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Taller and slenderer trees in Swedish forests according to data from the National Forest Inventory

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A R T I C L E I N F O

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A B S T R A C T

Changes over time in annual basal area growth and mean height for Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.) over the period, 1983–2020 were studied using sample tree data from temporary plots recorded in the Swedish National Forest Inventory. The annual basal area growth was derived from the last measured full ring on increment cores. Using 20 to 60-year-old dominant trees, the mean height and annual basal area growth were examined as functions of tree, stand and site conditions, and trends were assessed mainly using residual analyses over time. A significant increase in mean height at a given age was found for both species, but the annual basal area growth level remained stable over the 38-year period. Currently, at a given age of 50 annual rings at breast height, the mean heights of pines and spruces increased on average by 10.1% (i.e. ~2 m), compared to 50 year-old pines and spruces in the 1980s, and the increase was similar in the different regions. The results suggest that trees have become taller and slenderer in Swedish forests. Increasing tree height over time at a given age in Northern Europe has been documented in several reports and many causes have been suggested, such as changed forest management, increasing temperatures and nitrogen deposition. We suggest that elevated CO_2 in the air and improved water-use efficiency for the trees might also be strong drivers.

1. Introduction

Global efforts to mitigate climate change are focused on the reduction of greenhouse gas emissions into the atmosphere and on increasing the removal of carbon from the atmosphere (IPCC, 2014). Forests play a pivotal role as "natural climate solutions" as they sequester carbon dioxide (CO_2) through photosynthesis, and store it as biogenic carbon in biomass and soil (Pilli et al., 2015). Increasing forest growth has been recorded in Fennoscandia over the last 50 years (Högberg et al., 2021). The reasons for this increase are, however, unknown and it is important to follow the trend and try to understand its background in order to estimate its potential for future carbon balance.

The rate of tree growth can be influenced by management (e.g. soil scarification, genetic breeding, thinning, and fertilization) and by site amelioration through environmental changes (e.g. temperature, precipitation, CO_2 concentration and nitrogen deposition). Based on sample tree data from the Swedish National Forest Inventory (NFI), Elfving and Tegnhammar (1996) found increased trends for the main tree species in Sweden – Scots pine (*Pinus sylvestris)* and Norway spruce (*Picea abies)* – for both tree height and basal area growth in the period 1953–1992. The main reason was assumed to be changed forest management from selective cutting to clearcutting but also increased nitrogen deposition. Mensah et al. (2021) found a climate-related (temperature) height growth increase after the year 2000 in long-term experiments on those tree species. The development of the main climate factors in the period 1961–2018 is shown in Fig. 1.

However, in the latter study, site-specific variations in growth responses were observed, raising questions of how trees in a given region might respond to transient environmental factors, for instance, the drought conditions experienced during the summer of 2018 throughout continental Europe. One aim of the present study was to examine to what extent this increase in height and basal area growth has continued, as well as validate the reported growth trend seen in the experiments.

Identifying site-specific drivers that may affect tree growth is relevant for parameterizing regional growth models and for strategic forest management planning (Kahle et al., 2008; Rohner et al., 2018). The significance of growth drivers may vary depending on the species and the site-specific realization of the driver of concern (Rohner et al., 2018).

For the past four decades, the variation in annual growth has been of interest and most forest monitoring approaches have adopted

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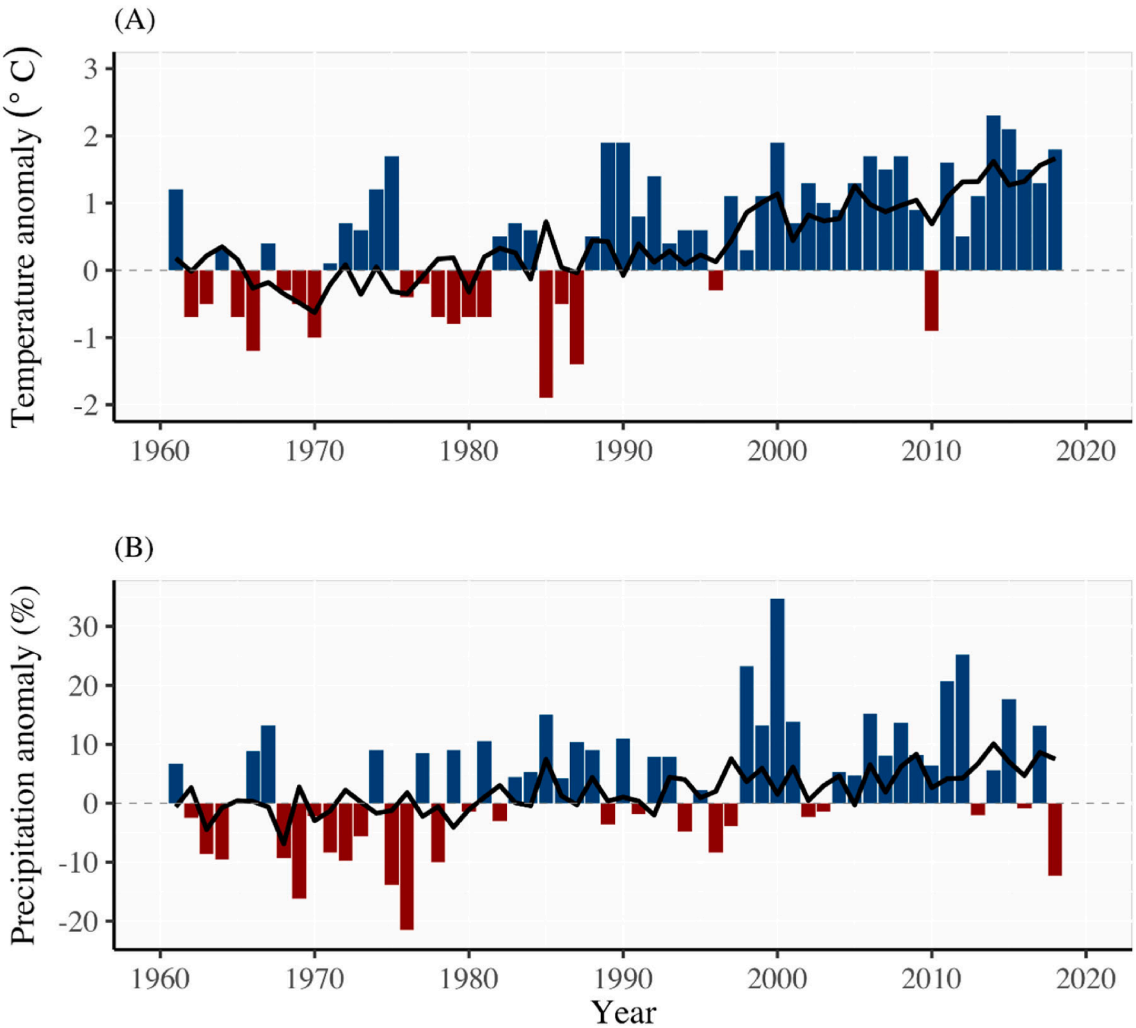

Fig. 1. Trend of annual mean temperature (A) and precipitation (B) in Sweden during the years 1961 – 2018 compared to the normal period (mean 1961 – 1990) (SMHI, 2018). The black line shows ensemble mean of the historic trend. The bars show historic data from observations (blue and red bars indicate higher and lower than normal, respectively).

dendrochronological methods to study the development of forests at national and regional scales (Schweingruber, 1988; Lebourgeois et al., 2005). Currently, most NFIs derive growth estimates for individual years based on radial increments from cores and other mensuration variables from a single survey (Tomppo et al., 2010). For instance, in Sweden, information from tree ring data is combined with tree caliper data to estimate the average volume growth over time for tree species, regions and the whole country (Svensson, 1988). Ols et al. (2021) also studied the recent radial growth trends of conifers in Western Europe using the French and Austrian NFIs. Tree ring chronologies, have thus become valuable growth data mostly because (1) environmental signals and management interventions can be linked to the year-to-year variations in the ring widths and (2) they represent a non-destructive source of deriving information (especially for conifers such as pine and spruce) on the inter-annual to inter-decadal changes in tree growth (Biondi, 1999; Mäkinen et al., 2002).

The extent and magnitude by which tree-ring widths capture inter-annual processes (either climatic or stand-driven) depend largely on the tree species and its surrounding environment (LeBlanc, 1990; Biondi, 1999). For a given species, the pattern of annual ring width variation is similar for neighbouring trees (hereafter, referred to as expressed population signal, EPS), even though the variations in different directions of the cross-sections of the stem can be quite large (Matérn, 1961; Mäkinen and Vanninen, 1999).

Despite increasing insights into growth processes and improvement in the spatial and temporal resolution of weather parameters, it has still been difficult to explain a larger proportion of the variance in ring widths. In Europe, the highest correlations between ring width and climate are mostly found with current summer temperatures in the north and precipitation in the south (Mäkinen et al., 2002). Other factors, such as fructification (Mund et al., 2010) and defoliation by pests and pathogens (Hoogesteger and Karlsson, 1992), can also explain some variations in ring width.

Stand-driven variations in ring width can, to some extent, be explained by variations in stand density and tree position in the stand. There are examples of trees grown in dense stands that increased their ring width by a factor of four over 3–5 years after release by thinning. This was observed for example, for pine and spruce in Sweden (Eklund, 1952) and white pine (*Pinus strobus*) in Canada (Bevilacqua et al., 2005). According to Jonsson (1995), this thinning response is independent of tree age and lasts 20–30 years for pine and spruce in Sweden. As shown by Eklund (1952), dominant and co-dominant trees are more sensitive to weather conditions than dominated and suppressed trees. For this reason, studies of EPS are often based on cores from dominating trees, especially when the main objective is to disentangle the influence of environmental signals rather than density-induced competition trends (Stern et al., 2021).

