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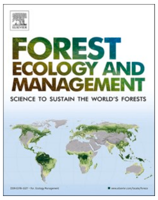

Evaluation of growth models for mixed forests used in Swedish and Finnish decision support systems

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ABSTRACT

Interest in mixed forests is increasing since they could provide higher benefits and positive externalities compared to monocultures, although their management is more complex and silvicultural prescriptions for them are still scarce. Growth simulations are a powerful tool for developing useful guidelines for mixed stands. Heureka and Motti are two decision support systems commonly used for forest management in Sweden and Finland respectively. They were developed mostly with data from pure stands, so how they would perform in mixed stands is currently uncertain. We compiled a large and updated common database of well-replicated experimental research sites and monitoring networks composed by 218 and 1,160 plot-level observations of mixed stands from Sweden and Finland, respectively. We aimed to evaluated the accuracy of Heureka and Motti basal area growth models in those mixed-species stands and to detect any bias in their short-term predictions. Basal area growth simulations (excluding mortality models) were compared to observed stand-level values in a period-wise process with update of the start values in each period. The residual plots were visually examined for different stand mixtures: Norway spruce (*Picea abies* Karst.)-birch (*Betula* spp), Scots pine (*Pinus sylvestris* L.)-birch and Scots pine-Norway spruce. We observed that the basal area growth models in both decision support systems performed quite well for all mixtures regardless of the proportion of species. Motti simulations overestimated growth in Scots pine-Norway spruce mixtures by 0.063 $m^2 \cdot ha^{-1} \cdot year^{-1}$ which may be acceptable for practical use. Therefore, we corroborated that both decision support systems can be currently utilized for short-term forest growth simulation of mixed boreal forests.

1. Introduction

Environmental and societal changes are creating new demands for the use of forests. The need for renewable raw materials is rising due to the growing bio-economy, while their role in mitigation and adaptation to climate change, biodiversity preservation, water regulation, nutrient cycling, and recreation and health for citizens is being emphasized (Huuskonen et al., 2021a). Increasing the diversity of forest ecosystems is one possible way to obtain multiple benefits from managed stands (Felton et al., 2016).

Mixtures could enhance resilience against biotic and abiotic disturbances (Guyot et al., 2016; Jactel et al., 2017), improve stability (del Río et al., 2017) or increase recreational and other ecosystem services (Felton et al., 2020; Huuskonen et al., 2021a). However, whether mixtures can use resources more efficiently and provide higher growth and yields is still under debate in the Nordic countries. Fichtner et al., (2018) found that tree productivity increased with neighbourhood species richness, although it could be modulated by climate and site conditions (Ammer, 2019; Jactel et al., 2018). Furthermore, the strongest positive mixed effects were related to some aspects of stand stability (del Río et al., 2022; Pretzsch and Schütze, 2021). On the other hand, Holmström et al., (2018) found no facilitative neither complementary effects when growing Scots pine and Norway spruce in mixture and Houtmeyers and Brunner, (2022) found no effect of neighboring species in conifer mixtures responding to drought. This could be a consequence of a negative influence of latitude on the mixing effect of those tree species (Bielak

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et al., 2014; Drössler et al., 2018). Recently Brunner and Forrester, (2020) demonstrated the importance of including stand density in the analysis of mixed forest growth. Accordingly, species trait differences seem to be more important than species diversity in forest function (del Río et al., 2021; Pardos et al., 2021; Scherer-Lorenzen et al., 2005). In addition, management for mixed stands is complex, so silvicultural prescriptions for different species mixtures are still scarce and more research is needed (Pretzsch et al., 2021). Growth simulations from decision support systems could help develop new silviculture guidelines specifically aimed at mixed-species stands, and for that, the first step would be to evaluate the growth model performance at short term with updated measurement data.

Forest growth simulators are commonly used to assess stand and tree growth according to particular silvicultural guidelines generated in forest planning and forest research. Their use has great relevance as management tools in Fennoscandia due to the high economic importance of Nordic forests (Elfving and Nyström, 2010; Wikström et al., 2011). However, forest growth simulators are frequently applied in a wide range of conditions for which they were not designed, and thus, simulators' performance should be evaluated under various conditions to enable users to apply them correctly and with confidence (Fahlvik et al., 2014).

Heureka and Motti are two decision support systems utilized commonly for forest management and silviculture simulations in Sweden and Finland respectively. The growth and yield models of Heureka and Motti are based on extensive empirical data covering all commercial tree species and all common forest management practices applied in practical forestry in Sweden and Finland over recent decades. Heureka is freely available software developed and hosted by the Swedish University of Agricultural Sciences (SLU). The system covers a wide decision support process from data inventory to plan alternatives with multi-criteria decision techniques, including a map viewer (GIS). It can be used for both large-scale and small-scale forestry, being designed for different users' specific problem areas: stand-level analysis, forest-level planning and analysis, multi-criteria decision analysis, and regional and national scenario analysis (Wikström et al., 2011). Forest growth projections and climate forecast models can be incorporated into the simulator to assess how forests evolve under different climate scenarios. Including these in a single system makes a holistic approach to forestry planning possible. This simulator includes a large set of models for calculating site features (such as site index), growth and mortality (Wikström et al., 2011). The user can select either stand-level or tree-level sub-models for predicting basal area growth (Elfving and Nyström, 2010), although the former shows higher precision (Fahlvik et al., 2014).

