tree height was projected using the predicted height curve, sample trees were also displayed to show random variation according to the procedure as follows: $h_i = h_{pred} + rand_{var}$, where h_i is the sample tree height with random variation, h_{pred} is the expected sample tree height according to the predicted parameters by Lee et al., 2021b, $rand_{var}$ is the inversed value of the normal cumulative distribution for randomly generated probability between 0 and 1 with mean of 0 and standard deviation of $s_e \times h_{pred}^{var_{power}}$, s_e is the standard deviation of residual errors, 0.2489, and var_{power} is the estimated power of the variance function, 0.4459 as provided by Lee et al., 2021b. More details about the model equations and the parameter estimates of this function were provided in Lee et al., 2021b and in Appendix B. Since the input predictors of those prior models include BA, DG, and HG, appropriate model output can support the model availability. To check the model developed in this study, stands with a wide range of SI and TPH were simulated from 5 to 30 years of stand age. Some descriptive examples of the overall performance of simulation were presented and discussed.

3. Results

3.1. Parameter estimates and fit statistics

The investigated predictors with several transformations were checked by fitting the models and examining the significance of the parameter estimates. Not all parameters were significant (P greater than 0.01) in the separate model approach, such as the dummy variables of *Forest* for the DG model and *Clay* for the HG model. However, in the multivariate model all parameter estimates were highly significant ($P <$ 0.0001) (Table 2). The parameter signs were as expected from the variable characteristics, i.e., the parameters in all models were positive with SI, a reciprocal form of AGE, and GDD5. The sign of TPH was different depending on the response variable: positive in the BA model vs negative in the DG model (Table 2). The dummy variables had opposite signs for the DG and the HG models. For example, Talty5+ and *Forest* were positive in DG model, but *Thinned*, *Forest*, and *Clay* were negative in HG model.

As a random effect, each plot in each trial was independently applied as one term of plotID. The estimated correlation between the random effect of each model in Table 2 showed highly correlated errors (r = 0.58–0.94) which enables calibration using BLUP, in case any of the modelled variable is known (see Siipilehto, 2011). When the residual plots were compared between logarithmic scale and back transformed arithmetic scale, no significant bias was detected over the predicted value, but a slight overestimation among the highest predicted basal area could be seen (Fig. 2). The residuals were all unbiased over stand age in both logarithmic and arithmetic scale (Fig. 3). The residuals over independent variables proved the model prediction being unbiased with 95% confidence intervals by the classes of the independent variables onto residual plots (Appendix A). The prediction precision metrics RMSE and MAE showed reasonable accuracy as shown in Table 3.

3.2. Model demonstration at stand level

To demonstrate the model behavior, simulations were executed over AGE in line with the change of SI (Fig. 4). The simulation was examined within the range of fitting data: $5 \leq AGE \leq 30$ and $20 \leq SI \leq 30$ by setting up other variables with median or mean values of observations. The simulated results were predicted stably within the range of modelling data for all the model types. Specifically, the range of predicted values at age 20, which is the base age of SI, was 16.5–31.3 m^2 ha^{-1} for BA, 17.3–23.2 cm for DG, 18.5–27.6 m for HG in SI 20–30 m. The predicted BA and DG lines were lower than some observations, which was mostly from the southern Sweden where GDD5 is equal to or larger than 1600. This simulated output covered the modeling data appropriately considering that GDD5 of 1500 mostly represented the northern experiments in Sweden. The variation in the predicted HG covered almost all the variation in the data, whereas some of the variation in the data was not detected for BA and DG, because much of the variation in these characteristics were related to stand density.

For the BA and DG models, an additional simulation was conducted, changing TPH, GDD5, and thinning operation (Fig. 5). Considering the range of most observations, TPH of 800 and 1600 was selected with the

Table 2
Parameter estimates and fit statistics of seemingly unrelated regression models for stand basal area (BA, $m^2\ ha^{-1}$), basal area-weighted mean diameter (DG, cm), and basal area-weighted mean height (HG, m) in hybrid aspen plantations.

		ln(BA + 0.1)		ln(DG)		ln(HG)	
		Estimate	S.E.	Estimate	S.E.	Estimate	S.E.
Fixed effects	Intercept	−18.6781	1.6972	−3.5554	0.7325	1.1340	0.1133
	ln(SI)	1.5771	0.1123	0.7260	0.0458	0.9841	0.0350
	ln(TPH)	0.6294	0.0217	−0.1651	0.0105		
	1/(AGE + 1)	−31.3463	0.3197	−15.6111	0.1592		
	1/(AGE + 5)					−29.0737	0.2250
	ln(GDD5)	1.9209	0.2516	0.8309	0.1079		
	Talty5+			0.0176	0.0028		
	Clay					−0.0606	0.0134
	Forest			0.0494	0.0066	−0.0485	0.0108
	Thinned					−0.1518	0.0165
	Thinned/(Talty + 10)					2.1114	0.1823
Random effects	std(plotID)	0.1924		0.0719		0.0498	
	corr with DG	0.935					
	corr with HG	0.702		0.583			
Residual	std(ε)	1.3041		0.8361		0.3088	
	corr with DG	0.974					
	corr with HG	0.806		0.764			
AGE^P	P	−1.6760		−1.9165		−1.2455	
Fit statistics	AIC	−4534.151					
	BIC	−4366.543					
	−2logLik	−4596.152					

Note: all fixed-effect parameters were highly significant ($P < 0.0001$). ln is the natural logarithm. SI is the site index (m) at the base age of 20 years. TPH is the number of trees per hectare (trees ha^{-1}). AGE is the stand age (year). GDD5 is the growing degree-days above 5 °C (°C·days) on an annual basis. Talty is the time after last thinning in year. Talty5+ is the dummy variable; code 1 if thinned five or more years ago or code 0 if not. *Clay* is the dummy variable; code 1 if the soil type is the clay or code 0 if not. *Forest* is the dummy variable; code 1 if the site type is a forest or code 0 if it is a former agricultural land. *Thinned* is the dummy variable; code 1 if the plot was thinned or code 0 if not. The P in AGE^P is the estimate in power form as a variance function in the age variable. corr refers to the correlation. std(ε) is the standard deviation of the residual in the model performance. AIC is the Akaike information criterion. BIC is the Bayesian information criterion. −2logLik is the − 2 × log-likelihood value.

three classes of GDD5 representing rounded minimum, mean and maximum value. Other variables were set to median value or default of no effect, i.e., SI = 25 and *Forest* = 0. The results of all models in arithmetic scale were logical from age 5, the minimum age of the modelling data. However, the predicted arithmetic BA before age 4 was negative because of the dependent variable structure with a constant, ln (BA + 0.1). Nevertheless, constant 0.1 improved BA model behavior considerably. The difference of the predicted values by TPH and GDD5 increased with the stand age developed (Fig. 5). This simulation clearly illustrated the large impact of TPH and GDD5 on the BA and DG results.

