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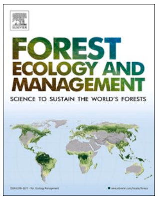

The millennium shift: Investigating the relationship between environment and growth trends of Norway spruce and Scots pine in northern Europe

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ABSTRACT

For boreal forests in colder climates, changes in environmental conditions are hypothesised to substantially affect ecosystem processes. In this study, trends of top height growth of Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst) were analysed using permanent sample plot data from more than 300 long-term experimental sites distributed from temperate zones to the boreal forest conditions in Sweden. By regression analyses, the effects of temperature-sum and precipitation-sum on top height growth were assessed in the period 1986–2018. A significant upward temporal trend in height growth was observed for both species, with the trend more pronounced after the millennium shift. The magnitude of the annual relative height growth after the millennium was about 16.92% and 9.54% higher than expected, respectively for Scots pine and Norway spruce. A potential climate response on height growth was found for both species with temperature-sum positively correlated with top height growth. No significant effect of precipitation-sum on height growth was observed for either species. Our results suggest improved growing conditions and forest sites became more productive in response to increasing temperature in the northern temperate and boreal regions. The increasing growth trends may offer shorter rotation periods and increased forest value for Norway spruce and Scots pine, coupled with contributions of boreal forests to the emerging bio-economy and the regulation of global atmospheric carbon.

1. Introduction

In recent years, the growth of forests under changing environmental conditions has been a major concern across the globe. In Europe, changes in forest growth in temperate and boreal forests during the latter part of the 20th century were investigated and summarized in Spiecker et al. (1996). In central European temperate forests, increased tree and stand-level growth has been recorded (Spiecker et al., 1996; Pretzsch et al., 2014). In boreal forests of northern Europe, increases in the forest growth have also been reported (e.g. Elfving and Tegnhammar, 1996; Salminen and Jalkanen, 2005; Solberg et al., 2009; Kauppi et al., 2014; Henttonen et al., 2017). Several possible reasons for increased growth trends comprise the following: changes in forest management and improved silviculture (e.g. Elfving and Tegnhammar, 1996; Henttonen et al., 2017), genetics (e.g. King et al., 2013) and site amelioration by increased air temperature, precipitation and nitrogen deposition (e.g. Laubhann et al., 2009; Solberg et al., 2009; Kauppi et al., 2014; Rohner et al., 2018; Etzold et al., 2020). Although, several difficulties have been encountered in attempts to isolate and quantify the magnitudes of forest growth changes attributable to management and climate (Spiecker et al., 1996; Kahle et al., 2008), and few attempts have been successful. For example, in the Finnish forests from 1971 to 2010, Henttonen et al. (2017) found differences in forest management and changes in environmental conditions explained 67% and 37% respectively of the observed increase in annual volume growth (8.98 million m^3 $year^{-1}$).

Based on estimates from the National Forest Inventory (NFI) of Sweden, annual volume growth has increased from about 60 million m^3 in the 1920s to 126 million m^3 in 2018 (Skogsdata, 2019). Earlier studies by Elfving and Tegnhammar (1996) observed an increase in basal area and height growth trends of Norway spruce (*Picea abies* (L.) Karst) and Scots pine (*Pinus sylvestris* L.) in Swedish forests between 1953 and 1992 using data from the temporary plots of the NFI. Reasons such as changes in silvicultural practice, i.e. from selective harvesting to clear felling,

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thinning from below, improved regeneration methods, nitrogen fertilization and ditching were largely proposed for the increased growth trends. In addition, increased dominant height growth of Norway spruce in southern Sweden due to a considerable higher atmospheric nitrogen deposition has been reported by Eriksson and Johansson (1993).

While effects of silviculture-induced growth trends have been assessed in the Swedish forests, growth trends due to changes in the ambient temperature and precipitation have less been investigated empirically on a national scale. By simulation, Claesson et al. (2015) estimated a positive climatic effect on growth, with the growth reaching about 56.8% more than expected after 100 years under Representative Concentration Pathways scenario analysis (RCP 8.5), using the Heureka Regwise model in Sweden. The report from the Swedish Commission on Climate and Vulnerability indicated a +2 °C increase in mean temperature during the periods 1961–1990 and 1991–2005, and thus, suggested a distinct warm period for the later decades in Sweden (Commission on Climate and Vulnerability, 2007). This provides a suitable window in which to investigate any environmentally related growth trends.

To detect a growth trend, repeated observations from long-term surveys or experiments are required (Spiecker et al., 1996; Pretzsch et al., 2019). A unique feature about long-term forest experiments is that they provide valid growth references relevant for estimating site quality and for detecting influences of site conditions on tree- and stand-level growth over time (Pretzsch et al., 2019). In Sweden, several long-term experiments were established during the 19th and 20th centuries throughout the country to examine effects of thinning and fertilization on growth and yield (e.g. Elfving and Kiviste, 1997; Valinger et al., 2000; Nilsson et al., 2010), wood quality (e.g. Pape, 1999; Pfister et al., 2007), biomass production (e.g. Eriksson, 2006) and stand stability (e.g. Valinger and Pettersson, 1996; Wallentin and Nilsson, 2014) of Norway spruce and Scots pine.

Assessment of forest site quality is vital for determining the productive capacity of forest sites and for providing a reference for silvicultural diagnoses and prescriptions (Burkhart and Tomé, 2012). Site index (SI), defined as the average height of the dominant trees of a given stand at a reference age is often used as a quantitative estimate to describe the realizable part of a site's potential to support tree growth (Skovsgaard and Vanclay, 2008). In Norway, an increased SI after 1940 has been reported (Sharma et al., 2012). In Sweden, new SI functions for Scots pine are steeper with higher growth curves (Elfving and Kiviste, 1997) compared to previous SI functions developed by Hägglund (1972; 1973; 1974). This necessitated further investigation of changed growth patterns in Scots pine stands of cultivated origin.