The Motti software for forest management analysis and decision support has been developed at the Natural Resources Institute Finland (LUKE). It has been applied both in stand-level (Ahtikoski et al., 2012; Haapanen et al., 2016; Hynynen et al., 2005) and in regional-level (Haikarainen et al., 2021; Huuskonen et al., 2021b; Hynynen et al., 2015) analyses. Motti include a large set of models to predict the dynamics in unmanaged and managed stands with different types of silvicultural treatments. The core of the Motti software is a stand simulator which consists of both stand-level models and distance-independent individual-tree models for predicting stand dynamics (regeneration, growth, and mortality) and stand structure (Hynynen et al., 2015; Salminen et al., 2005; Siipilehto et al., 2014). The regeneration and early growth of stands is predicted using the stand-level models by Siipilehto, (2006)and Siipilehto et al., (2014). Stand growth from the stage of canopy closure onwards is predicted with the distance independent individual-tree models of Hynynen et al., (2014, 2002).

Both decision support systems were designed for long-term forest planning on a regional or stand scale and have been widely used by Nordic forest owners and enterprises. They allow the user to analyse different silvicultural prescriptions from stand establishment through thinning treatments and the final harvest planning. Different scenarios can be evaluated by comparing their estimates of timber production, forest fuels, profit, biodiversity, and carbon sequestration (Hynynen et al., 2005; Lidman et al., 2021; Wikström et al., 2011). Both simulators are based on data from national forest inventories, long-term experiments and other forest-monitoring networks. In this regard, Sterba et al., (2002) showed that model evaluation with national forest inventories could result in growth estimation errors for mixed forest, which could be enhanced under temporally changing growing conditions. Although Heureka and Motti include species' proportions as a parameter for the simulations, both were calibrated and used mostly on pure stands and, thus, how they would perform in mixed-species stands is currently uncertain. Therefore, evaluating growth simulations for both systems under such conditions is an important priority.

Here, we used data from experimental research sites and repeated forest measurements from monitoring data in mixed-species stands. Data were from throughout the countries and included specific experimental sites for mixtures in Sweden and monitoring data of mixed stands in Finland, making up a common shared database. We compared the growth observations for each field measurement versus Heureka and Motti growth simulations at a stand level, considering different mixtures: Norway spruce (*Picea abies* Karst.)-birch (*Betula pendula* Roth and *Betula pubescens* Ehrh.), Scots pine (*Pinus sylvestris* L.)-birch and Scots pine-Norway spruce. Our aims were: (1) to evaluate the accuracy of Heureka and Motti basal area growth models in mixed-species stands, (2) to detect any bias and trend in their predictions depending on the species mixture. Thereby, we aimed to better understand the current and potential short-term use of both programs for mixed stands in both countries.

2. Material and methods

2.1. Study sites and data sources

The Swedish data came from 87 plots in 25 long-term experimental sites on mineral soils, and included well-replicated pure and mixed stands from throughout the country (Table 1). The pure plots were controls to check the differences in growth model performance along a gradient of species dominance at each site. The dataset was filtered according to the type of mixed species. We only used stands with a dominant height above 7 m to meet the restrictions of the evaluated growth models. A total of 218 stand measurements were included, with a mean time interval between inventories of six years. Data were obtained mainly from the 1980s, although some inventories for S. pine-N. spruce mixtures predated 1940. During each measurement, the size (diameter at breast height, 1.3 m), species identity and status (alive, dead, removed or missing) was recorded for every tree in the plot. Height was measured only on a subset of trees and estimated for the remaining trees using Näslund's height curves (Näslund, 1936). Stand ages ranged from 20 to 123 years and the dominant species made up 45–85 % of the mixtures. The average studied stand was 45 years old, with a basal area of 22 m^2/ha; in two-species mixtures the dominant species made up 65 % of the basal area (Table 1).

Finnish data consisted of all permanent plots sampled by LUKE. These include both long-term experiments established and managed by LUKE for specific research (permanent sample plots) and monitoring networks in stands owned and managed by other actors, all of them on mineral soils. None of the long-term experiments were designed to study mixtures but many mixed-species stands occurred naturally. The repeated monitories were mostly established in well-managed stands to cover the full extent of forest situations in Finland, thus including some mixed-species stands. In all cases, the measured stands included multiple plots with varying numbers of replicates. Stands were included if they had at least one plot where the dominant species accounted for less than 75 % of basal area to harmonize as best possible with the Swedish experimental design. Most of the data were obtained from 1980 to 2020, although some measurements were as old as 1940. During each revision,

Table 1

Description of the experimental sites and plots used for model evaluation. Mean values are shown, with ranges in parentheses.