To demonstrate the effect of Talty5+, the simulated DG lines were illustrated with thinning applied at age 15. By contrast, BA was affected by thinning according to decreased TPH only (Table 2). This simulation indicated a relatively marginal impact of the unmixed, sheer thinning effect itself on DG compared to major changes of TPH and GDD5. Indeed, the sheer thinning effect of Talty5 + dummy variable resulted in about 0.4 cm increase in DG at age of 30, while the effect of decreased density (e.g., the average intensity of 35% from TPH with GDD5 1600) resulted in about 1.8 cm increase in DG, respectively. Thus, all together DG increased 2.3 cm at age of 30 years due to thinning at age of 15 years (Fig. 5). The effect is larger if more intensive thinning is applied and vice versa.

The HG model did not include the continuous predictor variables used in the BA or DG model, such as TPH and GDD5, and thus, a simulation for the HG model was performed to examine the effects of changing the applied dummy variables, such as *Clay*, *Forest*, and thinning, by setting up SI to 25 m (Fig. 6). The simulation described that HG is higher when the soil type is not clay (*Clay* = 0), site type is not forest land (*Forest* = 0). In addition, the soil dummy variable (*Clay*) had a larger impact on the HG than the site type variable (*Forest*) according to the estimated parameters and the comparison among examples. After a thinning was performed, the HG increased only for the next four years in comparison to the unthinned condition, but no longer due to the complementary interaction with *Thinned*/(Talty + 10) (Fig. 6). The simulation illustrated a relatively slight thinning effect in contrast to the DG simulation as shown in Fig. 5.

3.3. Model application in conjunction with tree-level characteristics

The application of the models developed in this study was described at tree level by recovering diameter distributions via the 2-parameter Weibull function that was introduced in Lee et al., 2021b. For this simulation, the present models were used to predict the BA and DG following the prearranged SI, TPH, and AGE. The dummy variables were set to default values (*Forest* = 0, Talty5+=0) to demonstrate general conditions. As a result, the BA and DG were simulated depending on the stand conditions and the predicted values were provided at the age of 10, 20, and 30 years inside the plots of Fig. 7. Subsequently, the predicted BA and DG with the designated TPH were applied for parameter recovery of the Weibull function (Lee et al., 2021b). This simulation disclosed that the SUR models for stand characteristics were integrated feasibly with the diameter distribution model. The probability of large tree dbh was higher with high SI and low TPH (Fig. 7). Trees with dbh greater than 30 cm within 30 years of AGE were depending on the stand condition.

In addition to the applications of stand characteristics and diameter distribution, individual tree height-dbh allometry was, by extension, simulated using Näslund's height curve for hybrid aspen (Lee et al., 2021b). The simulations were also based on general conditions with default values of 0 for dummy variables similar to the diameter distribution of Fig. 7. The points represented a random sample of tree dbh from the Weibull distribution. Regardless of selected TPH, the number of sample trees was 30 to clearly describe the pattern with random variation. The height of sample trees suitably demonstrated the random variation on tree height-dbh allometric curves from Näslund's model by Lee et al., 2021b. The estimated tree height was shown to be higher with high SI and dense TPH (Fig. 8). In an entire series of models with stand- and tree-level predictions, the height of some of the largest trees at age 20 successfully tended to be around 20 m in SI 20 and 25 m in SI 25 in all simulation examples. It indicated that the predicted dominant height