Using permanent plot data from long-term forest experiments, we focused on top height growth trends for the two most dominant tree species in Sweden: Norway spruce and Scots pine. This is because height growth is highly correlated with volume production, and top height is not greatly influenced by stand density and thinning treatments, assuming thinning from below for even-aged monocultures (Eichhorn, 1902; Skovsgaard and Vanclay, 2008; Burkhart and Tomé, 2012). We defined a growth change trend as long-term site-related deviations from the expected top height growth (Spiecker et al., 1996). The main hypothesis tested in the present study was that, for the two species, the top height growth was higher than expected due to temporal changes in environmental conditions during the last 30 years in Sweden.

2. Material and methods

In this study, for a forest stand and given fixed temperature-sum and precipitation-sum, we assumed that SI was constant and top height development followed SI curves over time. Using permanent sample plot data from long-term experiments measured at two different time periods, we developed a reference top height growth function using data from the period (1950–1985), and applied the function to the validation data (1986–2018) to compute the expected top heights. The biases, calculated as the difference between the observed and predicted top heights were used to assess the top height growth trends of Norway spruce and Scots pine. The relationships between height growth changes and changes in environmental (climate) conditions expressed as temperature-sum and precipitation-sum were investigated.

2.1. Data

Data for the study comprised 330 different locations (sites) of long-term experiments (Scots pine = 226 and Norway spruce = 104) of even-aged stands distributed throughout Sweden (Fig. 1). The experiments largely described thinning, spacing, regeneration and fertilization treatments of Norway spruce and Scots pine (Nilsson et al., 2010). The control (unfertilized and thinned from below) plots of these experiments were used for growth analyses, assuming that they were not influenced of management that would affect height development. The distribution of the data is summarized in Table 1. Most of the stands had cultivated origin (regenerated naturally, planted or seeded from local seed sources) (Elfving and Kiviste, 1997; Nilsson et al., 2010).

For the Scots pine dataset, 4940 observations were made in 77 permanent sample plots with a net plot area of 0.1 ha (range is 0.01–0.50 ha) between 1925 and 2018. The time between the remeasurement of a plot ranged from 1 to 41 years (mean = 8), and plots were re-inventoried at least twice and at maximum of 11 times (mean = 4).

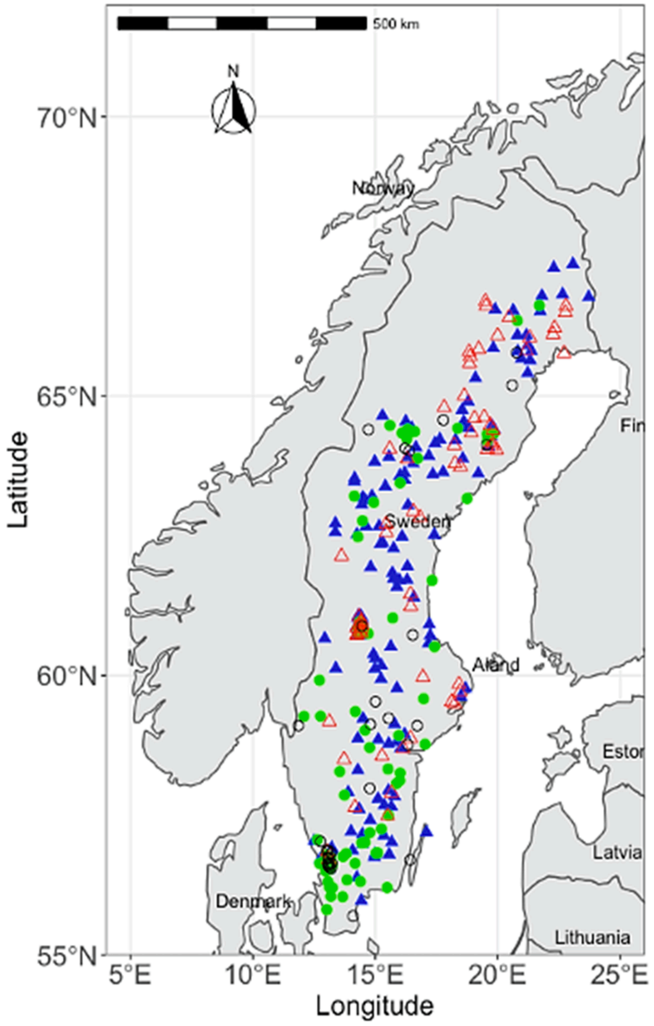

Fig. 1. Locations of the experimental sites in Sweden. Opened symbols denote reference sites, whereas validation sites are shown by filled symbols (triangles for Scots pine and circles for Norway spruce).

Table 1
Descriptive statistics of observed top height within age classes for Scots pine and Norway spruce in the experimental sites.

	Top height (m)[**]														
	Whole data (1925–2018)					Reference data (1950–1985)					Validation data (1986–2018)				
Age class (years)	N[a]	Mean	Min	Max	Sd	N[a]	Mean	Min	Max	Sd	N[a]	Mean	Min	Max	Sd
Scots pine (no. experimental sites)			**226**					**81**					**145**		
0–20	301	5.67	2.30	17.30	2.52	234	5.08	2.30	8.40	1.35	14	7.81	3.50	15.50	4.42
20–40	1611	10.73	3.70	19.80	2.92	837	10.03	3.70	17.00	2.81	321	11.91	6.20	19.80	2.94
40–60	1592	16.53	4.80	25.40	2.85	491	15.17	6.40	23.00	2.47	730	17.80	9.60	25.40	2.70
60–80	732	19.42	9.40	29.30	3.46	74	21.84	16.50	29.30	3.13	499	20.19	13.20	28.30	2.81
80–100	329	19.63	11.60	31.80	3.68	100	18.81	12.70	26.20	3.62	99	22.39	17.00	31.80	2.28
100–120	228	19.35	13.60	29.80	3.08	154	18.99	13.80	29.80	2.95	12	22.93	17.90	27.30	3.73
120–140	85	21.76	14.60	30.90	3.48	57	21.54	14.60	27.30	3.27	4	25.60	24.10	28.60	2.03
140–160	30	22.14	16.20	26.60	3.38	6	19.88	16.20	25.80	4.19	7	24.84	23.60	26.60	1.02
160–180	10	22.13	17.60	27.50	3.77	4	22.05	18.90	26.30	3.53	2	26.90	26.30	27.50	0.85
180–200	14	21.61	18.50	27.40	2.94	6	21.60	18.50	26.90	3.22					
200–220	4	23.95	20.60	28.40	3.84										
220–240	4	25.23	21.20	28.50	3.71										
Norway spruce (no. experimental sites)				**104**				**31**						**73**	
0–20	170	5.69	1.90	12.90	2.33	116	5.04	1.90	8.80	1.91	35	6.80	2.20	12.90	2.95
20–40	979	13.03	2.10	23.20	4.59	419	12.70	2.10	19.50	3.89	263	13.90	4.40	23.20	5.28
40–60	768	20.16	6.00	29.00	4.12	199	19.26	6.20	29.00	4.67	417	20.86	8.70	28.60	3.86
60–80	217	24.46	8.70	31.00	5.35	48	24.09	9.70	29.50	5.09	125	24.45	8.70	31.00	5.58
80–100	61	26.41	11.90	33.40	6.79	39	30.38	23.10	33.40	1.96	2	29.20	28.20	30.20	1.41
100–120	28	26.06	15.20	34.10	7.78	14	24.09	15.70	33.90	7.58	5	30.58	18.70	34.10	6.65
120–140	26	17.73	8.30	36.10	9.81	5	22.28	17.80	33.20	6.19	4	35.20	34.00	36.10	0.88
140–160	25	15.56	9.90	24.70	4.96	10	12.93	10.90	14.50	1.21	8	22.39	19.90	24.70	1.44
160–180	8	15.50	14.30	16.90	0.88	4	14.90	14.30	15.70	0.58					