		SWEDEN			FINLAND		
	Description	**N.spruce-birch**	**S.pine-birch**	**S.pine-N.spruce**	**N.spruce-birch**	**S.pine-birch**	**S.pine-N.spruce**
Sites	*Number of experimental sites (Sweden) or stands (Finland) evaluated*	10	3	12	68	102	164
Plots	*Number of mixed plots assessed*	38	9	40	105	166	324
n	*Number of inventories evaluated*	99	11	108	183	266	711
Measurement	*Range of measurement years*	1984–2019	1981–2003	1937–2020	1962–2019	1963–2007	1940–2019
Length	*Elapsed time between inventories*	6 (4–12)	15 (5–19)	7 (3–20)	7 (4–18)	9 (4–20)	7 (4–25)
Lat.	*Latitude in °N*	59.87 (56.38–64.18)	63.8 (63.40–64.23)	58.37 (56.40–60.54)	62.82 (60.28–66.75)	63.24 (60.28–68.12)	62.84 (59.97–68.12)
Long.	*Longitude in °E*	15.47 (12.15–19.44)	19.91 (19.52–20.36)	14.45 (13.50–16.90)	25.87 (25.70–25.97)	25.86 (25.63–25.97)	25.87 (25.63–25.97)
Age	*Mean initial stand age*	37 (20–69)	27 (24–29)	53 (21–123)	64 (12–99)	59 (17–99)	62 (13–99)
BA	*Basal area* ($m^2 \cdot ha^{-1}$)	24 (6–49)	21 (8–42)	29 (11–62)	23 (6–47)	21 (4–40)	23 (5–60)
N	*Number of stems/ha*	2,480 (766–5,000)	1,360 (620–2,620)	1,630 (270–4,870)	1,612 (240–4,670)	1,480 (308–4,285)	1,418 (190–4,547)
SIS	*Site index according to site factors for site-indicative species (m)*	26 (16–35)	22 (20–24)	27 (21–34)	27 (15–35)	25 (11–35)	21 (11–28)
Mix	*BA proportion of the dominant species (%)*	62 (45–85)	73 (53–83)	67 (46–84)	68 (40–85)	68 (39–85)	67 (35–85)
Spruce	*% of Norway spruce in the mixture by BA*	54 (15–85)	1 (0–7)	40 (15–79)	65 (11–85)	5 (0–25)	44 (9–85)
Pine	*% of Scots pine in the mixture by BA*	1 (0–13)	74 (54–83)	58 (17–84)	5 (0–26)	61 (11–85)	50 (8–84)
Birch	*% of birch in the mixture by BA*	44 (15–80)	25 (15–46)	1 (0–15)	28 (8–85)	33 (8–84)	5 (0–30)
Thin_N	*Number of thinnings*	2.4 (1–4)	2.5 (2–3)	2.2 (1–9)	1.4 (1–2)	2.1 (1–3)	2.3 (1–5)
Thin_freq	*Years between thinning*	6.5 (5–9)	12.7 (3–19)	7.9 (2–22)	6.5 (2–36)	7.5 (2–24)	8.6 (2–36)
Thin_int	*Thinning intensity* ($m^2 \cdot ha^{-1}$)	8.7 (0.1–21.6)	0.4 (0.1–2.8)	7.2 (0.3–21.7)	2.7 (1.9–24.0)	1.7 (1.6–23.8)	3.5 (1.9–23.2)

every tree in the plot was measured following the same practices as described above for the Swedish plots. On average the studied stands were 60 years old, with a basal area of 22 $m^2 \cdot ha^{-1}$ (Table 1).

2.2. Tested models

The evaluation focused on the basal area growth models in Heureka (Elfving and Nyström, 2010) and Motti (Hynynen et al., 2014). The Heureka model was developed at a stand level, using stand-level predictors and returning the total basal area growth. The suite of models used by Motti, on the contrary, used mostly tree-level growth and yield models and the total basal area growth prediction was the sum of the individual trees. Therefore, even though Heureka and Motti used different approaches (stand- vs tree-level), they estimated the same output, i.e., the stand-level basal area growth between inventories.

In the Heureka system, the basal area growth is calculated by a stand-based function (Elfving and Nyström, 2010). The model was built with data from temporary and permanent plots from the Swedish National Forest Inventory (NFI) and long-term thinning experiments based on 1983–1992 inventories and tested and calibrated for data from 1999 to 2005. This model estimates total growth more precisely than a single tree-based model (Fahlvik et al., 2014). The output variable is 5-year stand basal area growth. More than 20 input variables are used, covering a large range of characteristics: average stand features, climate, site fertility, thinning treatment and species composition (the relative basal area of conifers, pine and birch). Thinning treatments indicated if the plot had been thinned in the last ten years or within 11–25 years before start of the growth period. The creators of Heureka recommend regularly checking the model outputs with new data, since the growth rates of different species may vary substantially over time (Elfving and Nyström, 2010).

In the Motti system stand-level growth is aggregated from a set of tree-level models described by Hynynen et al. (2002, 2014). The models were built with monitoring data (years 1976–1992) on a large set of Finnish even-aged forests representative of various site types, where the dominant species comprised at least 50 % of the stand basal area. The output variable is 5-year tree-level basal area growth. Various variables are inputs for a series of interconnected species-specific models, covering a large range of characteristics and dynamics: competition (symmetrical and asymmetrical), climate, site, treatment, and environment. Species composition is expressed by using indices both for total competition and for species-specific components. Treatment is incorporated by modifying the crown ratio, which in turn impacts tree growth.

2.3. Data management

The Swedish and Finnish datasets were merged into a single database covering both countries with tree- and stand-level information required as input variables for Motti and Heureka. Some variables needed harmonization between the different countries, namely site index according to site factors (a required input for Heureka) and vegetation type (required in both simulators). Site index according to site factors was inferred from a species-specific linear model using data from permanent Swedish NFI plots, where site index, i.e. dominant height at 100 years, and latitude are used as explanatory variables (for more information see Supplementary Table SM1). Dominant height at 100 years for Finnish data, to be used as an input in the above model, was calculated for the dominant species by a model using only site and climate characteristics (Hynynen et al., 2002). Vegetation type is an ordinal indicator of growing potential based on forest floor vegetation, and was defined according to Elfving and Nyström, (2010) and Cajander, (1949) classifications for the Swedish and Finnish data respectively. Since there were no observational data for vegetation type in the Swedish experimental sites, mean values from the National Forest Inventory were used for each mixture composition. In addition, predictions from pure plots in each experimental site were used as controls to facilitate the calibration process and use an appropriate vegetation type for the mixtures. Accordingly, we supposed a common vegetation type index value of 3 (high fertility) for Norway spruce–birch and 0 (medium fertility) for the other mixtures in Sweden for Heureka simulations. Then, we harmonized the vegetation types between both countries according to Supplementary Table SM2. Therefore, we considered that most of the vegetation type for the Norway spruce–birch mixtures in Sweden would correspond to the *Oxalis-Myrtillus* type (OMT) in the Finnish system, suggesting high fertility. The other mixtures studied would match with