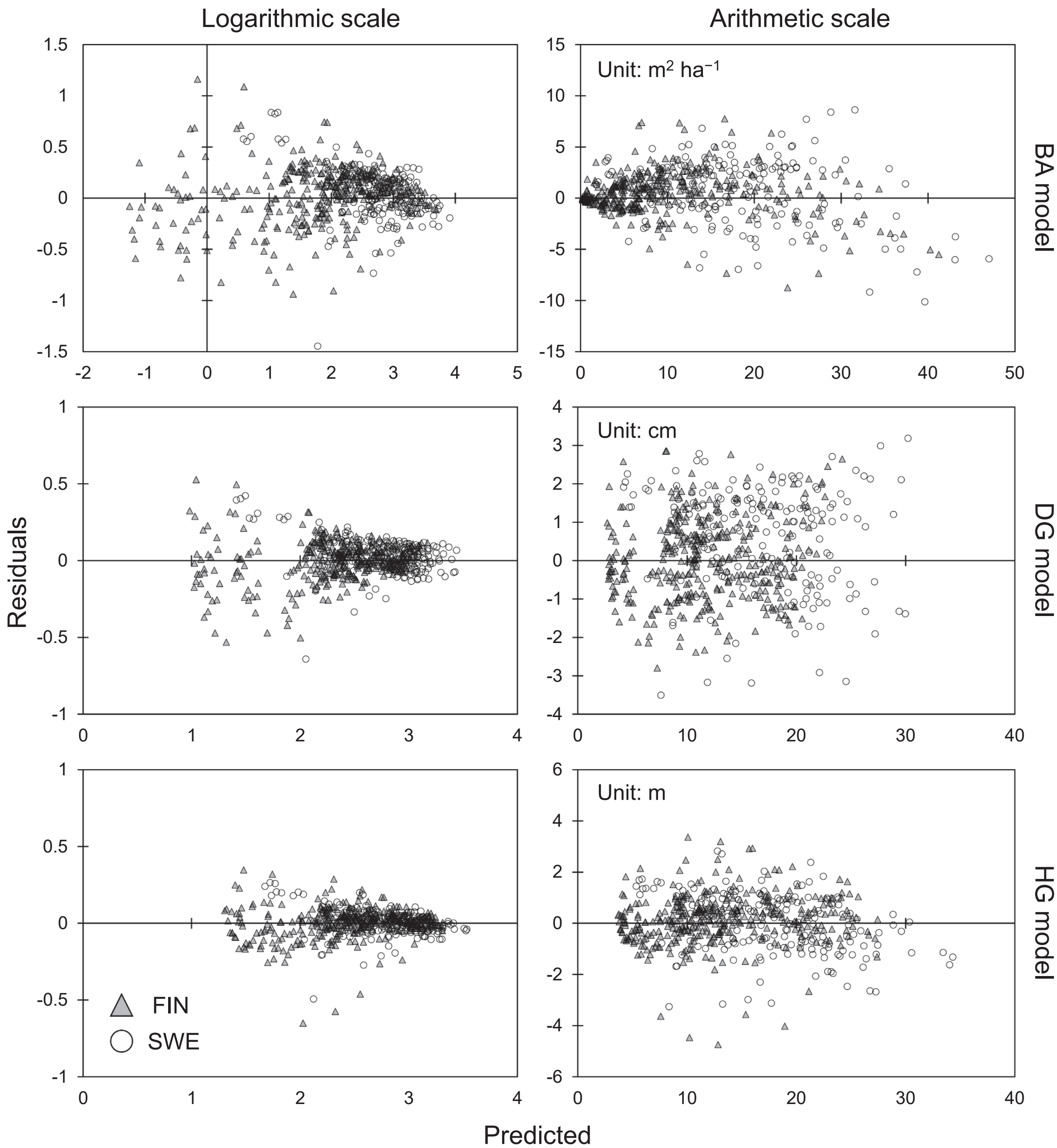

Fig. 2. Residual plots of each model over predicted values in both logarithmic and arithmetic scales. The predicted values were calculated based solely on the fixed-effect parameters provided in Table 2. BA: stand basal area per hectare (m^2 ha^{-1}). DG: basal area-weighted mean diameter (cm). HG: basal area-weighted mean height (m). FIN: Finland. SWE: Sweden.

corresponded to the appointed SI of each simulation because the base age of SI was 20 years. Consequently, the present model for stand characteristics was verified to offer feasible estimates for diameter distribution and tree height estimation.

4. Discussion

4.1. Model structure features and validity

The multivariate mixed-effect model fitted with the SUR approach resulted in more significant parameter estimates than each of the separate mixed-effect model respectively fitted for BA, DG, and HG. In a similar modelling approach, Siipilehto (2006) reported that the RMSE of BA, basal-area median diameter, and basal-area median height was 32%, 15%, and 18%, respectively, for Norway spruce (*Picea abies* (L.) Karst.). Moreover, the variables of *Forest* for DG and *Clay* for HG were highly significant only in the multivariate model but not in the separate models. This result may indicate the advantage of the SUR approach to fit stand characteristics simultaneously. To deal with heteroscedasticity of stand age in the final multivariate model, we applied the fixed variance functions in SUR fitting which was estimated via a power variance function from each model of BA, DG, and HG, and the estimated powers in AGE^P differed clearly between models (Appendix B). It was needed because a power variance function structure in a pure SUR fitting provided only one variance function term common for all models (Mehtätalo and Lappi, 2020). Furthermore, by excluding experiment

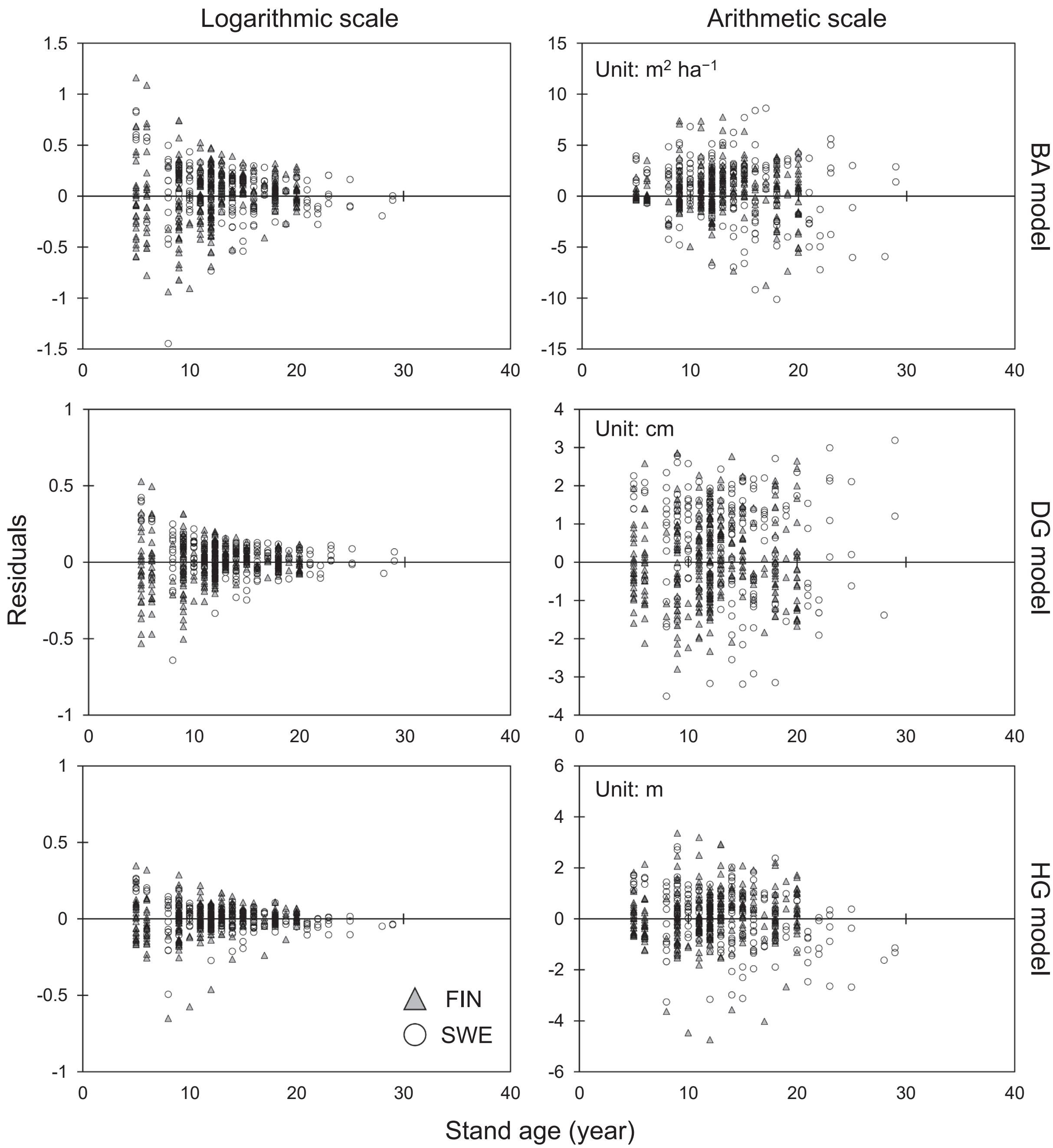

Fig. 3. Residual plots of each model over stand age in both logarithmic and arithmetic scales. The predicted values were calculated based solely on the fixed-effect parameters provided in Table 2. BA: stand basal area per hectare (m^2 ha^{-1}). DG: basal area-weighted mean diameter (cm). HG: basal area-weighted mean height (m). FIN: Finland. SWE: Sweden.