[a] Number of observations (measurements) in the age class.

[**] Mean (Mean), minimum (Min), maximum (Max) and standard deviation (Sd) of observed top heights in the age class.

For the Norway spruce dataset, about 2282 observations were conducted from 1927 to 2018 in 44 sample plots with a net plot area of 0.1 ha (range is 0.01–0.25 ha). The time interval for plot remeasurement ranged from 1 to 27 years (mean = 7). The remeasurement of sample plots was done at least once and at maximum of 14 times (mean = 4).

The tree height observations between 1940s and 1990s were made using Suunto hypsometers. From the 1990s to 2018, the Haglöf Vertex hypsometer was used for height measurements. Such changes in instruments could introduce errors in the measurements, however, in this study, the errors in tree height measurements were assumed negligible.

2.1.1. Top height estimation

At each plot remeasurement, H was measured for sample trees while calipered trees without measured heights were assigned predicted heights from Näslund's curve function (Eq. (1), Näslund, 1947). The

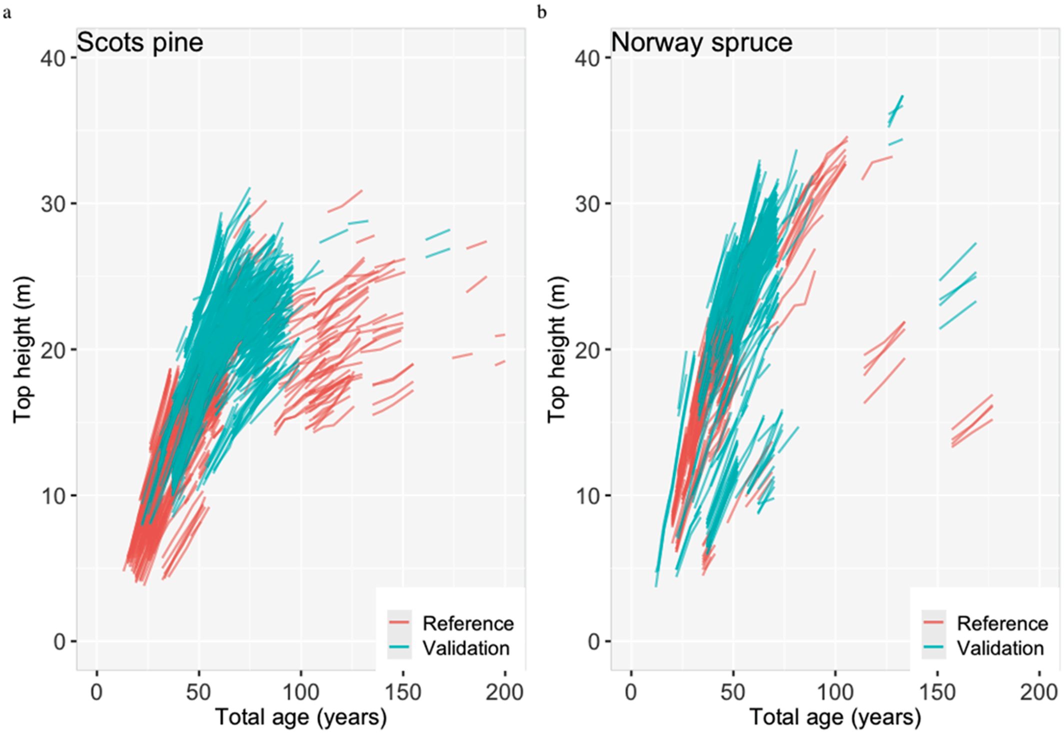

Fig. 2. Observed top height development for (a) Scots pine and (b) Norway spruce in experimental sites measured between 1925 and 2018 (whole dataset).

Table 2

Base and dynamic (GADA) equations considered for the reference growth modelling.

Function	Base equation	Dynamic equation
F01 (Korf)	$H = a_1\left[exp^{\left(\frac{-a_2}{T^{a_3}}\right)}\right]$	$H = b_1.\left(\frac{H_0}{b_1}\right)^{\left(\frac{T_0}{T}\right)^{b_2}}$
F02 (Elfving and Kiviste)	$H = \frac{a_1}{\lfloor 1 + (a_2/T^{a_3})\rfloor}$	$H = \frac{H_0 + d + r}{\left[2 + \frac{(4b_1/T^{b_2})}{(H_0 - d + r)}\right]}$Where $d = \frac{b_1}{Asi^{b_2}}, \quad r = \sqrt{(H_0 - d)^2 + 4b_1H_0{T_0}^{-b_2}}$
F03 (Schumacher)	$H = a_1\left[exp^{(-a_2/T)}\right]$	$H = H_0\left[\frac{exp^{(-b_1/T)}}{exp^{(-b_1/T_0)}}\right]$
F04 (Chapman-Richards)	$H = a_1\left[1 - exp^{(-a_2T)}\right]^{a_3}$	$H = H_0\left[\frac{1 - exp^{(-b_2T)}}{1 - exp^{(-b_2T_0)}}\right]^{b_3}$

function was modelled using paired *DBH* and *H* measurements of sample trees in the plot.

$$H = \frac{DBH^c}{(a + b.DBH)^c} + 1.3 \tag{1}$$

where *H* is the tree height (m), *DBH* is the calipered tree diameter at breast height (cm), *a*, *b* and *c* are parameters to be estimated. Mean top heights, defined as the arithmetic mean height of the 100 thickest (by diameter) trees ha^{-1} were computed for each sample plot (Elfving and Kiviste, 1997; Liziniewicz et al., 2016). The distribution and development of the measured top heights for the two species are shown in Table 1 and Fig. 2.