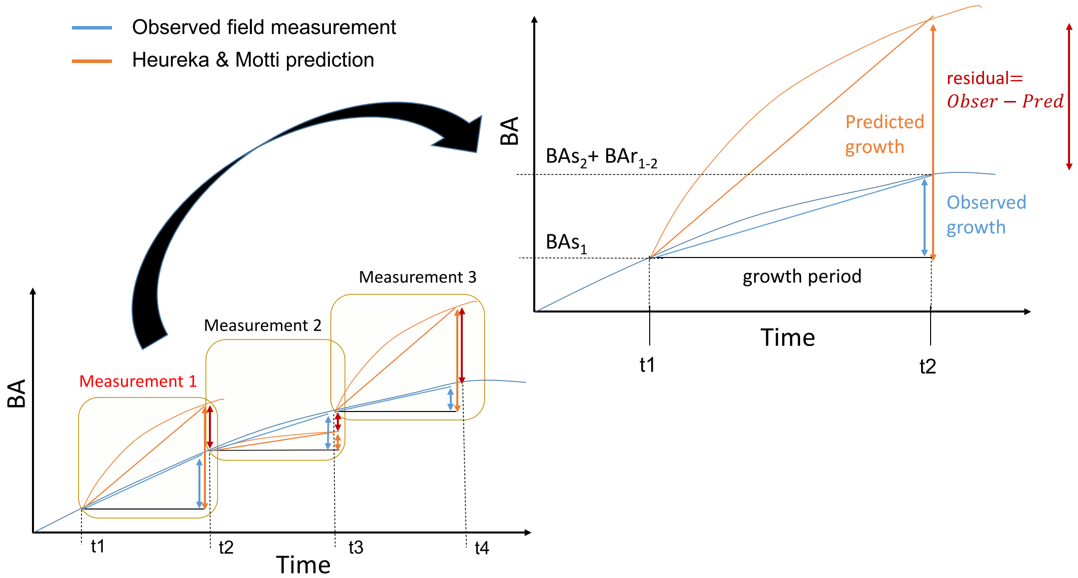

Fig. 1. Relationships among observed, predicted and absolute residual error of basal area (BA) values from Heureka and Motti simulations. Simulations started with the initial measurement data, calculated for 5-years periods and linearly interpolated when the elapsed time between inventories was greater than 5 years. Noted that, in this case, the time between inventories matches Heureka and Motti simulation intervals (five years), so linear interpolation was not necessary. Residual values would be negative in measurement 1 and 3, i.e., simulations were overestimated, while measurement 2 would cause a positive residual or underestimation. BAS_1: basal area from standing trees at t_1; BAS_2: basal area from standing trees at t_2; $Bar_{1\text{-}2}$: basal area removed between inventories.