Most previous studies of inter-annual growth variation were based

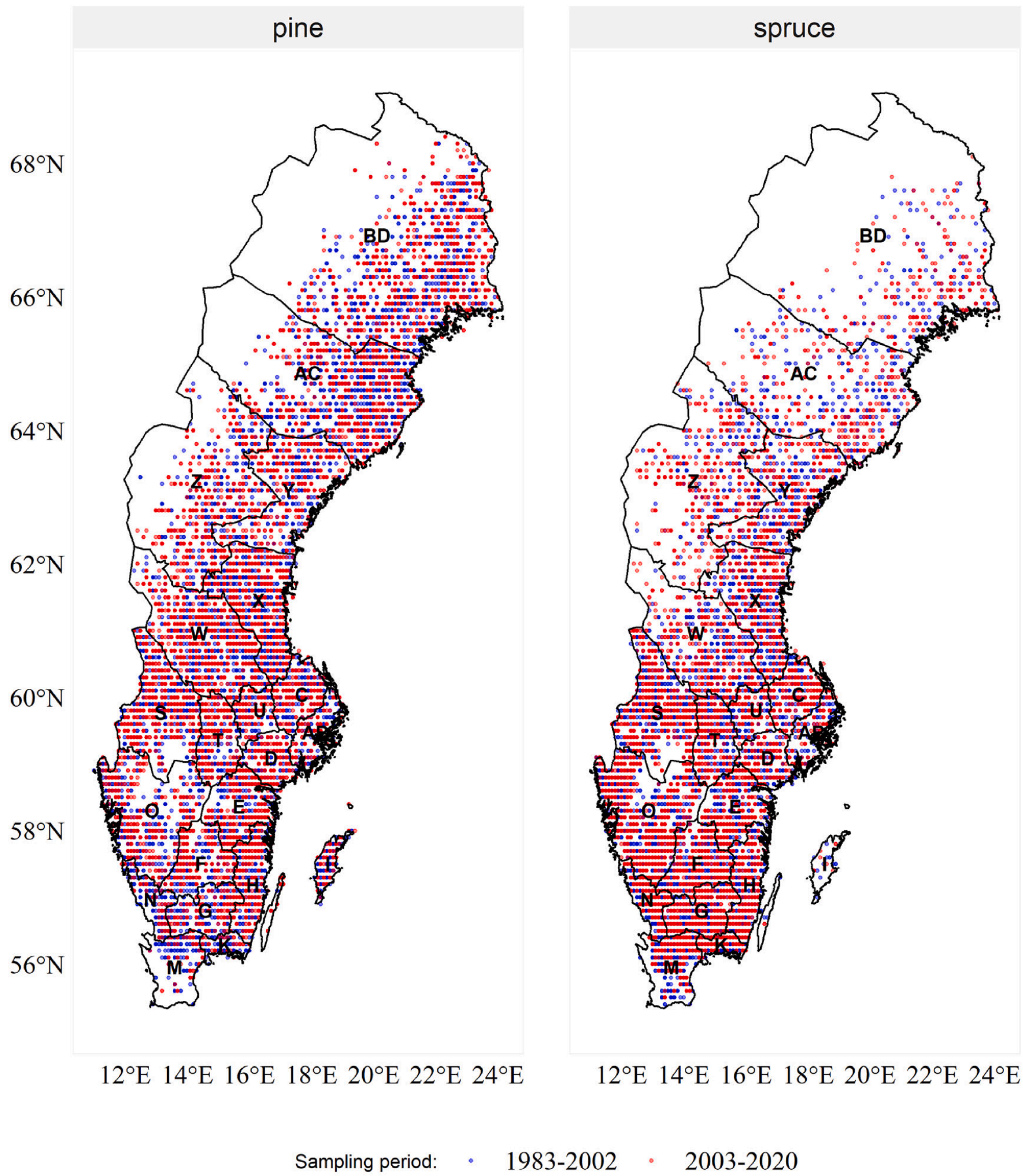

Fig. 2. Distribution of the tracts (grouped into the periods 1983–2002 and 2003–2020) used for the study. The letters describe the administrative codes of the regions (from north to south: Norrbotten – ***BD***; Västerbotten – ***AC***; Jämtland – ***Z***; Västernorrland – ***Y***; Gävleborg – ***X***; Dalarna – ***W***; Uppsala – ***C***; Västmanland – ***U***; Örebro – ***T***; Värmland – ***S***; Stockholm – ***AB***; Södermanland – ***D***; Östergötland – ***E***; Västra Götaland – ***O***; Jönköping – ***F***; Kalmar – ***H***; Gotland – ***I***; Kronoberg – ***G***; Halland – ***N***; Blekinge – ***K***; Skåne – ***M***).

Table 1
Datasets (dominating and co-dominating trees) used for the height and growth studies.

		Pine	Spruce
	N_{trees}	21,788	22,270
BAI (cm^2/year)	Minimum	0.14	0.09
	Mean	8.2	13.6
	Maximum	73.6	141.5
	Sd	5.7	11.4
	N_{trees}	21,788	22,270
Height (m)	Minimum	3.5	3.9
	Mean	14.4	17.4
	Maximum	31.9	34.5
	Sd	3.9	4.8

N_{trees}: number of sample trees; Sd: standard deviation.

on ring width series. Those series express the variation in relative terms. Ring widths generally show a progressive decline along a cross-sectional radius due to the increase in stem size and tree age over time (Biondi and Qeadan, 2008). Calibration of the ring width using tree diameter has several advantages: it (1) removes the biological trend, (2) enhances the formation of basal area growth series, and (3) allows meaningful growth comparisons in quantitative terms, for example, between tree species and geographical regions (Silva et al., 2010). By linking the basal area growth from cores with stand and environment conditions, it is possible to quantify growth trends and the inter-annual growth variation over time (Hornbeck et al., 1988).

The best data available in Sweden for this purpose are the measured tree ring widths on increment cores taken from several thousands of statistically representative sample trees each year on the NFI plots. The

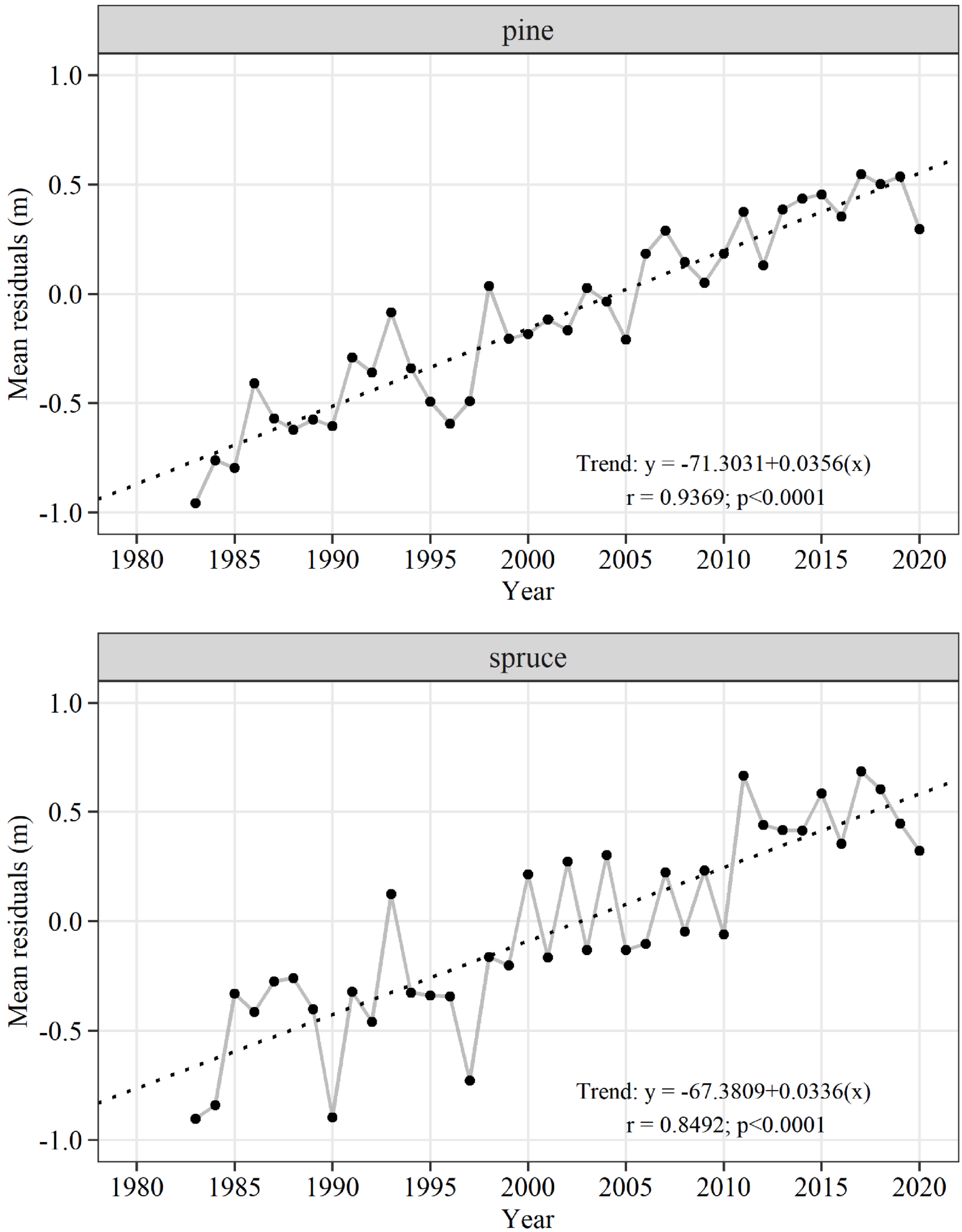

Fig. 3. Trends (dotted lines) in the mean height development of pine and spruce over the period 1983 – 2020. The mean residuals (m) denote the difference between the observed and the predicted height (Eq. (5)), averaged for each sampling year. The trend was specified by expressing the mean residuals as a linear function of the year of measurement.

Swedish NFI is a probabilistic survey design with well-spread samples across the entire country, a long time series (1923 to present) and covers large gradients of growth drivers. This guarantees an unbiased sample of the Swedish forest tree populations (Fridman et al., 2014). By examining comparable dominant trees sampled annually over a longer period, it is possible to evaluate growth trend changes.