2.2. Reference top height growth model

To estimate changes in growth trends, a reliable and efficient reference growth model is required. A reference growth model is considered valid when it suitably represents the site and stand conditions of the investigated forests during the reference period (Spiecker et al., 1996). To satisfy this condition, the data material were split into reference (Scots pine = 81 sites; Norway spruce = 31 sites) and validation (Scots pine = 145 sites; Norway spruce = 73 sites) dataset (Table 1). The reference data were used for calibrating the reference (baseline) growth model and consisted of repeated observations within the growth period 1950–1985. The validation data were used to analyse top height growth trends for the two species during the last three decades (1986–2018). The two datasets represented different time periods, but similar regeneration methods (local seed sources and soil preparation) and management. For both species, the distributions of SIs (estimated based on Elfving and Kiviste, 1997 at the latest remeasurement) were similar in the two periods, though the SIs were slightly higher (Scots pine: $t = 11.2$, $p < 0.0001$, $d.f. = 3514$; Norway spruce, $t = 2.9$, $p = 0.0042$, $d.f. = 1690$) in the validation period (Scots pine: mean = 26.1 m, range = 16.0–34.6 m; Norway spruce: mean = 31.5 m, range = 14.1–39.2 m) than in the reference period (Scots pine: mean = 24.8 m, range = 11.1–33.9 m; Norway spruce: mean = 30.8 m, range = 10.0–37.7 m) (Figure A.1, supplementary file). The wider ranges of SI in the two periods for the two species indicate that sites covered a large portion of the range of fertility in Sweden. Earlier reports suggested stable temperatures during the reference period in Sweden (Commission on Climate and Vulnerability, 2007). Additionally, using observations during the reference period to construct the reference growth models coincides with earlier studies (Hägglund, 1972, 1973, 1974; Elfving and Kiviste, 1997) utilizing observations in this window to develop SI functions for Norway spruce and Scots pine in Sweden. We assumed that the reference growth model depicted the climatic conditions within this reference period.

Modelling the relationship between top height and age can be used to investigate changes in tree growth patterns (Elfving and Kiviste, 1997; Cieszewski and Bailey, 2000; Pretzsch, 2009; Burkhart and Tomé, 2012). Dynamic growth functions formulated using algebraic and generalised-algebraic difference approaches (ADA and GADA) (Cieszewski and Bailey, 2000) are widely preferred to the static and fixed-base-age equations for assessing site quality, because they are parsimonious, robust and provide base-age invariant results (Cieszewski, 2001; Liziniewicz et al., 2016). The GADA functions theoretically transform basic growth functions into a dynamic form by replacing one or two parameters with site-specific coefficients, generating SI curves with polymorphic asymptotes (Cieszewski and Bailey, 2000; Burkhart and Tomé, 2012; Liziniewicz et al., 2016).

For this study, four dynamic growth functions (F01-F04) with high flexibility were used to develop the reference growth models (Table 2). These functions have yielded satisfactory outcomes for SI estimation in other studies (e.g. Rivas et al., 2004; Nord-Larsen et al., 2009; Johansson, 2012; Kahriman et al., 2018). The GADA formulations of the following base equations: (i) F01 (Korf, 1939), (ii) F02 (Elfving and Kiviste, 1997), (iii) F03 (Schumacher, 1939), and (iv) F04 – von Bertalanffy-Richards (henceforth called Chapman-Richards) (von Bertalanffy, 1938; Richards, 1959; Chapman, 1961) were considered. The F02 equation is a special dynamic formulation of the Hossfeld II base equation (Peschel, 1938) and has been widely used in Sweden for SI estimation. In the considered reference functions, $a_1, a_2, \cdots, a_n$ and *H*, *T* are parameters of the base equations, while b_1,$b_2, \cdots, b_n$ and T_0, T, H_0, H represent parameters in the GADA equations. Together with the global parameters$(b_1, b_2, \cdots, b_n)$ and by assuming the growth function passes through the current height (H_0) at current age (T_0), then the expected top height (H) at a future age (T) of a plot was expressed implicitly as: $H = f(T_0, T, H_0, b_1, b_2, \cdots, b_n)$. In all the tested functions, H_0 was considered as a site-specific parameter and was estimated locally for each plot. For the F02 function, initial starting values used were $b_1 = 7395.60$, $b_2 = 1.78, Asi = 25$ for Scots pine, and $b_1 = 1495.30, b_2 = 1.59, Asi = 10$ for Norway spruce. These values were obtained from (Elfving and Kiviste, 1997). The *Asi* parameter denotes the age corresponding to maximum growth and which minimizes the model residuals (Elfving and Kiviste, 1997). The starting values for other GADA functions were iterated using the "*selfStart*" function in the "*nlme*" package in R (R Core Team, 2018).