Table 3
Goodness-of-fit metrics of model prediction with root mean square error (RMSE), mean absolute error (MAE), and mean absolute percentage error (MAPE) for stand basal area (BA, m^2 ha^{-1}), basal area-weighted mean diameter (DG, cm), and basal area-weighted mean height (HG, m) in hybrid aspen plantation.

	Logarithmic scale			Arithmetic scale		
Model type	RMSE	MAE	MAPE	RMSE	MAE	MAPE
BA	0.2778	0.2079	0.3380	2.5887	1.9181	0.2209
DG	0.1304	0.0942	0.0476	1.2106	0.9912	0.0921
HG	0.0965	0.0658	0.0298	1.0485	0.7925	0.0670

level from random effect, the plotID random effect made GDD5, *Clay* and *Forest* variables more significant. Consequently, the present model reasonably described the geolocational and edaphic characteristics of sites.

The models were developed to be directly applicable in practice using commonly available stand characteristics. For example, AGE and TPH are commonly known after stand establishment. The site and soil type are described with a prevailing classification system applied in forestry (Cajander, 1949). The thinning treatment would be recorded as executed and GDD5 is publicly offered through the geo-web service ClimateDT (Institute of Biosciences and Bioresources, 2022). SI can be determined based on observations of a present stand development or the former stand information by applying the site index model by Lee et al.,

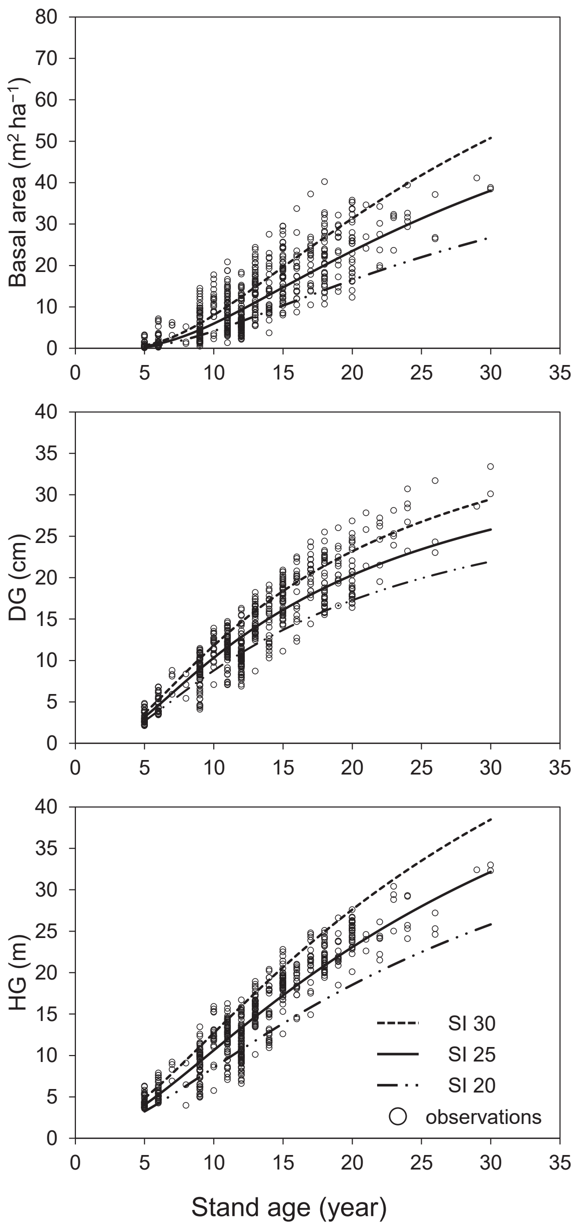

Fig. 4. Simulation examples of each stand characteristic over stand age by the general range of site index (SI). The observations were the samples used for modelling in this study. The simulated lines were predicted based on the fixed-effect parameters provided in Table 2. Other input predictors were set to the median values for the continuous predictors and 0 for the dummy variables, e.g., TPH = 800, GDD5 = 1500, *Clay* = 0, *Forest* = 0, *Thinned* = 0, and *Thinned/*(Talty + 10) = 0. BA: stand basal area per hectare (m^2 ha^{-1}). DG: basal area-weighted mean diameter (cm). HG: basal area-weighted mean height (m).

2021a. Another advantage of the present model is to be easily linked to the previously developed models for hybrid aspen such as diameter distribution and individual height estimation (Lee et al., 2021b). Particularly, the parameters of the Weibull function can be recovered the most reliably using DG among four kinds of diameter characteristics, thus supporting the model developed in the present study.

The simulated age range until age 30 was found to be adequate based on our modelling data and previous studies that suggested the final cutting age between 20 and 25 years, up to 30 years at most (Hynynen et al., 2004; Tullus et al., 2012; Rytter and Stener, 2014; Fahlvik et al., 2021). The present models were additionally checked by comparing with empirical data of previous growth and yield studies on hybrid aspen (e.g., Li et al., 1993; Karacic et al., 2003; Johansson, 2013b; Lutter et al., 2017). The tree height was around 3.2 m, 9 m, and 15 m at age 5, 10, and 15, respectively, by Li et al. (1993) in North America, which is comparable to the results from our HG model with SI 25 (Fig. 4). Also, the average output from our DG and HG models was similar at age 10 to the top height and mean DBH by Karacic et al. (2003) although initial density was much higher than for our study and BA was not comparable. Johansson (2013b) showed for mean dbh, mean height, and BA around age 20 overall similar growth range to our model despite a variation of soil type and TPH.

The DG and HG predicted by our models were consistent with the results in Estonia at the age of 5 and 15 years by Lutter et al. (2017). They reported stand mean characteristics including D400 and H400, i.e., average dbh and height, respectively, of 400 thickest trees for dominant tree characteristics. To check model validity, we predicted the minimum and maximum DG applying the range of the growing degree-days and initial density described in the Estonian data set. When comparing the predicted DG and HG each at age 5 and 15 with the results of Lutter et al. (2017), the minimum DG and HG were greater than their observed arithmetic mean diameter and height and the maximum DG and HG were close to their D400 and H400. Consequently, it demonstrated that our model prediction was ranged stably without any critical bias among their observations. According to Langhammer (1973) the average height of hybrid aspen was 5.3 m, 10.3 m, and 16.9 m at age of 7, 11, and 16 years respectively in southern Norway. The predicted HG was reasonably about 1 m higher, namely 6.3 m, 11.5 m, and 17.6 m, respectively. Consequently, the present models can be applicable also in neighboring countries like southern Norway and Estonia due to similar GDD5 variation.