The aim of this study was to give a retrospective view of the development over time, the mean height at given age and the annual basal area growth of trees with given diameter in Swedish forests, with a focus on pine and spruce. These species are dominant, constituting 80% (pine: 39%, spruce: 41%) of the total growing stock on productive forestland (Nilsson, 2021). We tested the null hypothesis that the mean height and the basal area growth of individual trees at comparable sites and stand conditions have not changed in the period 1983–2020. Specifically, we posed the following questions: (*i*) *trend in mean height development:* are trees, with a given age and growing under specified conditions, taller now than similar trees were 40 years ago? (*ii*) *trend in basal area growth*: are trees, with a given diameter and growing under specified conditions, growing faster now than similar trees did 40 years ago? To answer those questions, we used sample tree data (in the period 1983–2020) from the temporary plots of the Swedish NFI. Based on a modelling approach, the effects of tree and stand characteristics, such as stand density, site

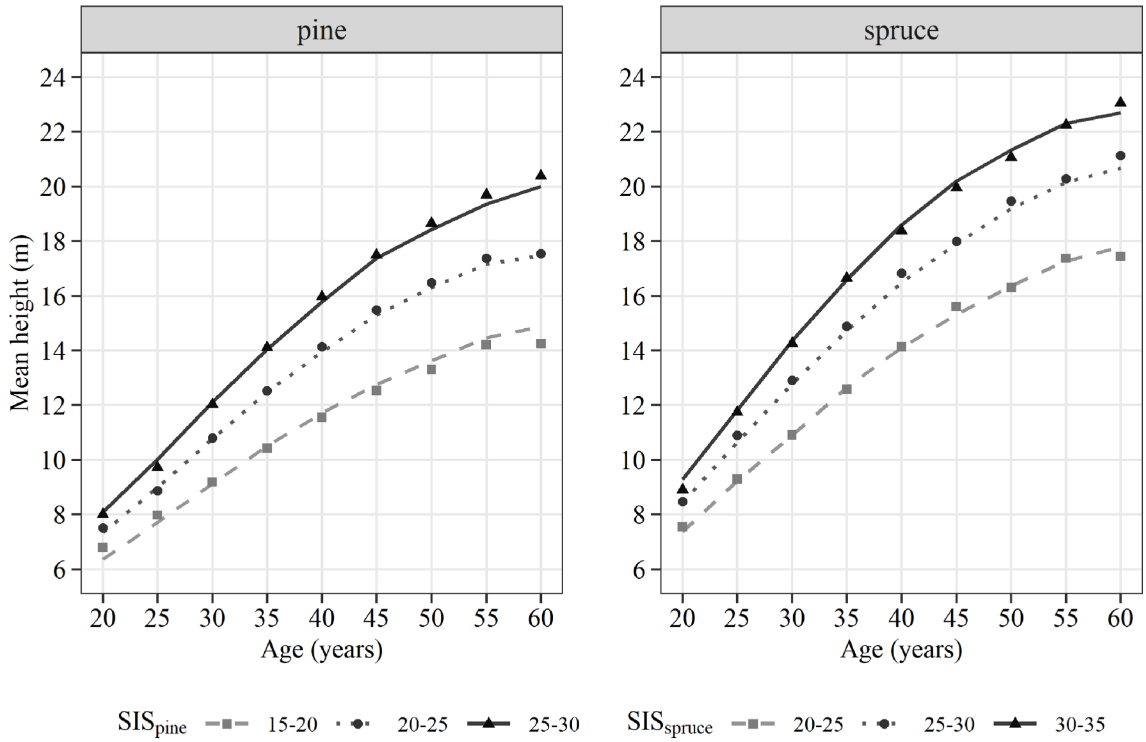

Fig. 4. Observed (dots) and calculated (lines) mean heights in different SIS and age classes.

Table 2
Parameter estimates for the tree-level height model (Eq. (6)).

	Pine			Spruce		
Parameter	Estimate	SE	SE_{rel} (%)	Estimate	SE	SE_{rel} (%)
b0	−119.6607	4.8570	−4.1	−112.6302	5.8728	−5.2
b1, SIS	0.9212	0.0157	1.7	0.8965	0.0156	1.7
b2,Age_{tot}	0.0335	0.0014	4.2	0.0334	0.0014	4.2
b3	1.6837	0.0566	3.4	1.6139	0.0541	3.4
b4,Th_{ind}	−0.2468	0.0209	−8.5	−0.1776	0.0152	−8.6
b5, SLH	2.5446	0.1447	5.7	2.8293	0.1799	6.4
b6, Year	0.0593	0.0022	3.7	0.0557	0.0029	5.2
$\widehat{V}(\varepsilon)$						
$\widehat{\omega}^2$	0.0007			0.0009		
$\widehat{\delta}_1$	0.9951			0.9945		
RMSE, m	2.0122			2.6356		
R^2 adjusted	0.7281			0.7012		
$RMSE_{rel}$,%	13.9736			15.1471		
n	21,788			22,270		

Variable definition: Age_{tot} is total age (in years), SE is the standard error of the estimate; SE_{rel} is the relative SE in percent; RMSE is the root mean squared error; n is number of observations for fitting the model.

productivity, soil type and management (e.g. thinning), on basal area growth and height development were accounted for and trends were investigated mainly by examining model residuals over time. Other effects relating to changing environmental conditions (e.g. temperature, precipitation, CO_2, nitrogen deposition), pests and diseases as well as changes in sample tree selection and measurement devices were not included in the modelling, but their potential effects were discussed.

2. Material and methods

2.1. Swedish NFI: design, sample trees, stand and site variables

Since 1923, the development of Swedish forests has been followed by the NFI through annual measurements on temporary and permanent plots. The Swedish NFI is a probability sample with a systematic cluster sampling design, covering large gradients in management and climatic conditions. Depending on the geographical location, the clusters (also called tracts) may consist of 4–12 circular sample plots located along the sides of a square, the side of which ranges between 400 and 1800 m. In southern Sweden, the tracts are smaller and the sampling intensity is higher than in the northern part of the country. Between 1953, when the system with tracts was introduced, and 1982, all tracts were temporary. Since 1983, the NFI has used an interpenetrating system where a set of both temporary and permanent tracts (about 6000 plots; 3500 permanent and 2500 temporary plots) are measured annually. Since 2017, temporary plots have been established using balanced sampling (Grafström et al., 2017). The permanent plots have an inventory cycle of 5 years. The circular sample plots have an area of 314 m^2 (radius of 10 m) on the permanent tracts and 154 m^2 (radius of 7 m) on the temporary tracts.

On all plots, a large number of variables concerning the administration (e.g. ownership), site (e.g. latitude, altitude, site productivity), stand and tree variables are recorded. Site productivity is determined by Site Index according to Site factors (SIS) (Hägglund and Lundmark, 1977). Site index is routinely calculated at the NFI and is an important prerequisite for our analysis. It is based on primary site variables such as climate (average temperature sum during the growing season in the period 1961–1976), soil depth, texture and moisture, and field vegetation type. SIS values are estimated for pine and spruce with different functions. Sites are classified as pine sites or spruce sites according to dominant species or to the species with the highest SIS value. Repeated estimations of SIS on the same plots have shown a measurement error of about 2 m for this variable, and no bias (Fridman et al., 2019). Among the stand variables (on ~ 20 m radius plot), stand closure (an indicator

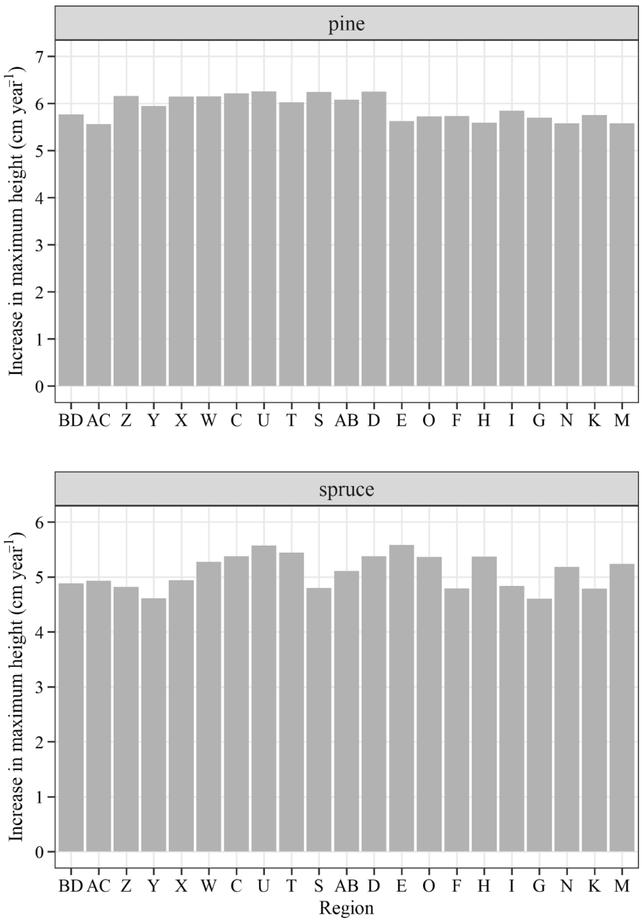

Fig. 5. Estimated slope coefficient of the variable sampling year (Eq. (6)), expressing the measure by which trees have increased their maximum heights per year in a region. Note: regions are ordered from north to south of Sweden (see Fig. 2 for the definition of codes).

Table 3
Parameter estimates for the stand mean height model.

Parameter	Estimate	SE	SE_{rel} (%)
Year	0.0644	0.0019	2.9
Th_{ind}	1.1136	0.0499	4.5
Tsum	15.082	0.9125	6.1
$(Tsum)^2$	−5.656	0.3988	−7.1
G_{sis}	−0.1108	0.0117	−10.6
G_{spr}	2.6299	0.2625	10.0
SIS^2	0.0043	0.0009	19.6
SIS	0.3485	0.0372	10.7
Stand age	0.1837	0.0036	2.0
b0 (intercept)	−14.988	0.5042	−3.4

Variable definition: Year refers to the year of inventory; Th_{ind} is a dummy variable of thinned (1, 5 – 15 years before measurement) and unthinned (0) plots; Tsum refers to temperature sum (rescaled by division with 1000); other variables are already defined (see Table 4).

of stand density), basal area measured by relascope sampling, basal area weighted mean height, tree species composition, and the type and time of forest management activities are all of interest in this study. All trees within the plot with a diameter greater than, or equal to, 40 mm are calipered at breast height (dbh, 1.3 m above ground) in the direction to the plot centre and a set of sample trees is selected with probability proportional to their basal areas at breast height. For each sample tree, tree species and tree class are registered and total tree height is measured.