2.3. Calibration of reference growth functions and autoregressive modelling

On the reference dataset, the reference GADA functions (Table 2) were fitted via the generalised nonlinear least squares regression function ("*gnls*") with the restricted maximum likelihood (*REML*) method in R (R Core Team, 2018). The parameters of the growth functions were estimated through autoregressive modelling and by accounting for within-plot and site variance. The presence of autocorrelation and heteroscedasticity may bias the model parameters and violate hypothesis testing procedures in standard regression analysis (e.g. Monserud, 1984; Rivas et al., 2004). The possible autocorrelation was modelled as a first order error structure, due to many plots having just two observations (Gregoire et al., 1995; Liziniewicz et al., 2016). The expanded error (Eqs. (2)–(3)) was structured as:

$$H_{ij} = f\left(H_j, t_i, t_j, \beta\right) + e_{ij} \tag{2}$$

$$e_{ij} = \rho e_{i-1,j} + \gamma e_{ij-1} + \varepsilon_{ij} \tag{3}$$

where H_{ij} is the height i prediction using height j (H_j), age i (t_i) and age j (t_j) as predictor variables together with the global parameters ($\beta : b_1, b_2, \cdots, b_n$) and age $j \neq$ age i; ρ is the parameter accounting for the autocorrelation between the current residual and the residual from estimating H_{i-1} using H_j as a predictor within each plot; γ denotes the parameter accounting for the autocorrelation between the current residual and the residual from estimating H_i using H_{j-1} as a predictor within each plot; and ε_{ij} is the independent and identically distributed errors with an expectation, $\mathrm{E}(\varepsilon) = 0$ and a constant variance, $\mathrm{Var}(\varepsilon) = \sigma^2$.

The within-plot and -site variations were modelled as power weighted variance of total age to improve upon the precision of SI curves in the young (less than 20 years) and the old stands (more than 150 years) (Rivas et al., 2004; Liziniewicz et al., 2016).

2.3.1. *Comparison of reference growth functions*

Performances of the reference growth functions after model fitting were compared using the following four statistical criteria (Eqs. (4)–(7)); Akaike information criterion (*AIC*), root mean square error (*RMSE*, to quantify the average difference between the observed and estimated top heights, lower value indicates a better model), relative RMSE (*relRMSE*, to assess the magnitude of the top height estimation error rate, lower value indicates a better model), and the adjusted coefficient of determination ($R^2{}_{adj}$, to measure the strength of the agreement between observed and estimated top heights, larger value indicates a better model):

$$AIC = n\log\left(\frac{\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}{n}\right) + 2p \tag{4}$$

$$RMSE = \sqrt{\frac{\sum\limits_{i=1}^{n}\left(\hat{y}_i - y_i\right)^2}{n-p}} \tag{5}$$

$$relRMSE = 100\%\text{x}\frac{RMSE}{\bar{y}} \tag{6}$$

$$R^2{}_{adj} = 1 - \frac{(n-1)\sum_{i=1}^{n}(\hat{y}_i - y_i)^2}{(n-p)\sum_{i=1}^{n}(y_i - \bar{y}_i)^2} \tag{7}$$

where $\hat{y}_i$, y_i and $\bar{y}_i$ are the predicted, measured and average values of the dependent variable, respectively; n represents the total number of observations used for fitting the model and p denotes the number of model parameters.

The residuals of the fitted growth functions were investigated for potential heteroscedasticity and autocorrelation by using both graphical and numerical analyses. The Durbin-Watson test statistic (d) was used to detect autocorrelation in lag residuals after modelling. Values of $d = 2$ indicate absence of autocorrelation, smaller values ($0 \leq d \leq 1$) indicate positively correlated successive error terms and larger values ($d > 2$) suggest negative correlation of successive error terms (Durbin and Watson, 1971). The test statistic d was expressed as:

$$d = \frac{\sum_{i=1}^{n}(e_i - e_{i-1})^2}{\sum_{i=1}^{n}e_i^2} \tag{8}$$

where e_i is the error value for the i^{th} data and n is the number of observations.

The reliabilities of all reference growth functions were explored by the trajectories of the SI curves (passing through the top heights (m): 36, 32, 28, 24, 20, 16 and 12 at 100 years) on the profiles of the observed top height development. This was considered as an important step for final evaluation, as even though the models could have significant parameters, yet they might not adequately describe the data used to construct them (Dieguez-Aranda et al., 2005; Liziniewicz et al., 2016). The iteration of SI was done by setting the index age to 100 years for both species, as this age is closer on the average to actual rotations in Sweden.

2.3.2. *Estimation of the observed and expected top height growth*

After model evaluation, the best reference growth model was applied to the validation dataset to compute the expected top heights for the two species. The expected top heights ($\hat{h}_2$) at time (age) two (t_2) were predicted from the SI model using information on observed top heights (h_1) at time one (t_1) and time two (t_2). The observed and expected top height growths were estimated as follows:

$$ih = h_2 - h_1 \tag{9}$$

$$\widehat{ih} = \hat{h}_2 - h_1 \tag{10}$$

where ih and $\widehat{ih}$ are the observed and expected top height growth respectively.

The ih and $\widehat{ih}$ values were compared and the absolute bias (Δih, growth difference, cm), normalised bias (Δih_n, annual growth difference, cm/year) and relative bias (Δih_{rel}, %/year) in top height growth were computed as:

$$\Delta ih = ih - \widehat{ih} \tag{11}$$

$$\Delta ih_n = \frac{\Delta ih}{t_2 - t_1} \tag{12}$$

$$\Delta ih_{rel} = 100\text{x}\frac{\Delta ih_n}{\widehat{ih}_n} \tag{13}$$

where $\widehat{ih}_n$ denotes the expected annual top height growth $\left(\frac{\widehat{ih}}{t_2 - t_1}\right)$ in cm/year.

The relative height growth bias estimator, Δih_{rel} was considered in this study, as the response variable to quantify the magnitude (i.e. proportion) of the observed annual height growth in relation to the expected annual height growth. This was intended to capture site-specific growth response. A positive value of Δih_{rel} suggests the annual top height growth was higher than expected, while negative value indicates the observed growth was less than expected.

2.4. *Weather data*

Annual temperature and precipitation data were obtained from the Swedish Meteorological and Hydrological Institute (SMHI). The SMHI produced monthly annual weather data, based on the European FP7 project on the re-analysis of meteorological observations (http://www.uerra.eu). Weather variables were delivered in a 55 × 55 km resolution raster covering the study area. The annual temperatures were expressed as temperature-sums (in degree days), defined as the summation of day-mean degree Celsius (°C) when the air temperatures exceed +5 °C during the vegetation period (Perttu and Morén, 1994; Bergh et al., 2005). Precipitation was also expressed as annual precipitation-sums during the vegetation period. The temporal resolution of the climate data provided was from 1961 to 2018, and thus covered a significant portion of our top height measurements.