The present models demonstrated suitable simulation results with varying input predictors when applied to the predictions for diameter distribution using parameter recovery of the Weibull function via DG method according to Lee et al., 2021b. The entire series of models with stand- and tree-level prediction also confirmed that the predicted dominant height was analogous to the predetermined SI (Fig. 8), which was a predictor for each stand characteristics, BA, DG, and HG via the present models. In addition to the applied series of our models, tree volume equations (Tomppo et al., 2011) and timber assortment (Heinonen and Kukkola, 1996) can be applied further if the commercial volume is needed.

4.2. *Interpreting the effects of predictors on response variables*

The predictor variables of the models were different depending on the response variables (Table 2). Still, SI and AGE were commonly applied to all of the three model types because they refer to two important growth factors, site productivity and the stage of stand development, respectively. Considering the significance of the parameter estimates, the developed model and simulations demonstrated the general availability of SI across the country. It implied the SI estimation developed by Lee et al., 2021a was applicable for the southern regions of both countries.

Stand density is known to have stronger effect on the increment of tree diameter than tree height (Staudhammer and LeMay, 2000). In our analysis, TPH was significant in the BA and DG models, but insignificant in the HG model. Lee et al., 2021a, however, reported that the high stand density led to a higher HDOM. Also in Germany, the higher initial density clearly promoted height growth (Liesebach et al., 1999). In our study, stand age and SI were such strong driving variables for HG that the effect of stand density became insignificant (Table 2).

In the modelling dataset, natural mortality was negligible, so mortality models could not be developed based on these data (Lee et al., 2021a). Due to the absence of the mortality model, simulations with the present model did not reflect any changes of TPH, and by extension, the impact on BA and DG. However, it is known that density-dependent mortality will rapidly increase as a stand approaches the stage of self-

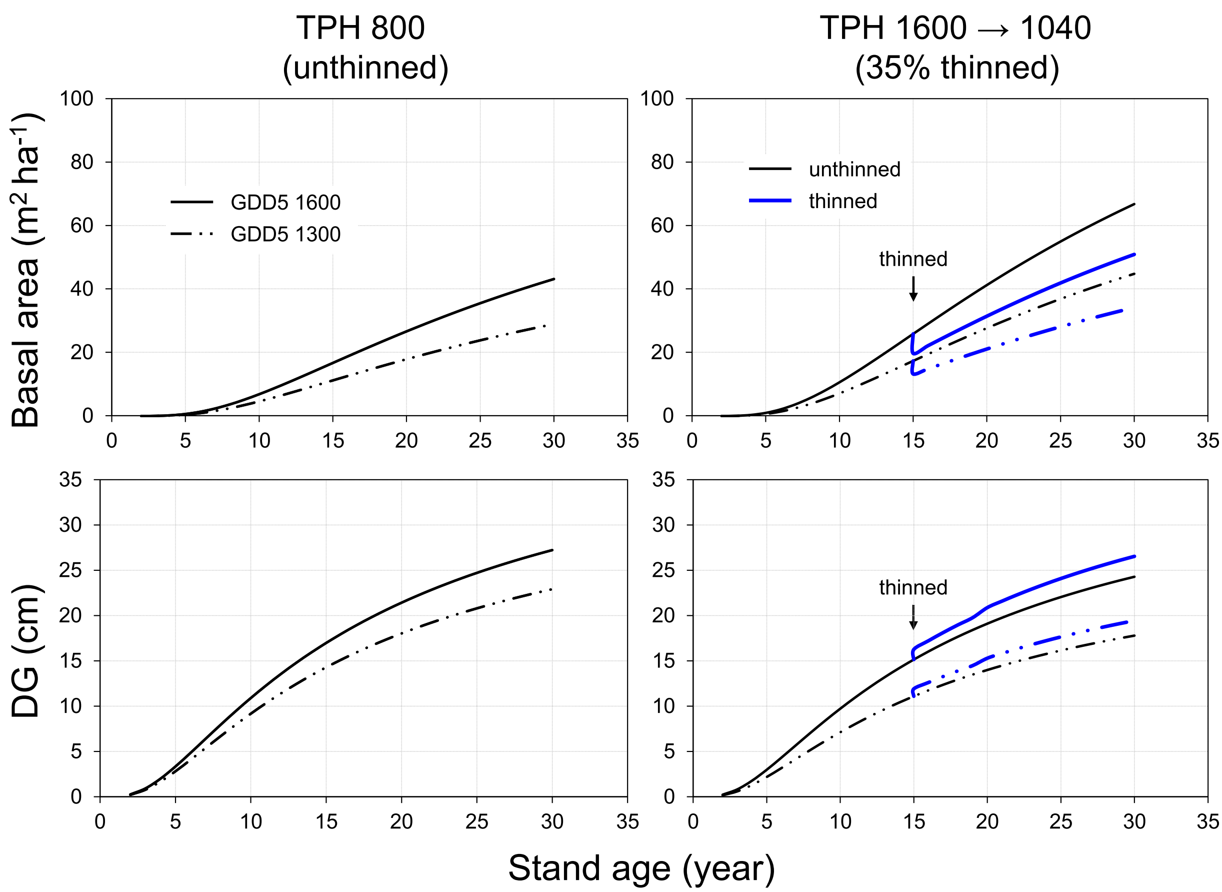

Fig. 5. Simulation examples of BA and DG models over stand age in line with growing degree-days (GDD5, °C·days) and the number of trees per hectare (TPH, trees ha^{-1}). The simulated lines were predicted until age 30 based on the fixed-effect parameters provided in Table 2. The thinning effect was illustrated by changing TPH and Talty5+ (dummy variable; code 1 if thinned five or more years ago or code 0 if not). Site index (SI, m), the other input variable, was set to the median value of 25 in all the simulations.

thinning. Self-thinning models have not been developed for hybrid aspen, and thus, the best available reference model was reviewed from the North American trembling aspen (*P. tremuloides*) (Perala et al., 1999). When the TPH was simulated using the present model with SI 25, TPH 1600 and GDD5 1400–1600, the predicted TPH from AGE 25 depending on the input GDD5 started to exceed the self-thinning line of the reference model by Perala et al. (1999). Therefore, simulation of unthinned stands with stationary TPH leads to overprediction particularly over age 25 with high values of initial TPH, SI, and GDD5.

To explain the geographic region effect, Johansson (2013a) examined the countries and the latitudes using previous studies for height comparison of hybrid aspen. In our study latitude was substituted by the averaged long-term annual GDD5 from 1991 to 2020. GDD5 is also biologically more relevant than latitude for tree growth (Liziniewicz et al., 2023). The GDD5 effect was significant for modelling BA and DG but insignificant in the model for HG (Tables 1 and 2, Fig. 5). In both countries the range of GDD5 was rather small because the experiments were located only in the southern parts. Combining the data sets increased the variation in GDD5 considerably, and thus, provided a more reliable estimate for its effect on stand characteristic. Hence, the combined data enabled more generally applicable models.