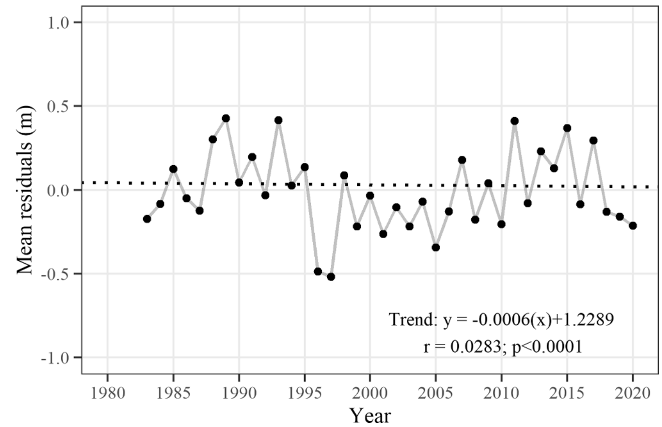

Fig. 6. Residuals from the stand mean height model (see Table 3).

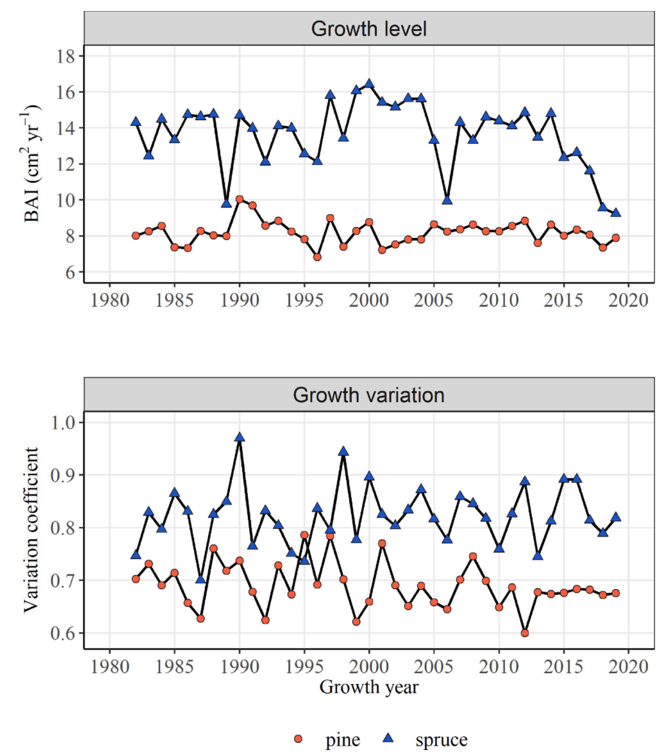

Fig. 7. Observed mean annual basal area increment (BAI, upper panel) and corresponding inter-annual growth variation (expressed as variation coefficient i.e. the ratio of standard deviation to the mean BAI, lower panel) of pine and spruce in the period 1983 – 2020.

On temporary plots, an increment core at breast height to the pith is taken from each sample tree in the direction towards the plot centre for later determination of tree age and annual ring width using a modified Eklund instrument (Eklund, 1949). Broken cores with suspected missing rings, and with disturbances such as rot or branch wood, are discarded (on average about 12% of the cores). In cores missing the pith, the number of missing rings is estimated in order to register the total age at breast height. Only up to the last 60 full rings are measured. An extensive account of the history of, and changes to, the Swedish NFI design is given in Fridman et al. (2014).

2.2. Basal area growth and mean height estimation

Our study was restricted to sample tree data of pine and spruce from undivided temporary plots on productive forestlands (where yield ca-

Table 4
Parameter estimates for the basal area growth function (Eq. (4)).

Parameter	Pine			Spruce		
	Estimate	SE	SE_{rel} (%)	Estimate	SE	SE_{rel} (%)
Intercept	0.8019	0.0633	7.9	1.1648	0.1054	9.1
dbh	0.0221	0.0013	5.9	0.0217	0.0011	5.1
1/dbh	−11.7961	0.4163	−3.5	−14.4672	0.4449	−3.1
SIS	0.0431	0.0012	2.8	0.0439	0.0032	7.3
SLH^2				0.7136	0.1002	14.0
SLH	−0.2515	0.0207	−8.2	−1.1148	0.1462	−13.1
Th_{ind}	0.0480	0.0094	19.6	−0.0464	0.0091	−19.6
treeclass	−0.1583	0.0076	−4.8	−0.1737	0.0085	−4.9
G_{spr}	0.5379	0.0528	9.8	0.1453	0.0737	50.7
G_{sis}	−0.0222	0.0021	−9.5	−0.0068	0.0032	−47.1
CR	1.6125	0.0288	1.8	1.4266	0.0307	2.2
RMSE	0.5022			0.5669		
R^2 adjusted	0.4944			0.5225		
$RMSE_{rel}$,%	26.718			24.647		
n	21,788			22,270		

Variable definition: G_{sis} is the product of G_{spr} and *SIS*, n is the number of observations used for fitting the models. The dependent variable (BAI) is expressed in logarithmic form.

pacity is ≥ 1 m^3 ha^{-1} $year^{-1}$) with a basal area-weighted mean height above 7 m and inventoried in the period 1983–2020 (Fig. 2). Only dominant and co-dominant trees (21788 pines and 22,270 spruces) within the age groups (at breast height) 20 to 60 years were included (Table 1). The upper age limit was chosen to avoid lower representation of fertile sites due to shorter rotations. The shortest legal rotation period on fertile sites is around 60 years (Swedish Forest Agency, 2022). The lower age limit was chosen to avoid exclusion of stands that had not reached a mean height above 7 m. From the calipered dbh on bark at the time of the inventory, the dbh under bark (DUB, cm) was calculated by subtracting the double bark thickness. To find the DUB before growth, we subtracted the double ring width (DI), so the basal area increment (BAI, cm^2) was calculated according to Eq. (1).

$$\mathrm{BAI} = \left(\mathrm{DUB}^2 - (\mathrm{DUB} - \mathrm{DI})^2\right) \times \frac{\pi}{4} \tag{1}$$

Bark thickness was estimated using the available functions for each species (Söderberg, 1992). Using the last measured full ring means that the growth associated with the inventory year of 2020 refers to the growth year 2019. The annual ring for the inventory year was excluded since the inventory is carried out during the growing season.

2.3. Statistical analysis of mean height development and basal area growth trends

For examination of the changes over time in mean height at a given age, tree height as a nonlinear function of age was modelled from two components: an asymptote and a shape over age describing how the asymptote is reached. The model was based on the 3-parameter Chapman-Richard's function (Eq. (2)):

$$h = a\left(1 - e^{-bt}\right)^c + \varepsilon \tag{2}$$

where *h* is the response variable, height (m) describes the change in size with time *t* (total age, years); parameter *a* is the asymptote (i.e. the expected maximum height as *t* approaches infinity), *b* is related to the growth rate, *c* is related to the location of the inflection point and *ε* is an error term. The total age was estimated by adding time to reach breast height (Eq. (B.1), Appendix B) according to Elfving (2010). Based on Eq. (2), we focused on two main measures: the mean heights at a given age and year, and the change of the theoretical asymptote over time. Therefore, the asymptote, rate and shape parameters of the height-age model (Eq. (2)) were adjusted further by including variables describing the effects of stand density, site productivity, soil type and management. Stand density was expressed by stand closure (SLH, estimated from basal area and mean height, with values 0–1.1). Site productivity was described by site index according to site factors (SIS, m). Soil type was a dummy variable for peat ($Peat_{ind}$). Management (Th_{ind}) referred to plots thinned 6–25 years before the measurement. The variance of the error term was modelled using a power model (Eq. (3)) with two parameters (scale and shape, denoted as ω^2 and δ_1, respectively) to ensure residual homoscedasticity over predicted height ($\hat{h}$, from Eq. (2)) and the other independent variables.

$$\hat{V}(\varepsilon) = \omega^2 |\hat{h}|^{2\delta_1} \tag{3}$$

To determine a potential trend in the development of mean height over time, the following steps were carried out. First, the residual ($h - \hat{h}$) computed as the difference between the observed (*h*) and the predicted ($\hat{h}$) height was averaged for each sampling year. Second, the mean residuals (from step one) were expressed as a linear function of the year of measurement. The significance and direction of the coefficient for the year gives an indication of any possible trend. Third, to estimate the magnitude of the trend, the asymptote (from Eq. (2)) was adjusted for the year of measurement. Thus, the coefficient for the year directly expressed the measure by which trees have increased their maximum heights during the observation period.

For the basal area growth, the function relating the annual basal area growth to a set of independent variables was expressed as:

$$\mathrm{BAI} = f\left(\mathrm{dbh},\ \text{tree class},\ \mathrm{SLH}, \mathrm{CR}, \mathrm{SIS}, \mathrm{Th_{ind}}, \mathrm{Peat_{ind}}, \mathrm{G_{spr}}\right) + \varepsilon \tag{4}$$

where *tree class* refers to the social position as either dominant or co-dominant, *CR* is the crown ratio (the ratio of crown length to tree height) and G_{spr} is an indicator for spruce sample trees in a typical pine stand. All other variables are already defined. The dependent variable (BAI) was expressed in logarithmic form in order to satisfy normality assumptions. Appropriate transformations of the other numerical covariates were made to ensure residual homoscedasticity. The parameters of the function *f* were estimated using the general multiple linear regression with ordinary least squares. To determine a trend in the annual basal area growth for the period 1983–2020, the residuals of Eq. (4) were regressed on the growth year.