Similar to the measured top height dataset, the climate data were also split into reference (1961–1985) and validation data (1986–2018). On the reference dataset, we computed for each site, the average temperature- and precipitation-sums within the 24-year period (Eq. (14)).

On the validation data, the observed climate values for each site in the growth period were calculated (Eq. (15)) as means over time one and two, corresponding to the years of top height measurements. Finally, we computed the relative bias (ΔY_{rel}) in the climate value (Eq. (16)) for each site to describe the magnitude of changes in climatic conditions within the validation period compared to the reference period. Positive values of ΔY_{rel} suggested the climate value was higher in the validation period than in the reference period, while negative values suggested otherwise. The ΔY_{rel} values were used as regressors to assess the height growth response of Norway spruce and Scots pine to changes in climatic conditions.

$$\overline{Y}_{refk} = \frac{1}{n_i}\sum_{i=1}^{k} y_i \tag{14}$$

$$\overline{Y}_{pk} = \frac{y_{t_1} + y_{t_2}}{2} \tag{15}$$

$$\Delta Y_{rel} = 100\text{x}\frac{\overline{Y}_{pk} - \overline{Y}_{refk}}{\overline{Y}_{refk}} \tag{16}$$

where $\overline{Y}_{refk}$ represents the observed mean climate variable (as either temperature-sum or precipitation-sum) for site k in the reference period, n_i is the number of annual observations for each site within the reference period, y_i is the observed annual climate values for site k in the reference period, $\overline{Y}_{pk}$ is the mean climate variable in the growth period (p) corresponding to the top height measurements at time one (y_{t_1}) and time two (y_{t_2}) for site k in the validation period, and ΔY_{rel} (%/year) denotes the relative temperature-sum or precipitation-sum bias.

2.5. *Modelling top height growth and weather relationship*

Preliminary analysis involved testing the significance of the relative height growth bias (Δih_{rel}) and the climate bias (ΔY_{rel}, i.e. relative temperature-sum bias and relative precipitation-sum bias) trends over years, in the validation period. The year was set as the mid-point of two consecutive measurements. We used the Mann-Kendall's (MK) non-parametric tau coefficient as an estimate (δ) to determine the temporal (annual) height growth and climate trends for the two species. Presence of a statistical trend is recorded when δ differs significantly from zero ($p < 0.05$), positive δ indicates an upward temporal trend, while negative δ is indicative of a decreasing trend. The MK test was fitted using the "*MannKendall*" function in R (R Core Team, 2018). Prior to fitting the MK test, we investigated whether the values of relative height growth, temperature-sum and precipitation-sum biases were serially correlated using the "*acf*" function in R. We observed the presence of partial temporal autocorrelations (Figure A.2). Therefore, the MK test was applied in conjunction with block bootstrapping using five fixed block lengths as lag intervals and over 1000 repetitions. Summary of the results on the growth and climate trends were reported for δ and two-sided p-values at 95% confidence interval.

To investigate the relationship between changes in the top height growth and climate within the validation period, multivariate regression analysis using the generalised least squares method was fitted separately for Norway spruce and Scots pine. The model was fitted to account for the growth-site heterogeneity and temporal autocorrelations (Zuur et al., 2009). The heterogeneity was modelled as power weighted variance proportional to the response variable, and the autocorrelation was modelled as the first order autocorrelation adapted to the site and year of measurement. The predictors included climate (relative temperature-sum bias and relative precipitation-sum bias) and plot variables (total age, latitude, altitude) and the interaction between these predictors. Non-significant variables were excluded from the final regression models. Statistical and graphical analyses were done to assess the normality and heteroscedastic patterns of the model residuals. The normality of residuals was tested by the Shapiro-Wilk test (W) and the heteroscedastic patterns were assessed by the distribution of residuals over year of measurement, latitude and total stand age.

3. Results

3.1. *Performance of reference growth models*

The autoregressive modelling procedures for reference growth functions converged successfully for both Scots pine and Norway spruce. The model parameters and fitting statistics produced for the two species are summarized in Table 3. In all functions for both species, the model parameters were statistically significant from zero ($p < 0.0001$). The fitting statistics were similar for all models and indicated more than 95% of the total explained variance (based on R^2_{adj}) in the fitting phase. However, those of Korf (F01) and Elfving and Kiviste (F02) were much more superior to the Schumacher (F03) and Chapman-Richards (F04) functions. Compared to the other functions, the Schumacher (F03) function exhibited the poorest performance based on the residual error variance (RMSE = 0.64 m for Scots pine and 1.07 m for Norway spruce).

Graphical analysis of the fitted SI curves for both Norway spruce and Scots pine showed realistic height-age patterns for the models based on F01 and F02 (Fig. 3). The growth curves of F01 and F02 followed the trajectories of the observed top height development compared to the functions F03 and F04, which displayed strong intersections with the underlying top height profiles. Hence, models F03 and F04 were excluded from further analyses.

For Scots pine, function F02 exhibited higher accuracy than F01 (Table 3). For Norway spruce, the F01 model marginally out-performed the F02 counterpart. However, the smoothness and flexibility of the F01 curves indicated higher site indices at both younger and older ages compared to the F02 function (Fig. 3e and f). Thus, the Elfving and Kiviste function (F02) was finally considered as the reference growth model for the subsequent top height growth analysis of the two species. The parameters of the F02 model reflect the range of boreal site conditions and the model is widely used for SI estimation in Sweden.

The residual plots of F02 (Figure A.3) showed no apparent trends of heteroscedasticity across the range of observed top heights and stand age for the two species. Both graphical and numerical analyses of the model residuals indicated absence of autocorrelation for Norway spruce ($d = 1.66$, $p < 0.0001$) and Scots pine ($d = 1.42$, $p < 0.0001$). The observed and predicted top heights also showed a good agreement for the two species.