The effect of thinnings on hybrid aspen plantations have been sparsely studied in Fennoscandia. According to Rytter and Stener (2014), a significant positive effect for DG was observed 6–16 years after thinning. Fahlvik et al. (2021) mentioned that relatively heavy thinning can promote the tree development in size without jeopardizing total volume production. Therefore, the thinning effect should be applied for the DG and HG models (Table 2). In our study, Talty5+ was applied for the thinning effect in the DG model. The parameter indicated a positive effect of thinning on DG from five years on after the last thinning. However, there was no significant immediate effect right after thinning (Table 2). Nevertheless, a clear increase in DG results from the decrease in TPH after thinning (Fig. 5). The HG model showed an immediate positive effect with the *Thinned*/(Talty + 10) parameter, but in the long term, thinning appeared to have a negative effect on tree height, due to the negative parameter sign of *Thinned* (Table 2, Fig. 6). The result was consistent with previous findings that the positive effect of high stand density on tree height increment was not continued in a later stage, e.g., after age 15 (Lee et al., 2021a).

Hybrid aspen is often planted on former agricultural land, but cultivation on fertile forest site is also feasible (Rytter and Stener, 2005; Tullus et al., 2012; Johansson, 2013b). In our dataset, most stands were on former agricultural land and only 16% on forest sites (Table 1). Because of this difference, caution is needed using the parameter magnitude for *Forest*. However, the parameter sign was considered as logical and acceptable, the negative parameter indicating a superior HG growth on former agricultural land (Table 2), which may be related to higher soil nutrient due to past fertilization (Tullus et al., 2010). On the other hand, the estimated parameter in the DG model was positive, and thus favorable to forest site (Table 2). This might be caused by less competitive tree height growth, as shown with the lower HG, on forest sites, allowing dbh to increase more.

The soil effect was significant only for the HG model with the *Clay* dummy variable in the final fitting and with SUR mixed-effect approach (Table 2, Fig. 6). The negative effect of clay is in line with the findings that soils with heavy texture (clay) are considered less favorable for

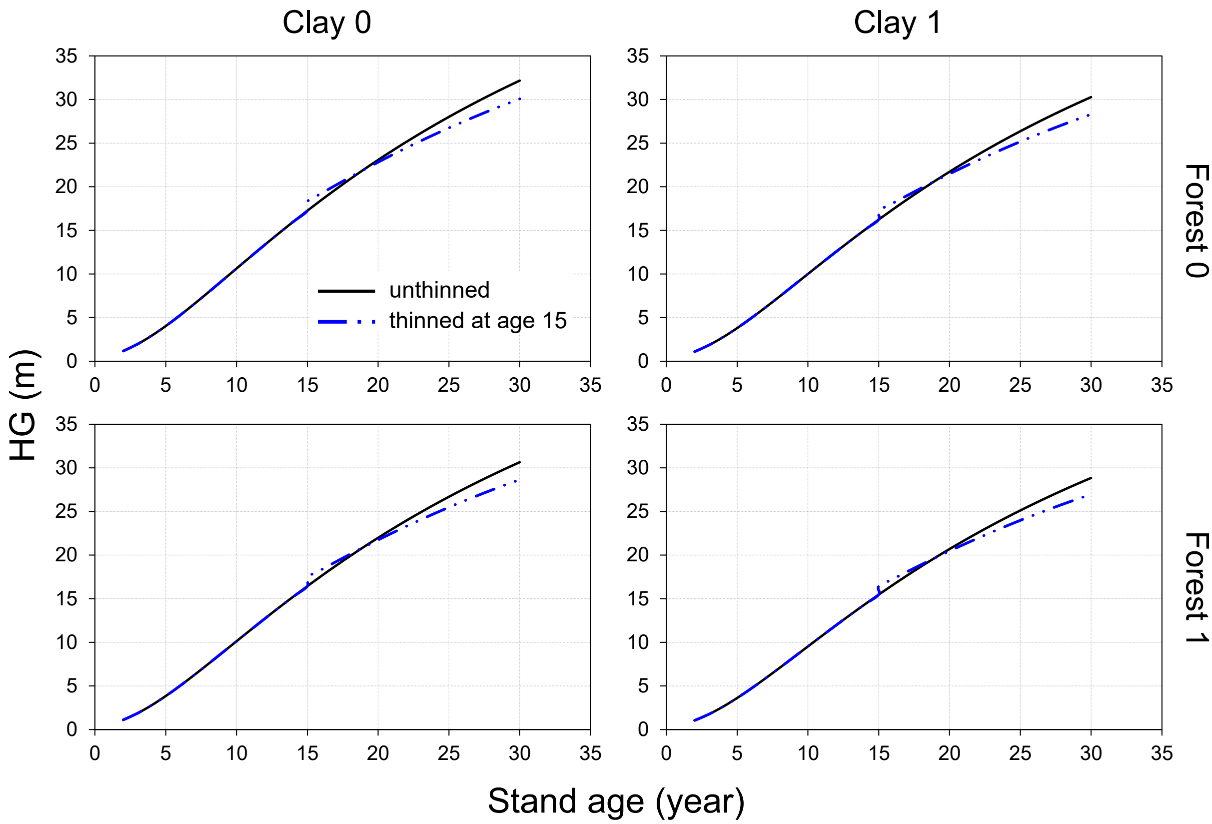

Fig. 6. Simulation examples of basal area-weighted mean height (HG, m) model over stand age in line with a dummy site type (*Forest*), a dummy soil type (*Clay*), and thinning effect (*Thinned* and *Thinned*/(Talty + 10)). The number of trees per hectare (TPH, trees ha^{-1}) was set to 1600 at initial stage and changed to 1040 with 35% thinning intensity at age 15. The simulated lines were predicted until age 30 based on the fixed-effect parameters provided in Table 2. Site index (SI, m), the other input variable, for this simulation was set to the median value of 25 m at base age 20.

hybrid aspen (Hynynen et al., 2004; Rytter and Stener, 2005, 2014). Also Tullus et al. (2007) reported that height increment of hybrid aspen was significantly poorer on clay loam than on the other soil types, but that increased sand concentration clearly promoted height growth of hybrid aspen on hydromorphic (fine-textured) soils.