In a totally different approach, plots in stands with a total mean age of 40–60 years were selected, and mean height was modelled as a function of total mean age, SIS and the year of measurement. In total, 13,628 plots were included in this analysis.

All the statistical analyses were made separately in the R-environment (R Core Team, 2020). The significance of model parameters was tested at 5% alpha levels, with non-significant variables (*p* > *0.05*) being removed from the final height and basal area growth models.

3. Results

3.1. Trend for mean height development at the tree level

The preliminary height model to examine the changes in mean tree height at a given age of pines and spruces was of the form shown in Equation (5); the estimated model parameters are shown in Table A1 (Appendix A). Together, the functions explained 70% of the variance in height, with the model residuals not showing any apparent signs of heteroscedasticity.

$$h = [b_0 + b_1(\mathrm{SIS}) + b_5(\mathrm{SLH})] \times \left[1 - e^{(-b_2(Age_{tot}))}\right]^{b_3 + b_4(\mathrm{Th_{ind}})} \tag{5}$$

By examining the residuals of Equation (5) as a linear function of the year of measurement, a strong and significant positive (upward) trend was observed for both pine ($R^2 = 88\%$) and spruce ($R^2 = 72\%$) (Fig. 3). This indicated that at a given age, the mean heights of pines and spruces

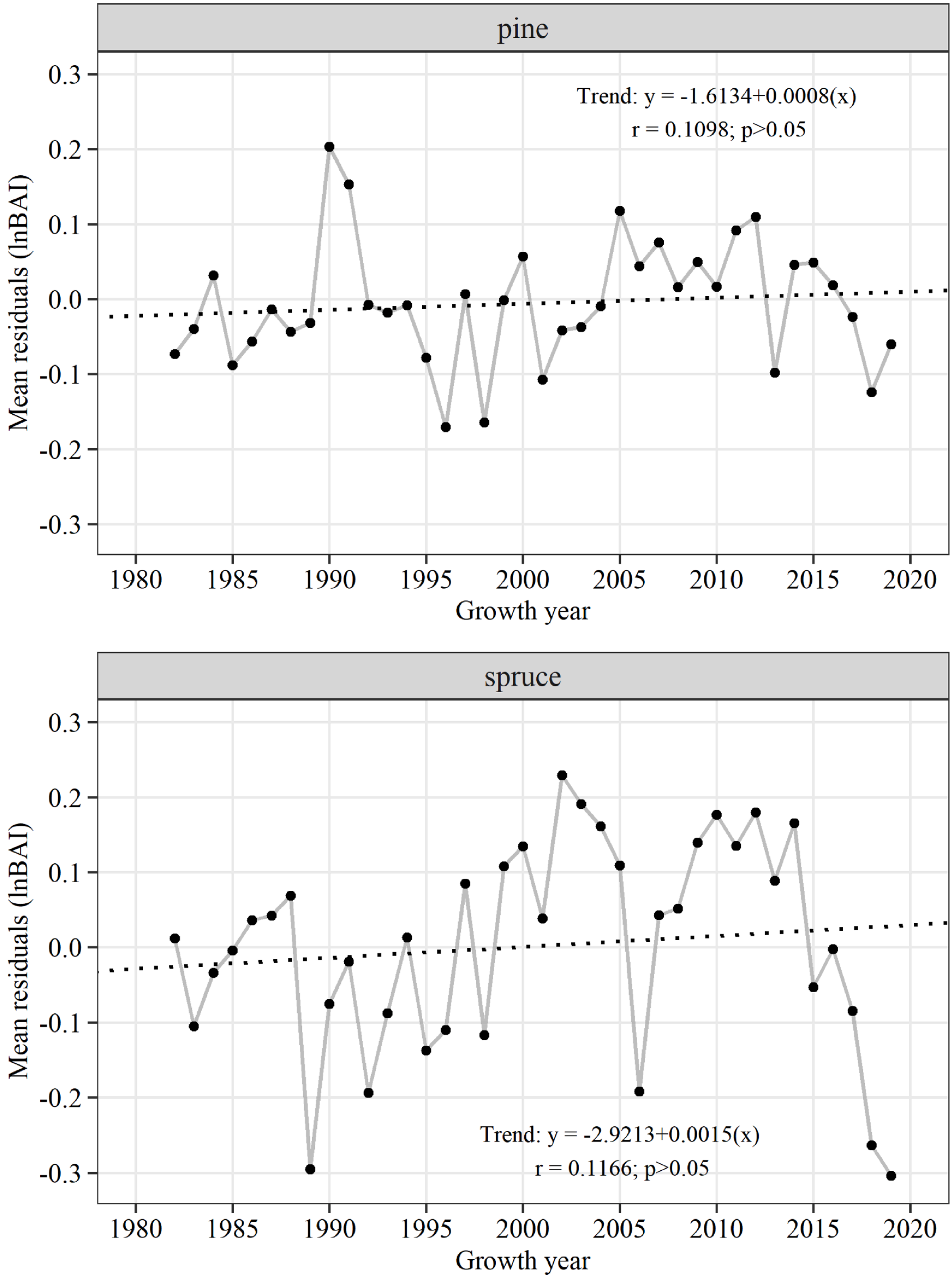

Fig. 8. Trends (dotted lines) of the annual basal area growth level for pine and spruce in the period 1983 – 2020.

have increased over the period 1983–2020. To estimate the magnitude of the increase in mean height over time, the asymptote of Equation (5) was modified with the year of measurement and the parameters were re-estimated for the model (Eq. (6)).

$$h = [b_0 + b_1(SIS) + b_5(SLH) + b_6(Year)] \times \left[1 - e^{(-b_2(Age_{tot}))}\right]^{b_3 + b_4(Th_{ind})} \quad (6)$$

The function showed good adaptation to the data (Fig. 4) and all parameters were significant (Table 2). Site index (SIS) and stand density (SLH) had positive effects, while that of thinning was negative. Together, the functions explained about 73% and 70% of the variance in height, respectively for pine and spruce. The residual variations around the mean height were about 14% for pine and 15% for spruce, the error variance was satisfactorily modelled by the power function and the residuals showed no systematic deviations (Fig. 1A, appendix). The coefficient of year (b_6) was significant and indicates that, over time, trees at a

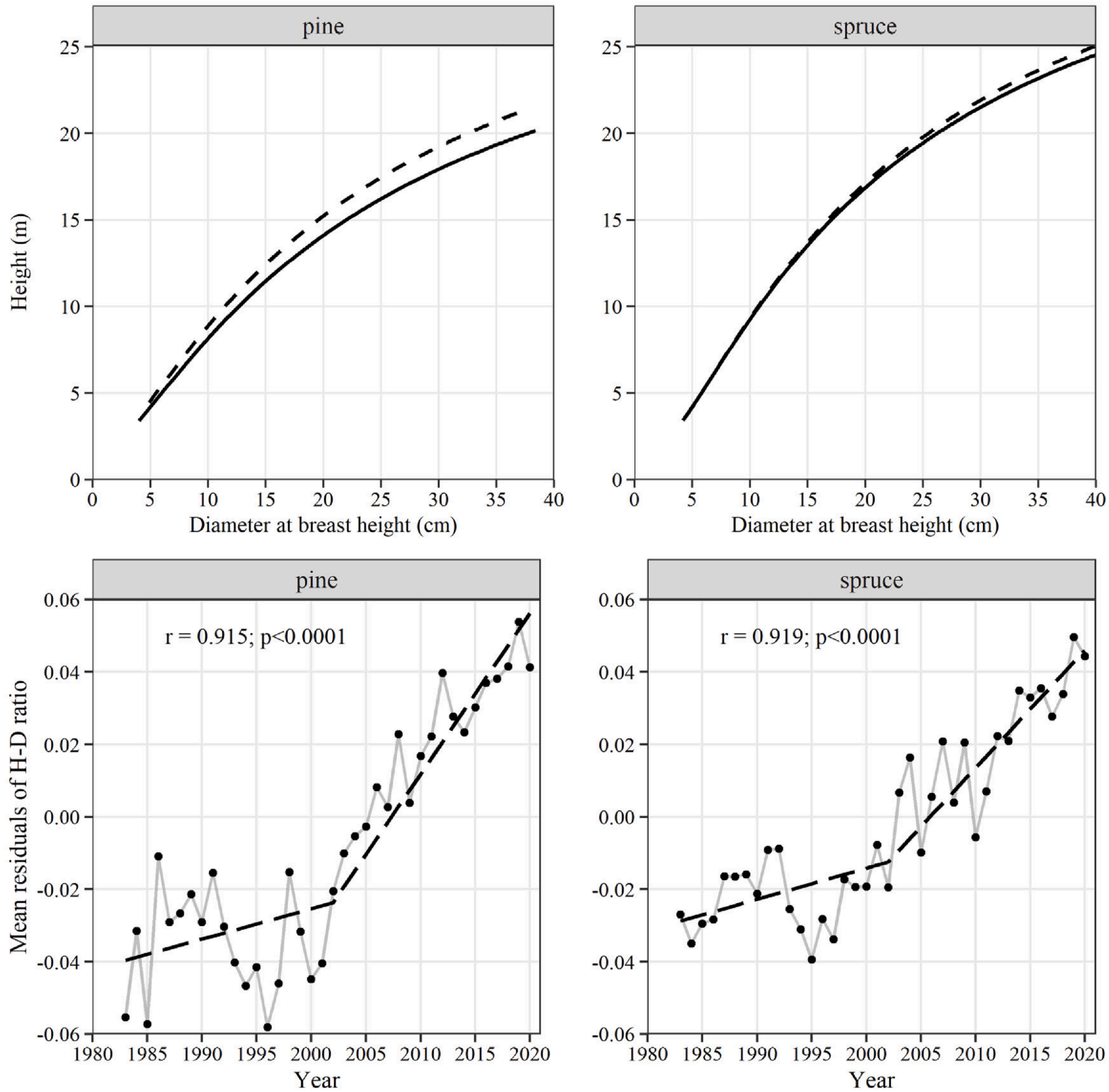

Fig. 9. Upper panel: height-diameter relationships for pine and spruce in the periods 1983 – 1987 (solid lines) and 2016 – 2020 (broken lines). Lower panel: Increased trend (dashed lines) of slenderness (H-D ratio) in the period 1983 – 2020. Note: the trend of slenderness was described by the linear (spline) function with a knot at 2002 as: $y = \beta_0 + \beta_1(x) + \beta_2 max(x - 2002, 0) + \varepsilon$, with the parameter estimates for pine ($\widehat{\beta}_0 = -1.697; \widehat{\beta}_1 = 0.001; \widehat{\beta}_2 = 0.004; \widehat{V}_{(\varepsilon)} = 0.013$) and for spruce ($\widehat{\beta}_0 = -1.731; \widehat{\beta}_1 = 0.001; \widehat{\beta}_2 = 0.002; \widehat{V}_{(\varepsilon)} = 0.010$).

given age and site index have increased maximum heights. In total, the maximum mean heights are estimated to have increased by about 2.25 m (0.0593 × 38) for pine and 2.12 m (0.0557 × 38) for spruce over the 38-year period. For both species, the trend was examined for the different regions and the increase in maximum mean height was similar (Fig. 5). According to the functions (Table 2), and with given average stand conditions (SIS = 22.5 m and SLH = 1), pines with 50 annual rings at breast height (total age is 59 years) had an average height of 16.54 m in 1983 and 18.25 m in 2020. The corresponding values for spruce were 16.39 m in 1983 and 18.01 m in 2020.