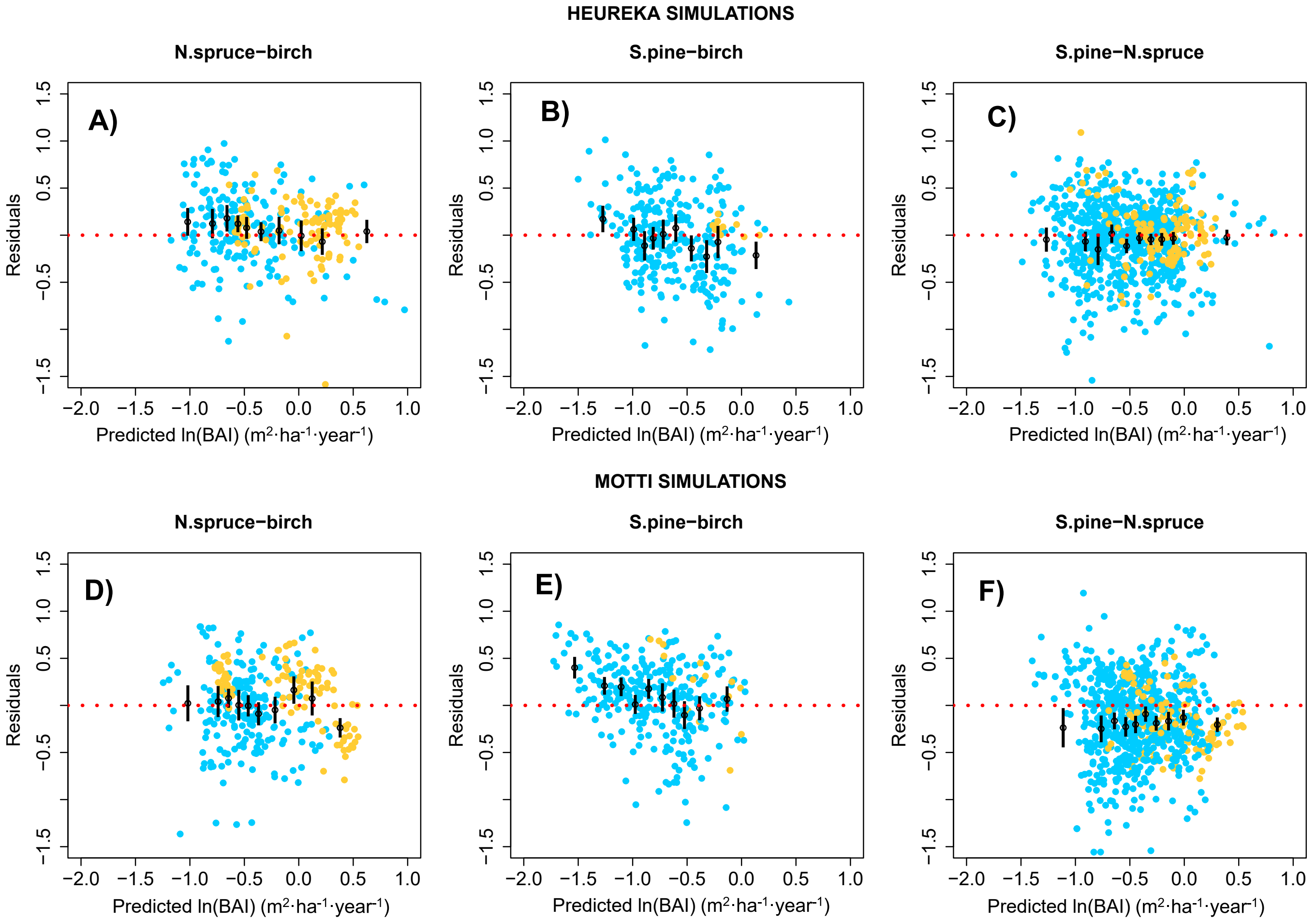

Fig. 2. Residual values versus predicted values in logarithmic scale for the Heureka (top row) and Motti (bottom row) simulations in different type of mixtures. Blue and yellow dots are Finnish and Swedish data, respectively. Error bars show means (central dots) and standard errors (bars) for different intervals based on both data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Myrtillus type (MT) and *Vaccinium* type (VT) corresponding from medium to dry conditions and lower fertility respectively. We proceeded in the same way to transform Finnish vegetation type classes to Swedish codes (Supplementary Table SM2).

2.4. Growth observations, simulations & evaluation

The observed plot growth values were calculated as differences between inventories in a period-wise process with update of the start values in each period. The mean annual observed basal area increment (BAI) for each plot and measurement was calculated according to eq.1.

$$BAI_i = \frac{(BAs_{i+1} + BAr_{i+1} - BAs_i)}{(t_{i+1} - t_i)} \tag{1}$$

where BAI_i is the annual basal area increment ($m^2 \cdot ha^{-1} \cdot year^{-1}$) for the measurement at $t = i$, BAs_{i+1} is the basal area ($m^2 \cdot ha^{-1}$) from standing trees at $t = i + 1$, BAr_{i+1} is the basal area removed (including natural mortality and thinning treatments) between inventories, BAs_i is the basal area from standing trees at $t = i$, $(t_{i+1} - t_i)$ is the number of years between inventories.

The Heureka and Motti growth simulations were predicted over a series of five-year intervals starting at the time of the first measurements of each site (Fig. 1). The starting point for every new simulation was the time of a new measurement, and at that time, we consider all the standing living trees to project future stand-level growth. Mortality was not included in the simulations to avoid increasing error and noise, which could complicate the evaluation of the growth models studied. When the time between two measurements was different than five years, the necessary number of basal area growth simulations was linearly interpolated to the starting year of the next inventory.

Table 2
Residual values and goodness of prediction for Heureka and Motti basal area growth (m^2/ha $year^{-1}$) simulations by mixture composition. Bold numbers denote a significant difference from zero (p-value less than 0.05). RMSPE: root-mean-squared-prediction-error and MAPE: mean absolute prediction-error.

		Logarithmic scale				*Absolute scale*			
Composition	*Model*	*Mean residual*	*SD*	*RMSPE*	*MAPE*	*Mean residual*	*SD*	*RMSPE*	*MAPE*
N. spruce-birch	*Heureka*	**0.069**	0.373	0.360	0.255	0.026	0.389	0.373	0.226
	Motti	−0.001	0.412	0.412	0.327	−0.044	0.327	0.330	0.253
S. pine-birch	*Heureka*	−0.047	0.408	0.406	0.322	−0.039	0.241	0.241	0.187
	Motti	**0.103**	0.378	0.391	0.313	0.068	0.198	0.209	0.159
S. pine-N. spruce	*Heureka*	−0.054	0.448	0.440	0.284	−0.036	0.264	0.259	0.178
	Motti	**−0.186**	0.521	0.553	0.377	−0.063	0.277	0.284	0.220

Basal area growth residuals were calculated as the differences between observed and predicted values in logarithmic units according with the scale in which the original models were defined. Goodness of prediction was evaluated by different statistical metrics such as mean and standard residual values, root mean squared prediction error (RMSPE; Eq.2) and mean absolute prediction error (MAPE-Eq.3) on both logarithmic and absolute scales (Kutner et al., 2005):

$$RMSPE = \sqrt{\frac{1}{n}\sum\nolimits_{i=1}^{n}(y_i - \overline{y_i})^2} = \sqrt{\frac{1}{n}\sum\nolimits_{i=1}^{n} r_i^2} \tag{2}$$

$$MAPE = \frac{1}{n}\sum\nolimits_{i=1}^{n}|y_i - \overline{y_i}| = \frac{1}{n}\sum\nolimits_{i=1}^{n}|r_i| \tag{3}$$

where y_i is the observed growth value, $\overline{y_i}$ corresponds to the predicted growth, n is the number of observations and r_i denotes the residual value for the ith observation. The residuals were plotted against predicted values to evaluate the consistency of Heureka and Motti simulations in the different mixtures studied. Residuals were also plotted against species mixture proportion, to check for potential areas of inaccuracy. The standard error of means was calculated for ten classes of predicted values with the same number of points and included in the residual plots to analyse the homogeneity of residuals using the *lmfor* R package (Mehtatalo and Kansanen, 2020). All analyses were carried out in the R statistical environment version 4.1.2. (R Development Core Team, 2022).