4.3. Applicability of the stand-level models

Before applying the presented models in practice, predictor ranges and inherent stand conditions have to be considered. Previous studies based on mean annual increment of total production in volume suggest a final cutting age between 20 years and 30 years (Hynynen et al., 2002, 2004; Tullus et al., 2012; Rytter and Stener, 2014; Fahlvik et al., 2021). In our study, the modeling data were mostly distributed within 20 years, ranging up to 30 years in Sweden (Table 1, Fig. 4). The use of the models for stands beyond the age of 30 years is not recommended, because model behavior in those stands has not been investigated. Furthermore, due to the restricted coverage of modelling data in juvenile stands, the BA model is recommended to be applied only for stands with age ≥ 5 (Fig. 4). Since our modeling data covered a wide range of site indices (Table 1, Fig. 4), it can be assumed that the present models would be appropriate to all site indices for hybrid aspen plantations unless severely out of range. To estimate site index, the parameters and methods suggested by Lee et al., 2021a were applied in this study and are also recommended for simulation.

The common planting density was 1100–1600 seedlings ha^{-1} because high density cultivation was not feasible due to high regeneration costs (Tullus et al., 2009; Tullus et al., 2012). Therefore, planting trees<2000 seedlings ha^{-1} was generally recommended in Scandinavia and the Baltics (Tullus et al., 2012). Because of this, our modeling data mainly ranged from 1000 trees ha^{-1} to 2000 trees ha^{-1}; in some plots of spacing trials (Luke 1), planting density was only 400–800 trees ha^{-1} (Table 1). The TPH range of modelling data can be considered as realistic in practice, but one should be cautious when extrapolating the TPH predictor for densities over 2000 trees ha^{-1}. In case of simulating for a high initial density, it must be noticed that mortality models for hybrid aspen do not exist yet. Our models are based on data treated with prevailing thinning types in practice, i.e., thinning from below or row thinning (Rytter and Stener, 2014). The models are not recommended to be used for stands thinned from above.

Rytter and Stener (2014) reported superior performance of hybrid aspen plantations with annual total production larger than 20 m^3 ha^{-1} $year^{-1}$ within the altitude and latitude range, covered by our data. Tullus et al. (2012) suggested that, because of local adaptation, clones originating from the same geographical region should be used for plantations. A transfer to the north would result in a different growing season and with that a possible increased risk of frost damage. Consequently, GDD5 that includes geographical characteristics should be applied within the similar geographical range from southern Finland to southern Sweden (Fig. 1). Our models are applicable to former agricultural land with various soil types and forest site (Table 1), but statistically significant impacts of the edaphic variables (*Clay* and/or *Forest*) were found in the DG and HG models (Table 2, Fig. 6). Both *Clay* and *Forest* dummy variables were significant being less favorable to height growth of hybrid aspen (Rytter and Stener, 2005; Johansson, 2013a).

The models predict the development of successfully established stands, in which no major damage occurs. The experiments were established after mechanical or chemical site preparation to provide optimal and equal site conditions. Furthermore, at several sites, the plots

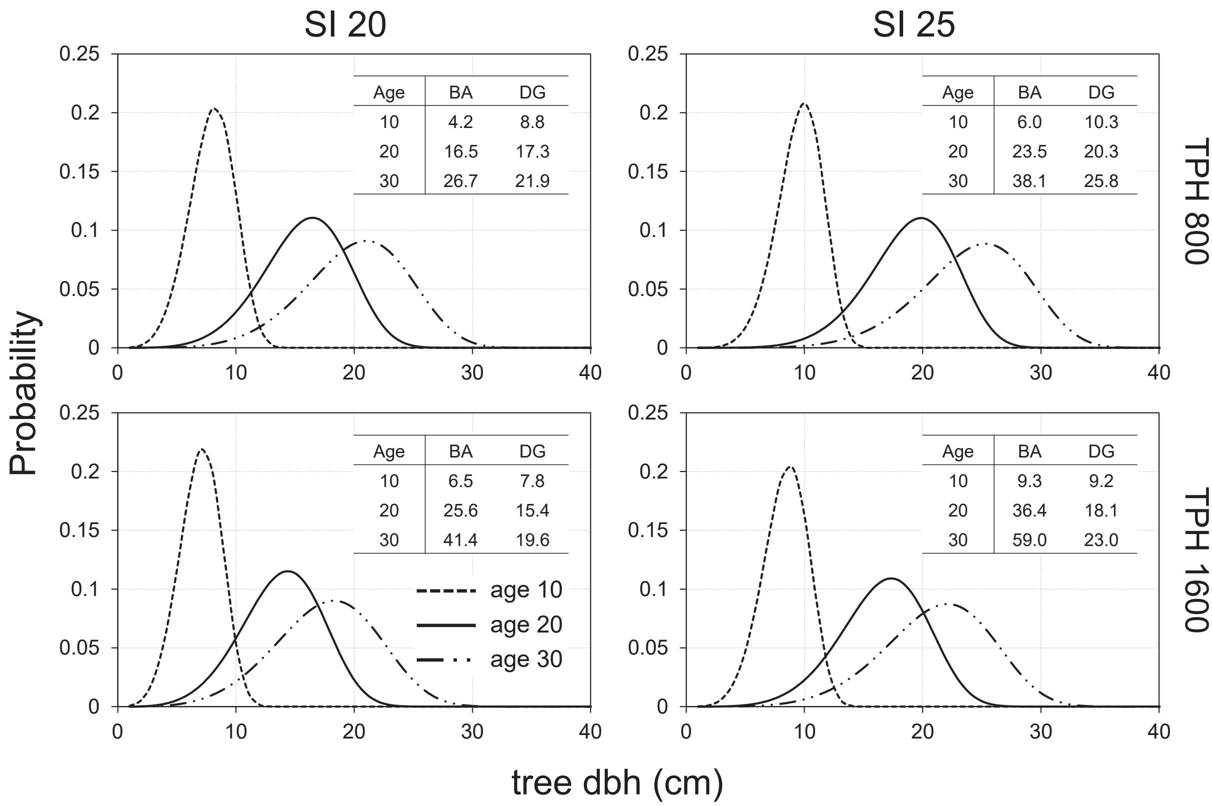

Fig. 7. Model application in conjunction with diameter distribution using the predicted stand characteristics of stand basal area (BA, m^2 ha^{-1}) and basal area-weighted mean diameter (DG, cm) in the present study. The predicted BA and DG were calculated based on the fixed-effect parameters provided in Table 2. The 2-parameter Weibull function was applied with parameter recovery for predicting diameter distribution according to Lee et al., 2021. The simulated factors were stand age (AGE, year) site index (SI, m) and the number of trees per hectare (TPH, trees ha^{-1}) and the growing degree-days (GDD5, °C·days) was fixed to 1500 in all examples.

were fenced and/or the seedlings were protected with tubes against herbivorous mammals (Fahlvik et al., 2021; Lee et al., 2021a; Rytter and Stener, 2014; Tullus et al., 2012). In the models clonal variation (Table 1) was not considered, although it is known to result in variation in growth (Rytter and Stener, 2003, 2014; Stener and Karlsson, 2004). This was because the trial design was unbalanced with respect to clonal variation. Since our main objective was to develop stand-level models for universal hybrid aspen clonal plantations, we acquired the sample plots regardless of clonal types. Still, the model developed in this study can be used for clonal hybrid aspen plantations, the growth of which is superior to European aspen (Hynynen et al., 2002, 2004; Fahlvik et al., 2021).