3.2. Trend for mean height development at the stand level

The result from the regression of mean height in the stands included in the dataset in the age class 40–59 years on relevant variables is given in Table 3. With 13,628 stands, the explained variance (R^2) in mean height was 70% and the residual error was 2.35 m. Residuals for this function are shown in Fig. 6. The coefficient for the trend was 0.0644. For stands with average conditions (age 50 at breast height, SIS = 22.5 m and Tsum = 1180), the estimated mean height was 16.13 m in 1983 and 18.51 m in 2020. The span was higher than was indicated by the tree-level height model (16.5 and 18.1 m in average for pine and spruce at age 50 years at breast height), but the estimated height was similar in the mid-point year (in 2002: 17.3 m at age 50 years at breast height). A similar analysis of the mean basal area development was made for the included stands. The trend in mean basal area development was not significant.

3.3. Trend for annual basal area growth at the tree level

The mean annual basal area growth level was 8.22 cm^2 for pine and 13.63 cm^2 for spruce, in the period 1983–2020 (Table 1). The corresponding variation in the inter-annual growth was about 0.69 for pine and 0.82 for spruce. For both species, longer and shorter periods of higher and lower growth in individual years were observed, with the growth patterns for the two species differing in the different regions (Figs. 7 and A2). Table 4 shows the final basal area growth function. The functions explained 49% and 52% of the growth variance in pine and spruce, respectively. Examining the model residuals over year revealed that, the annual basal area growth level of 20 to 60-year old dominant trees was stable over the last 38 years (Fig. 8).

The increased height but stable basal area growth level indicates an allometric growth condition suggesting that trees have become taller and slenderer. Slenderness, defined as the ratio of height to diameter (H-D ratio), was examined further using height-diameter relationships. The height-diameter relationship was primarily investigated for trees only in the periods 1983–1987 and 2016–2020, using the 2-parameter Näslund model (Eq. (A.1), Näslund 1947). The parameter estimates and goodness-of-fit statistics for the model are given in Table A2 (Appendix A). The variation in H-D ratio was studied as a linear function of tree age at breast height, SIS and stand density, and the trends in slenderness were studied by residual analyses over the year of inventory. The parameter estimates are given in Table A3. For a given diameter, trees in the period 1983–1987 were, on average, 1 m shorter than trees in the last 5 years (2016–2020), and the trend shows increasing slenderness over the 38-year period (Fig. 9).

4. Discussion

The results obtained supported the null hypothesis on basal area growth but not on the mean height development. The mean height of 20 to 60-year-old trees had changed over time, but the annual basal area growth level was stable in the period 1983–2020. According to Elfving and Tegnhammar (1996), the mean height of trees with 50 rings at breast height was 14.5 m in 1953 and 17.5 m in 1992. According to this study, the corresponding mean heights were 16.5 m in 1983 and 18.1 m in 2020. Those figures are the means for dominating and co-dominating sample trees of pine and spruce. Comparable data for stands at age 50 at breast height (in average for pine and spruce) had a higher range (16.1 m in 1983 and 18.5 m in 2020) than indicated by the tree-level model. However, in the midpoint year (year 2002), the estimated heights at 50 years (breast height age) by the tree-level and stand-level height models were similar (17.3 m). The difference in mean height estimates (at a given age) between the tree-level and stand-level height models may be the age addition to reach breast height when estimating the total age. Those values have probably decreased since the values applied at NFI were estimated (Appendix B). The reliability of the results and possible causes of the trend are discussed below.

4.1. Data and models

The Swedish NFI data form an ideal database for growth studies. Sweden is covered by closed stands of two dominant tree species between latitudes 55.4 and 68.4 °N and altitudes from sea level to the arctic tree line, 500–800 m above the sea level. Representative data on stands and trees have been gathered since 1923 with the methods of measurement being fixed for long periods. Still, there are important limitations to the results presented here. Those of the highest interest are related to a change of the method for sample tree selection in 2003 and successive changes of instruments for height measurement. Sample trees have always been selected in proportion to the trees' basal areas but, in the period 1983–2002 without accounting for their spatial distribution and, in the period 2003–2020, with 1–3 trees per plot (Fridman et al., 2014). A detailed study on the effects of the changed selection system is provided in Appendix C, but a summary is given here.

Before 2003, the probability of a plot being represented increased with the density and sizes of the trees on the plot. The number of sample trees per plot varied from zero to nine. This resulted in larger sample trees in the 1983–2002 data than in the 2003–2020 data (dbh 23.6 and 21.5 cm). There was also a larger difference in the distribution of trees in the classes of dominant and co-dominant trees, but the background to this difference is hard to explain. In the models, site productivity was registered by site index (SIS, m). The SIS was, on average, 22.8 and 22.1 m respectively, for the 1983–2002 and 2003–2020 data. There is also a possible shift in the classification of sites according to the most suitable tree species. For example, the proportion of plots that were classified as spruce sites was 54% in the 1983–2002 data and 47% in the 2003–2020 data.

When considering surveys, changes in the instruments for tree height measurements are possible sources of variation (Eriksson, 1970). Until 1970, the Tiréns altimeter was used, and in the period 1970–1995, the Suunto hypsometer. After that, the Haglöf-HEC electronic clinometer was used even though the Suunto was used to some extent on the sample plots from 2002 to 2007. Since 2008, the Haglöf-Vertex hypsometer has been used. The accuracy of the measured heights was higher for the Haglöf-Vertex hypsometer (upward bias by 2 cm) than for the Haglöf-HEC clinometer (upward bias by 20 cm) and the Suunto hypsometer (downward bias by 12 cm), in a controlled examination by the Swedish NFI (Fridman et al., 2019).

In our estimation of the annual basal area growth (BAI), we only pulled off the bark (using dbh at the time of the inventory) to obtain the diameter below bark at the end of the last growth period. Since the inventory is carried out during the growing season, the last incomplete growth ring should also had been subtracted. Previously, the incomplete growth was not measured but, currently, the core is measured continuously from the bark boundary and inwards, and the ring boundaries are marked. This implies that the width of the latest, incomplete ring is also registered. A rough estimation indicates that the effect of ignoring the ring under development is an overestimation of BAI of about 0.7%, and we judge that this has little influence on the results.

In a similar fashion, the magnitude of the increased mean height may be underestimated, for example, in the southern parts of Sweden. The inventory usually begins in southern Sweden in early May and ends in the northern parts during September. During the inventory, total tree height is measured to the tip of the crown, and height growth in the growing season is mostly completed by early July. This implies a loss in part of the height increment in southern Sweden, but not in the northern parts of the country. Despite this limitation, the magnitude of the increase in the maximum mean height over time (from the asymptote of the height model, Eq. (6)) was similar in all regions for both species (Fig. 5).

4.2. Interpretation of the trends

As is the case with much survey data, it is difficult to isolate the causes of changes in forest growth trends. Here, the trends are discussed with reference to changes in forest management and environmental conditions in Sweden. Forest management affects growth trends largely through silvicultural practices, for example, changes in harvesting systems and precision silviculture with improved site preparation, nitrogen fertilization, stand density regulation and planting with improved genetic materials (Kahle et al., 2008). In the period 1953–1992, an increase in both basal area growth and mean height was observed in Swedish forests, and the major contributing factors were attributed to the shift from selective cutting and thinning from above to clear-felling, cleaning and thinning from below (Elfving and Tegnhammar, 1996). Similarly, Henttonen et al. (2017) also found largely a silviculture-induced (67%) growth increase in Finnish forests in the period 1971–2010.

In this study, the results obtained indicate that the increase in mean tree height at a given age (Fig. 3; Tables 2 and 3) has continued to present day in Swedish forests and corroborates well with the reported increase from the Swedish long-term experiments (Mensah et al., 2021) as well as in other forest regions (Sharma et al., 2012; Kauppi et al., 2014; Socha et al., 2021). However, the stable level of the basal area growth (Fig. 8) may imply that a peak growth was reached around 1992. This effect is probably not due to increasing stand density in the latter years. The mean basal area was about the same in the period 1983–2002 as in the period 2003–2020 (see Appendix C). Still, in the period 1950–1970, nearly 1 million hectares of productive forests were thinned (tending and commercial thinning) annually in Sweden. Currently, the total thinned area has decreased to about 0.4 million hectares. Increasing stand density generally has little influence on the height growth (especially for dominant trees) but the basal area growth of single trees is greatly reduced (Assmann, 1970).