3.2. *Temporal trends in height growth, temperature-sum and precipitation-sum*

The temporal (annual) trends (δ) in relative height growth bias and temperature-sum bias were positive and differed significantly from zero ($p < 0.05$), suggesting the presence of statistically upward trends for both species in the validation period, except for the relative precipitation-sum bias which was non-significant for either species (Table 4). The trends appeared more pronounced after the millennium (year 2000) as shown in Fig. 4. The mean top height growth over the whole validation period was estimated as 3.94% year^{-1} for Scots pine and 0.89% year^{-1} for Norway spruce. However, after the millennium shift, the magnitude of the top height growth was 16.92% year^{-1} and 9.54% year^{-1} higher than expected respectively, for Scots pine and Norway spruce.

3.3. *Height growth and climate relationship*

Pearson's correlation (R) was used to explore the initial relationship

Table 3
Parameter estimates and goodness-of-fit statistics for the four tested GADA models for Scots pine and Norway spruce. “Par” is the parameter and “SE” is the standard error. “ρ” is the first-order autocorrelation parameter.

				Confidence interval			Fit statistics			
Model	Par.	Estimate	SE	2.5%	97.5%	P-value	*AIC*	*RMSE*(m)	*relRMSE*(%)	R^2_{adj}
Scots pine										
F01	b_1	55.23	2.12	51.08	59.38	< 0.0001	1068.63	0.57	3.93	0.99
	b_2	0.72	0.02	0.68	0.76	< 0.0001				
	ρ	0.06								
F02	b_1	6435.04	306.83	5833.67	7036.41	< 0.0001	1235.09	0.55	3.79	0.99
	b_2	1.71	0.02	1.67	1.75	< 0.0001				
	ρ	0.14								
F03	b_1	35.37	0.28	34.83	35.91	< 0.0001	1922.26	1.05	7.24	0.97
	ρ	0.47								
F04	b_1	0.02	0.001	0.016	0.019	< 0.0001	1656.02	0.64	4.41	0.98
	b_2	1.48	0.03	1.42	1.54	< 0.0001				
	ρ	0.36								
Norway spruce										
F01	b_1	68.46	4.67	59.31	77.61	< 0.0001	1038.57	0.81	4.68	0.99
	b_2	0.71	0.03	0.64	0.78	< 0.0001				
	ρ	0.08								
F02	b_1	1981.88	124.12	1738.61	2225.15	< 0.0001	1081.97	0.86	4.97	0.99
	b_2	1.69	0.04	1.62	1.77	< 0.0001				
	ρ	0.06								
F03	b_1	35.61	0.41	34.79	36.41	< 0.0001	1232.79	1.25	7.22	0.98
	ρ	0.05								
F04	b_1	0.02	0.002	0.018	0.024	< 0.0001	1214.12	1.07	6.18	0.98
	b_2	1.52	0.05	1.41	1.62	< 0.0001				
	ρ	0.05								

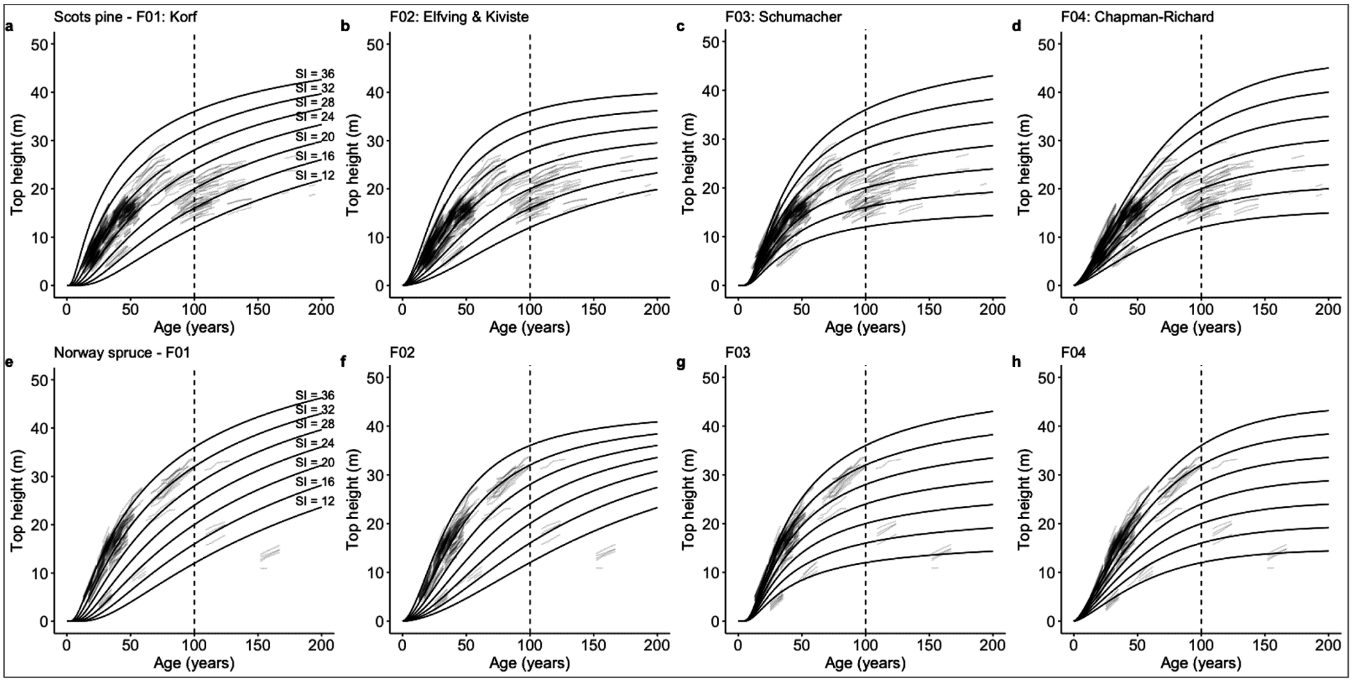

Fig. 3. Fitted SI curves of the reference growth functions using the reference data (1950–1985) for Scots pine (a-d) and Norway spruce (e-h). The curves represent the top heights at base age of 100 years (vertical dashed lines) and overlaid on the observed top height-age profiles.

between relative top height growth and the climate variables. For both species, Scots pine ($R = 0.19, p = 0.0017$) and Norway spruce ($R = 0.24, p = 0.003$), the growth correlations with temperature-sum was significant and positive, whereas no significant correlation with precipitation-sum was found for either species (Figure A.4). The full regression analyses involved modelling the relative height growth bias as a function of climate and plot characteristics for each species (Table A.1). The effects of precipitation-sum, total stand age and altitude were not significant, hence removed from the final regression models.