5. Conclusion

The models for stand characteristics of BA, DG, and HG were suitably developed using multivariate mixed-effects regression approach based on data from clonal hybrid aspen plantations in southern Finland and southern Sweden. The driving variables comprised mainly of AGE, SI, and TPH, depending on response variable types. Additionally, the variables related to geographic, edaphic, and silvicultural treatment were significant such as GDD5, *Forest*, *Clay*, Talty5+, *Thinned*, *Thinned*/(Talty + 10). The model validity to the previous, comparable studies demonstrated that the present models were stable and applicable to similar hybrid aspen plantations. Moreover, we demonstrated that the developed models can be easily applied to diameter distribution and individual tree height predictions in connection with the existing models of the precedent research.

Considering that the mortality model for hybrid aspen was not considered in this study, a simulation with an extreme stand situation, such as over AGE 30 or TPH > 2000, can bring about overprediction of BA. Our study was not able to consider the various clone characteristics and site preparations, so future studies can examine these factors further if necessary. Overall, the present models were evaluated to be useful for predicting the stand-level BA, DG, and HG of universal clonal hybrid aspen plantations in southern Finland and southern Sweden and even in neighboring countries where the clonal, geographical, and edaphic conditions were analogous to the present model.

6. Data availability

The data are stored with the Natural Resources Institute Finland (Luke) and the Forest Research Institute of Sweden (Skogforsk), respectively, and are not publicly available due to their ownership. The data in this study are available upon reasonable request by contacting the authors, Jari Hynynen (Luke) and Nils Fahlvik (Skogforsk).

CRediT authorship contribution statement

Daesung Lee: Conceptualization, Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Jouni Siipilehto:** Conceptualization, Formal analysis, Methodology, Software, Validation, Writing – original draft, Writing – review & editing. **Egbert Beuker:** Data curation, Investigation, Resources, Writing – review & editing. **Nils Fahlvik:** Data curation, Investigation, Resources, Writing - review & editing. **Mateusz Liziniewicz:** Data curation, Investigation, Resources, Writing – review & editing. **Jari Hynynen:** Conceptualization, Data curation, Funding acquisition, Investigation, Project administration, Resources, Supervision, Writing – review & editing.

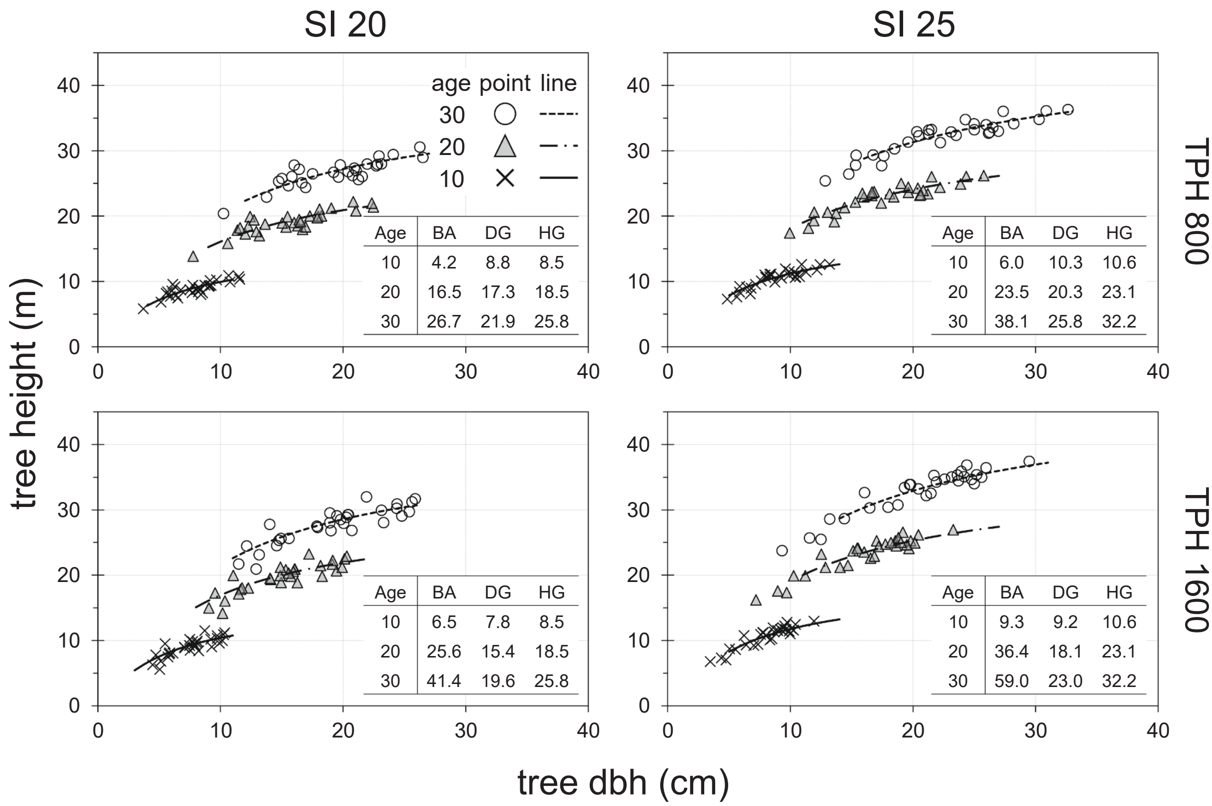

Fig. 8. Model application in conjunction with individual tree height estimation using Näslund's model from Lee et al., 2021. The input variables of stand basal area (BA, m^2 ha^{-1}), basal area weighted mean diameter (DG, cm), and basal area weighted mean height (HG, m) were predicted using the fixed-effect parameters of the models (Table 2) developed in the present study. The predetermined stand age (AGE, year), site index (SI, m) and the number of trees per hectare (TPH, trees ha^{-1}) were applied in this simulation. Other predictors were preset to GDD5 = 1500, *Forest* = 0, *Clay* = 0, Talty5+ = 0, *Thinned* = 0, and *Thinned*/(Talty + 10) = 0 for demonstration of general stand condition. For each simulated stand condition of AGE, SI, and TPH, the tree dbh was randomly generated from the recovered Weibull distribution in conjunction with Fig. 7. The predicted height curves were the values predicted only using fixed-effect parameters and the tree height of sample points was computed with random variation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgements

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Appendices. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2023.121066.

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