3. Results

Overall, the residual plots show that the studied basal area growth models used in Heureka and Motti performed quite well for mixtures according to the simulations for the whole data set composed of information from both countries (Fig. 2). However, we observed smaller significant biases of mean residuals for N. spruce-birch mixtures in Heureka (Fig. 2A) and S. pine-birch mixtures in Motti (Fig. 2E). Motti simulations also overestimated S. pine-N. spruce mixture growth across the range of the predicted values (Fig. 2F). This was confirmed by the mean residual values which were significantly different from zero (Table 2). According with the metrics calculated for goodness of prediction, in general terms, prediction error was similar for Heureka and Motti simulations regardless of species composition. Growth simulations for mixed forests were suitable for both decision support systems, although the results obtained for S. pine-N. spruce mixtures with Motti should be used carefully.

Heureka predictions primarily worked fine for all mixtures regardless of stand composition. Low predicted values for the N. spruce-birch mixture indicate small but consistent underestimation errors (Fig. 2A; Table 2). Similarly, for S. pine-birch mixtures there were some underestimations at the lowest prediction intervals (Fig. 2B), although the mean value of residuals was not significantly different from zero (Table 2). On the other hand, the trend of the standard error intervals for S. pine-N. spruce mixtures was close to zero across the predicted range (Fig. 2C). Overall, no trend were observed in the residual plots from Heureka simulations.