Variations in environmental conditions over time may strongly influence tree growth rates. The rising summer temperatures are mainly due to an increasing level of atmospheric CO_2. Temperature sum is also a very strong variable in the determination of SIS. However, the stable level for basal area growth surprised us and posed the question as to whether the increased CO_2 level itself has a direct impact on the height growth. The tallest trees are often found in humid climates. Givnish et al. (2014) studied Eucalyptus in Australia over a humidity gradient and found that tree heights decreased from 60 to 10 m from the humid to the dry sites. The water-use efficiency means the balance between carbon intake and water loss through the leaf stomata and seems to have a strong impact on the height growth of trees. Increasing atmospheric CO_2 levels means that the stomata can take in required carbon faster with a smaller loss of water (Keenan et al., 2013).

Swedish forest soils are nitrogen deficient, and it is expected that increases in nitrogen deposition would improve tree growth (Etzold et al., 2020). However, the atmospheric deposition of nitrogen in Sweden decreased by 30% during the period 1983–2013 (Andersson et al., 2018), suggesting a marginal effect of nitrogen deposition on forest growth changes in Sweden.

These factors aside, forest growth changes can also be attributed to complex cosmoclimatologic processes such as incidence of solar radiation and galactic cosmic rays (Bontemps and Svensmark, 2022). Direct solar radiation has been found to be less efficient for terrestrial photosynthesis and productivity, compared to diffuse light which has better light penetration in forest canopies (Urban et al., 2007). Over the second half of the 20th century, the release of anthropogenic aerosol to the atmosphere has been excessive, thereby resulting in increased fraction of diffuse radiation and cloud cover. This has been reported to be a major driver of the global increase in terrestrial vegetation carbon sink (Mercado et al., 2009).

It is important to point out that, it is unclear for how long the mean heights at a given age of pines and spruces will continue to increase, or will there be a change in the annual basal area growth level in Swedish forests, especially, with a changing climate and management. In this study, the effects of warming climate, elevated CO_2, pests and diseases, storms and fires were not accounted for in the models, but the residuals from Figs. 3, 6 and 8 provide valuable information about the combined effects of the latter on growth (Girardin et al., 2014; Belyazid and Giuliana, 2019; Forzieri et al., 2021). For instance, a decline in the mean height and basal area growth was seen in the period 2015–2020 for both species (Figs. 3, 6 and 8). This period also coincides with pronounced heatwaves and droughts, and outbreak levels of the spruce bark beetle in Sweden. It is therefore recommended that, future research should address the interactive effects of abiotic and biotic factors on growth changes in Swedish forests.

5. Conclusion

The objective of this study was to give a retrospective view of the development over time of mean height and annual basal area growth in Swedish forests. The study was made of two of the most important tree species in Sweden, Scots pine and Norway spruce, using temporary sample plot data from the Swedish NFI for the period 1983–2020. The asymptote (based on the height model, Eq. (6)) for mean height of pines and spruces at a given age has increased over time. The increase is on average 2.2 m over the 38-year period in both species. At a given age of 50 annual rings at breast height, the mean heights of pines and spruces currently have increased on average by 10.1%, compared to 50 year-old pines and spruces in 1983. However, the annual basal area growth level was stable, despite large inter-annual variability. Many factors may have contributed to the increase in tree height, but we postulate that elevated CO_2 and forest water-use efficiency may be strong drivers. Overall, the results suggested that current trees are becoming taller and slenderer. The use of top height as an indicator of site productivity may not be valid anymore, and site curves must be revised and include a time factor that mirrors the ongoing transition of the growing conditions.

CRediT authorship contribution statement

Alex Appiah Mensah: Conceptualization, Methodology, Data curation, Formal analysis, Writing – original draft, Writing – review & editing. **Hans Petersson:** Writing – review & editing, Funding acquisition, Supervision. **Jonas Dahlgren:** Data curation, Writing – review & editing. **Björn Elfving:** Conceptualization, Methodology, Data curation, Formal analysis, Writing – review & editing, Supervision.

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

Data will be made available on request.

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Appendix A

See Tables A1-A3

Näslund's height-diameter function:

$$h = 1.3 + \frac{dbh^{\gamma}}{(\alpha_0 + \alpha_1 \times dbh)^{\gamma}} \tag{A.1}$$

where h is tree height in m, dbh is diameter at breast height in cm, α_0 (shape) and α_1 (slope) are parameters to be estimated from the data and γ has a value of 2 for pine and 3 for spruce.

Table A1
Parameter estimates for the mean tree height model without year (Eq. (5)).

Parameter	Pine			Spruce		
	Estimate	SE	SE_{rel} (%)	Estimate	SE	SE_{rel} (%)
b0	−1.0368	0.1528	−14.7	−1.2387	0.1669	−13.5
b1, SIS	0.9701	0.0208	2.1	0.9104	0.0164	1.8
b2, Age_{tot}	0.0301	0.0015	4.9	0.0333	0.0015	4.5
b3	1.5629	0.0568	3.6	1.6317	0.0575	3.5
b4, Th_{ind}	−0.2855	0.0261	−9.1	−0.2234	0.0196	−8.8
b5, SLH	2.6061	0.1489	5.7	2.7519	0.1734	6.3
$V(\varepsilon)$						
ω^2	0.0238			0.0388		
δ_1	1.9715			1.7247		
RMSE, m	2.0584			2.6682		
R^2 adjusted	0.7159			0.6944		
$RMSE_{rel}$,%	14.2944			15.3345		
n	21,788			22,270		

SIS is site index according to site factors, Th_{ind} is a dummy variable for thinned (1) and unthinned stands (0), Age_{tot} is total age (in years), SLH is stand closure (scale 0–1).

Table A2
Parameter estimates (±SE) for the Näslund height-diameter function (Eq. (A.1)) using sample tree data measured in the periods 1983–1987 and 2016–2020.

Species	Period	n	$\widehat{\alpha_0}$(±SE)	$\widehat{\alpha_1}$(±SE)	RMSE (m)
Scots pine	1983–1987	1630	2.056 ± 0.039	0.177 ± 0.002	2.068
	2016–2020	3276	1.869 ± 0.029	0.175 ± 0.002	2.042
Norway spruce	1983–1987	2413	2.009 ± 0.023	0.300 ± 0.001	2.056
	2016–2020	2786	2.023 ± 0.025	0.297 ± 0.001	2.110

Table A3
Parameter estimates of height-diameter ratio as a linear function of age, site index and stand density.

Parameter	Pine			Spruce		
	Estimate	SE	SE_{rel} (%)	Estimate	SE	SE_{rel} (%)
b0 (intercept)	0.3410	0.0122	3.6	0.4459	0.0118	2.6
Age	0.0014	0.00012	8.6	−0.00035	0.00001	−2.9
SIS	0.0038	0.00031	8.2	0.0025	0.0003	12
Tree class	0.0081	0.00023	2.8	0.1012	0.0021	2.1
Altitude	−0.00009	0.000008	−8.8	−0.00071	0.0001	−14.1
SLH	0.1513	0.0064	4.2	0.1522	0.0059	3.9
R^2 adjusted	0.152			0.184		

Appendix B:

Function for the estimation of time to reach breast height based on Elfving (2010)

At the Swedish NFI, the determination of stand age is generally based on the counting of year rings on increment cores taken at breast height from basal area mean trees. To compute total stand age, a value for "time to reach breast height" is added. This value ($T_{1.3}$, years) depends on species, site index according to site factors (SIS, m) and latitude (LAT, ^{o} N). The function is given as:

$$T_{1.3} = 37 - 0.605 \bullet (\text{LAT}) - \frac{1121}{\text{SIS}} + 21.92 \bullet \left(\frac{\text{LAT}}{\text{SIS}}\right) + 29.5 \bullet \left(\frac{\text{SPRUCE}}{\text{SIS}}\right) \tag{B.1}$$

The variable SPRUCE is an indicator where a value of 1 means a spruce dominated stand or otherwise a pine stand (0).
See Figs. A1 and A2

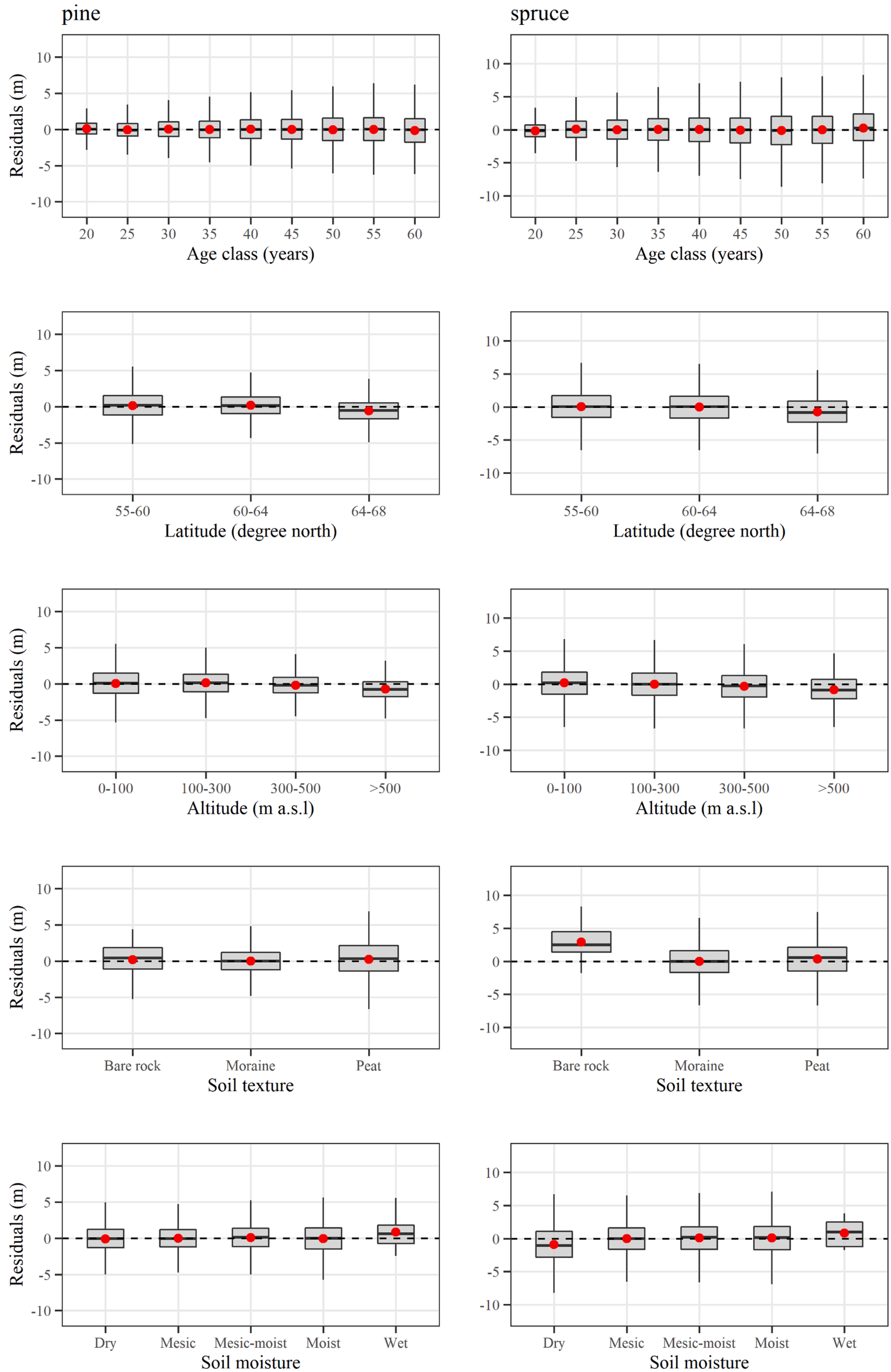

Fig. A1. Distribution of model residuals (Eq. (6)) over site conditions.