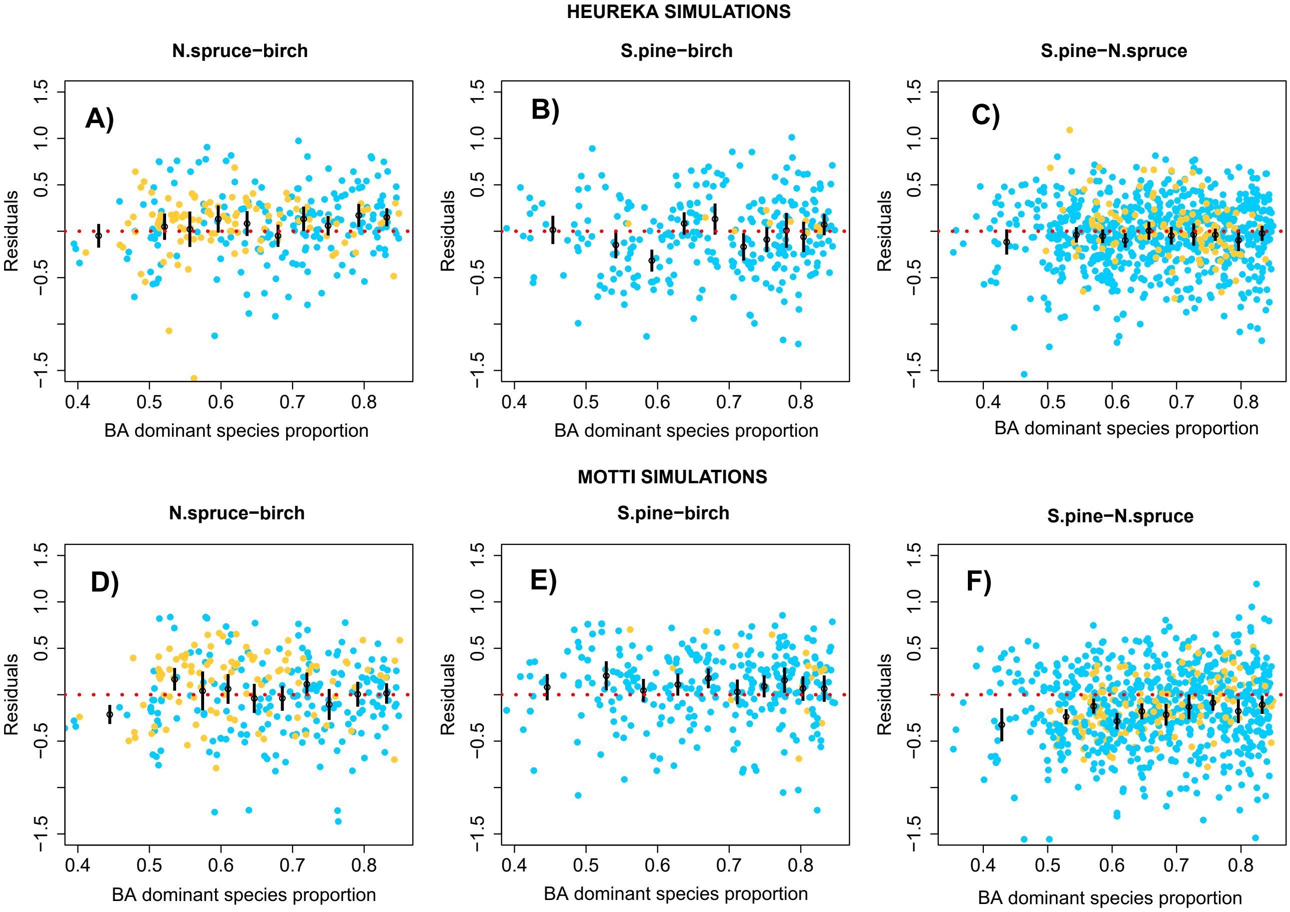

Fig. 3. Residual values in logarithmic scale versus basal area proportion of the main species in the mixture for the Heureka (top row) and Motti (bottom row) simulations in different types of mixtures. Blue and yellow dots are Finnish and Swedish data, respectively. Error bars shows means (central points) and standard errors (bars) for different intervals based on both datasets. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In general, Motti predictions performed well for mixtures. N. spruce-birch mixture only showed two standard error intervals out of ten significantly different from zero, one of them driven by Swedish data (Fig. 2D). Motti underestimated broad area present for low predicted values in S. pine-birch mixtures (Fig. 2E) and, on the contrary, overestimated for S. pine-N. spruce mixtures (Fig. 2F; Table 2). The simulations for that mixture were the most biased, although they were only overestimated by 0.063 $m^2 \cdot ha^{-1} \cdot year^{-1}$ on average in absolute terms (Table 2). Therefore, despite of the consistent and statistically-significant errors, they are tiny for practical purposes.

No trends were visually observed for the residual plots versus the basal area proportion of the main species in the mixture (Fig. 3). Although the previously mentioned systematic overestimation in Motti simulations for S. pine-N. spruce mixtures remains clear, no pattern was found with respect to the basal area proportion of the dominant species in the mixture (Fig. 3F). Therefore, the absence of a clear trend in the residual plots along the proportion gradient of the dominant species confirms the potential use of Heureka and Motti growth models for mixed forests.

4. Discussion

This analysis has shown for the first time that the Heureka and Motti models have consistently small mean differences between observed and predicted growth in mixed stands using the same large databases from both countries. This suggests that Heureka and Motti are valuable to evaluate updated forest management practices for mixed-species stands. In particular, we observed that both decision support systems worked well with records from other countries after data harmonization, which showed the potential ability to extrapolate their use to other geographical regions for which they were not originally developed. According to the absolute residual value, the overestimation of Motti simulations for S. pine-N. spruce mixtures was not serious (Table 2) and undesirable systematic patterns were not detected (Fig. 3F), posing no obstacles to its use. In addition, since there is no consistent bias as a function of mixture proportion, growth simulations can be compared between different mixing ratios. Overall, we confirmed our hypothesis that the basal area growth models checked would perform well for the mixtures studied here regardless of the species proportion and country.

An achievement of this study was to compile a unique large dataset of mixed forests in Sweden and Finland that was used for the growth simulations in both systems. It could result in more realistic growth evaluation compared to model development using national forest inventory data (Sterba et al., 2002). In this way, we evaluated the growth models included in both decision support systems at different spatial and temporal scales in which they were defined, showing, even so, great performance. The part of the Finnish data was also used previously in the calibration of the model. However, they were used for fitting the model at tree level and here we calculated the stand level outcomes and, hence, it should not pose any obstacle to its use. Model evaluation was restricted to performance of basal area growth prediction. Mortality, which is an important component of stand dynamics, was not included in the analysis. If the mortality is considered simultaneously with growth models, it could certainly be useful to evaluate the long-term performance of both decision support systems for mixed stand predictions, which could be the subject of a future study.

The models tested here were built with data from temporary and permanent plots based on 1980–90s inventories and we predicted outside the spatial and temporal definition range of the models. There is a clear evidence of improved growing conditions, with forests becoming more productive in response to increasing temperatures in the northern temperate and boreal regions from 2000s (Appiah Mensah et al., 2021; Henttonen et al., 2017). Although Heureka and Motti have been calibrated with recent national forest inventory data to account for climate change, our results may need revaluation as temperatures increase further, especially if species will react differently. The use of improved breeding material in plantations during the last decades may also limit the use of the growth models tested here (Egbäck et al., 2017; Haapanen, 2020; Haapanen et al., 2016). The elapsed time between inventories was sometimes far from 5 years (Table 1) which is the simulated growth period in the Heureka and Motti models and, hence, it could also increase the error in the predicted values. The combined Swedish-Finnish dataset was built from different data sources and variables, which could affect the results, for instance by the harmonization of vegetation type definitions. Understory vegetation may change more in mixed stands compared to pure stands according to the tree species proportion, tree spatial arrangement and basal area (Hedwall et al., 2019), which makes it difficult to assign a suitable vegetation type. In this regard, since the Swedish data came from well-replicated experimental mixed-stand designs, it was easy to use the monocultures as controls to determine an appropriate vegetation type for the mixtures. On the other hand, the number of plots evaluated from Sweden was much lower than from Finland (Table1). The growth models evaluated were defined at different spatial scales, which is another potential source of error. While Heureka gives stand-level predictions, Motti gives tree-level output. The scaling of results from tree to stand level for Motti simulations could affect the outcome and be a potential cause for the observed bias in S. pine-N. spruce stands. Overall, the large database from both countries allowed us to check the growth models included in Heureka and Motti and confirm their use in spatial and temporal ranges which they were not originally targeted to.

There would be a multitude of factors causing errors in the basal area growth predictions, which can compensate or accelerate each other, and hence it would be worth describing some of them. A possible explanation of the slight systematic overestimation for S. pine-N. spruce mixture growth by Motti (Fig. 2F) might be the pervasive difference in the site quality of the species' stands. While Norway spruce monocultures are usually established on fertile soils, mixtures occupy poorer sites (Huuskonen et al., 2021a) and hence, the predicted growth for Norway spruce would be lower than expected. Another hypothesis is that the model used in Motti was unable to correctly include the change in tree competition caused by the variation of species proportion. Appiah Mensah et al., (2020) showed that this type of mixture is commonly characterized by a few large pine trees and many small spruces. Scots pine could benefit from the mixture at low proportions, while Norway spruce is harmed (Aldea et al., 2021; Ruiz-Peinado et al., 2021). Scots pine may benefit from mixtures at early development stages since, as a light-demanding pioneer species, it occupies the dominant crown layers and grows faster (Huuskonen et al., 2021a). On the other hand, Norway spruce suffered from light competition due to canopy stratification, growing slower in mixtures than pure stands (Holmström et al., 2018; Mina et al., 2018). Despite a potential advantage of mixtures in terms of productivity (Ruiz-Peinado et al., 2021), both species could suffer from competition for light and water resources in mixed stands (Huuskonen et al., 2021a; Lutter et al., 2021). In this regard, the admixture of Scots pine with Norway spruce decreased basal area growth in a way that might not have been considered properly in the Motti model. However, the absence of a trend in the residual vs basal area percentage of the dominant species plot (Fig. 3F), makes it possible to compare simulations between different mixing proportions for Scots pine-Norway spruce mixtures.

Low growth values for Heureka in N. spruce-birch mixtures (Fig. 2A) and Motti simulations in S. pine-birch mixtures (Fig. 2E) could be a potential error source with underestimated predictions (Table 2) and thus, should be considered cautiously in future simulations. Such underestimation of growth values in Heureka simulations for N. spruce-birch mixed stands could be related to a high proportion of birch and low proportions of N. spruce in the mixture (Figures SM1 and SM2). Regardless of the regeneration method, abandoned areas and conventional management practices for regenerating coniferous forest are suitable for establishing N. spruce-birch mixed forest stands (Holmström et al., 2016; Lidman et al., 2021). Such mixed forest stands usually start as birch-dominated, with eventual successional or planted ingrowth of Norway spruce (Grönlund and Eliasson, 2019; Hynynen et al., 2010). The different growth pattern and shade tolerance of birch and Norway spruce would decrease the level of competition between these two species (Hynynen et al., 2010). Under these circumstances, the possibility of maintaining high stand density without a reduction of growth has been demonstrated (Lidman et al., 2021). Another possible cause of growth underestimates is a lower site index estimation from Heureka when Norway spruce is suppressed by birch at the pre-commercial thinning stage (Lidman et al., 2021). Growth underestimates of Motti simulations of S. pine-birch mixtures may be related to a high proportion of birch (Figures SM1 and SM3). Because both species are shade intolerant, the competition between pine and birch is stronger than that between birch and Norway spruce, being birch the fastest-growing canopy tree species in this region (Hynynen et al., 2010). A high proportion of birch in a mixed stand has been found to decrease the stand production compared with a conifer monoculture (Heräjärvi, 2001; Hynynen et al., 2011). However, fertile sites would favour higher birch proportions in mixtures and might compensate for the reduction in basal area growth for pine (Huuskonen et al., 2021a). Another hypothetical reason could be that such reductions were lessened by the birch nursery effect, helping to increase survival and growth of Scots pine in young stands, which is similar to Norway spruce in mixtures with birch (Tham, 1994). Since S. pine-birch mixtures could become more common due to regeneration failure of Scots pine plantations (mainly by browsing) (Ara, 2022), the use of the decision support systems to evaluate new observed growth measurements is foreseeable. In these circumstances, we recommend being cautious with Heureka and Motti's predictions for stands with high proportion of birch when mixed with Norway spruce and/or Scots pine at early stand development stages.

5. Conclusions

Due to the current interest in mixed stands, the evaluation of different silvicultural regimens via decision support system simulations is increasing to resolve the lack of clear forest management guidelines for mixtures. At this point, the evaluation of the existing growth models for mixed forest at short term is essential and one of the first steps to take. Here, we assessed the most commonly employed models included in Heureka and Motti using a large and updated database composed of well-replicated experimental research sites and monitoring data from mixed stands in Sweden and Finland. We corroborated that the tested models performed well at short temporal scale and for updated measurements of the studied mixtures regardless of the species proportion. Therefore, Heureka and Motti have been proved as a practical tool to be currently utilized for short-term forest growth simulation of mixed stands which will support forest owners and managers to promote a wider range of ecosystem services in northern forests in the future.

Data availability

The research data are confidential but available for scientific research on request to their corresponding owners SLU and LUKE for Swedish and Finnish inventory data respectively.

CRediT authorship contribution statement

Jorge Aldea: Data curation, Methodology, Formal analysis, Investigation, Writing – original draft. **Simone Bianchi:** Data curation, Methodology, Formal analysis, Investigation, Writing – review & editing. **Urban Nilsson:** Methodology, Investigation, Writing – review & editing. **Jari Hynynen:** Methodology, Investigation, Writing – review & editing. **Daesung Lee:** Investigation, Writing – review & editing. **Emma Holmström:** Conceptualization, Project administration, Funding acquisition, Writing – review & editing. **Saija Huuskonen:** Supervision, Conceptualization, Project administration, Funding acquisition, Writing – review & editing.

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 authors do not have permission to share data.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2022.120721.

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