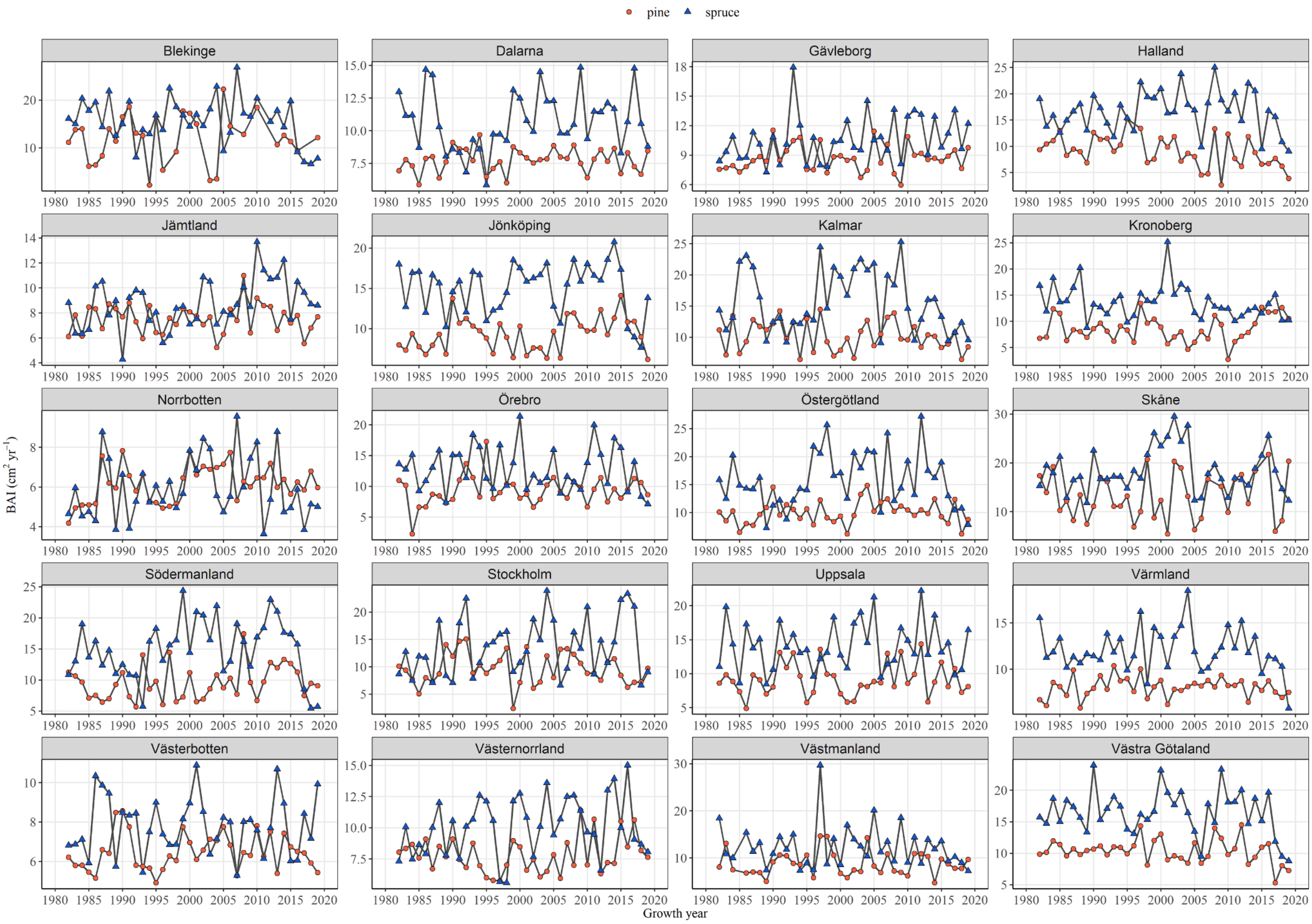

Fig. A2. Observed basal area increment (BAI) levels of pine and spruce in the period 1983 – 2020 in different regions.

Appendix C:

Comparison of cored sample trees from the periods 1983–2002 and 2003–2020 in the National forest inventory

The Swedish National Forest Inventory (NFI) is carried out as an annual countrywide sampling of both permanent and temporary circle plots (Fridman et al., 2014). The plots are located in systematically dispersed tracts with the sampling density roughly proportional to the productivity, which means higher density in the south than in the north. Permanent and temporary plots are located in separate tracts. The distribution net for temporary tracts changes between years.

The permanent plots have a radius of 10 m, were established in the period 1983–1987, and comprised about 16,000 plots on productive forestland. They are normally re-measured at an interval of 5 years with slightly more than 3000 per year. Single trees are identified by polar coordinates. All trees with dbh > 10 cm are calipered and heights are measured on representative sample trees. No bore cores are taken from those trees.

The temporary plots have a radius of 7 m. All trees with dbh > 4 cm are calipered and sample trees are randomly selected in proportion to tree basal area. Bore cores are taken from those sample trees and tree age is determined by counting the tree rings. The widths of up to 60 last rings are also measured. In the period 1983–2002, the sample trees were selected without accounting for their spatial distribution and, in the period 2003–2020, with 1–3 trees per plot, depending on plot basal area. This difference in the system for sample tree selection causes differences in which plots are represented, and how many trees can be selected per plot. In studies of trends for the forests' development over time, this change of the system for sample tree selection can cause some difficulties and the aim of this comparison of the datasets 8302 and 0320 is to facilitate interpretations in trend studies. The comparison is restricted to undivided plots on productive forestland with a basal area weighted mean height above 7 m. Only plots with sample trees of conifers are represented. The estimation of mean height is based on height measurements of trees judged to represent basal area weighted mean diameter trees within a radius of 20 m from the plot centre. Also, stand age and stand basal area are judged for this larger area. For estimation of the stand basal area, the measurements on the net plot are complemented with relascope measurements from two points outside the net plot.

The 8302 data consists of 83,496 trees on 43,351 plots while the 0320 data consist of 58,807 trees on 25,287 plots (Tables C1 and C2). The average number of measured trees per plot was 1.93 and 2.33 in the two periods and the number of included plots per year was 2168 and 1405, respectively. In all examined mean parameters, the values were higher in the 8302 data than in the 0320 data. The basal area was, on average, 22.8 m^2/ha in the period 1983–2002 and 22.5 m^2/ha in the period 2003–2020. The corresponding values for mean height were 16.8 and 16.5 m. Those figures indicate decreased growth in the observed period, probably due to the decreased mean age, from 81 to 77 years. In addition, a slightly more southern location of the 8302 plots can explain the differences in basal areas and mean heights (Tsum was, on average, 1129 and 1090, respectively). On the other hand, a recent thinning was assigned to a larger part of the 8302 plots than for the 0320 plots (23 and 16%). Site indices were 22.8 and 22.1 m. This

Table C1
Plot data for the periods 1983–2002 (8302) and 2003–2020 (0320).

Dataset	8302	0320
Total number of plots	43,351	25,287
% with assigned treatments	51.7	47.9
% thinned 5–15 years before	22.9	16.4
% spruce sites	54.4	47.1
SIS, m	22.81	22.13
Temperature sum, degree days	1129	1090
Basal area, m^2/ha	22.77	22.51
Mean height (basal area weighted), m	16.76	16.47
Mean age (total age)	81.3	77.0

Table C2
Tree data, distribution on tree classes. Total number of trees 8302 = 83496, 0320 = 58807.

Tree class/ data set	8302	0320	8302	0320	8302	0320	8302	0320
	% of trees		Mean dbh, mm		Mean height, dm		Mean age	
Free growing	0.3	0.1	278	276	164	170	75	83
Dominant	49.3	56.5	286	253	193	178	77	68
Co-dominant	32.5	26.2	209	185	160	147	66	60
Dominated	11.4	11.0	146	137	122	116	63	59
Suppressed	3.6	3.7	104	99	85	85	57	54
Undergrowth	1.4	1.6	73	78	63	67	35	35
Standard	1.6	0.8	348	351	177	179	131	127

difference is both affected by the more southern location of the 8302 plots and by a shift in the classification of sites according to the most suitable tree species. The proportion of the plots that were classified as spruce sites was 54% in the 8302 data and 47% in the 0320 data.

The sample trees in the 8302 data were larger than the sample trees in the 0320 data (dbh 23.6 and 21.5 cm). There was also a larger difference in the distribution of trees in the classes of dominant and co-dominant trees. The background of this difference is hard to interpret. A difference between the datasets is also the proportion of sample trees (cores) without counted age at breast height. It was 15% in the 8302 data and 7.5% in the 0320 data.

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