The final regression results for the two species are summarized in

Table 4
Mann-Kendall estimates for temporal trends in height growth, temperature-sum and precipitation-sum bias of Norway spruce and Scots pine.

	Scots pine		Norway spruce	
	δ	P-value	δ	P-value
Relative height growth bias	0.30	< 0.0001	0.20	< 0.001
Relative temperature-sum bias	0.36	< 0.0001	0.41	< 0.0001
Relative precipitation-sum bias	0.03	0.432	0.09	0.108

Table 5. The model residuals of both species were normally distributed (Scots pine: $W = 0.991$, $p = 0.099$; Norway spruce: $W = 0.992$, $p = 0.589$) and exhibited no patterns of heteroscedasticity over measurement year, latitude and total age (Figure A.5). In both species' models, the estimated autocorrelation levels (ρ) were smaller (Scots pine: $\rho = 0.054$ and Norway spruce:$\rho = 0.071$). The effects of temperature-sum on the height growth were significant and positive for both species, suggesting positive height growth response to climatic changes. The effect of temperature-sum was larger for Norway spruce than for Scots pine.

4. Discussion

4.1. Data and models

To detect growth trends, a reference growth model (or value) is required (Spiecker et al., 1996). Permanent plot observations from long-term forest experiments are essential for developing reference growth models, and for quantifying site-related growth deviations (Pretzsch et al., 2019). In this study, control plots in long-term experiments with observations dating back from the early 20th century, facilitated the investigation of growth trend changes in Swedish forests. Particularly, splitting the data material into reference (1950–1985) and validation (1986–2018) periods enhanced smooth comparison of the observed and expected top height growth trends (Table 1). The similarities in the distribution of site indices (SIs) for the two periods, coupled with the wider ranges of SIs suggested our growth assessment captured a large portion of the fertility gradient in Sweden (Figure A.1). In Table 1, the age class distribution was quite different in the two datasets for both species and this was due to fewer number experiments for young stands, especially in the validation dataset. Those young stands analysed in the validation dataset were mostly located in fertile sites (Figure A.6) in contrast to the distribution of young stands in the reference dataset. Such discrepancies could have significant effects on the parameters of the SI models; however, the wider range of top heights in young stands presumes that the variability was captured in the growth trend analyses.

The performances of the tested top height growth functions (Table 2) were highly accurate at the fitting phase for both Norway spruce and Scots pine (Table 3). The functions exhibited realistic growth characteristics (Fig. 3) as they (i) represented a parsimonious and dynamic site equations, (ii) polymorphic with variable asymptotes allowing them to adapt to different site conditions, (iii) had a zero-point and (iv) were increasing (Elfving and Kiviste 1997; Cieszewski and Bailey, 2000; Burkhart and Tomé, 2012; Liziniewicz et al., 2016). The Elfving and Kiviste growth function (F02) which is a special formulation of the Hossfeld II growth equation, best described the data and exhibited no trends of residuals' heteroscedasticity and autocorrelation (Table 3; Fig. 3; Figure A.3). This function has been widely used for SI modelling in Sweden, and its flexibility and reliability in this study, indicates the reflection of changing growth patterns in Swedish boreal forests (Elfving and Kiviste, 1997). Additionally, the models' adaptation to age class discrepancies ensured satisfactory residual distribution and reliability of SI curves (Fig. 3; Figure A.3).

The temporal and spatial resolution of the climate data aided the analysis of changes in environmental conditions over time. The annual time series of temperature- and precipitation- sums showed on the average stable climate conditions in the reference period (1961–1985) and increasing trends in the validation period (1985–2018) for both species (Figure A.7). More importantly, pairing measured climate values in the calibration and validation periods enhanced the characterization of height growth response to changes in climatic conditions for the two species (Table 5).

The absence of heteroscedasticity in the final regression models linking the relative height growth bias as a linear function of climate variables, showed a well-adapted model structure and satisfactory outcomes of the height growth response to climatic conditions for Scots pine and Norway spruce (Table 5; Figure A.5).

4.2. Interpretation of the growth trends

Our study has revealed increased top height growth trends during the 30-year period, with the trend more discernible after the millennium shift for Norway spruce and Scots pine in Sweden. Likewise, we found significant temporal upward trends in temperature-sum for both species. Neither species showed significant precipitation-sum trends over time (Table 4; Fig. 4; Figure A.4). After the millennium shift, we observed that the magnitude of the relative increases in height growth were about 16.92% year^{-1} and 9.54% year^{-1} higher than expected, respectively for Norway spruce and Scots pine. On the local (site) levels, there were substantial variations in the magnitudes of top height growth, with the relative annual height growth varying considerably from −70% (less) to +70% (more) than expected. This highlights the site specific signals of climate effects on forest growth (Cook and Peters, 1997). The trends of top height growth were similar for both species as the growth declined (growing less than expected) in the early-to-mid 1990′s in Sweden. This observed growth decline is similar to the growth patterns observed for Norway spruce and Scots pine stands using ring-width indices in the Kronoberg and Kalmar counties (Tufvesson and Holmström, 2018). The authors found the radial growth decline to be highly correlated with the hot and dry summers of 1992–1997, and that could partly explain our observed growth decline within this period. We also speculate that the larger variations in growth may be due to factors such as disturbances, management, pests and pathogens.

The presence of significant positive correlation between the height growth and temperature-sum (Figure A.5; Table 5) suggests climate changes that occurred within the studied periods are at least related to the height growth trend increase in Sweden. This supports our main hypothesis. The correlation was moderately stronger for temperature-sum for both species. In both species, precipitation had not changed over time (Fig. 4). This probably suggests that boreal forest ecosystems in northern Europe might show greater responses to changes in air temperature than to precipitation. The results are in agreement with other growth studies done in the northern European forests (e.g. Salminen and Jalkanen, 2005; Kauppi et al., 2014; Henttonen et al., 2017). Using the Finnish NFI data, Kauppi et al. (2014) and Henttonen et al. (2017) observed positive correlations between the growing season temperature-sum and tree growth in Finnish's forests. In stands located at the latitudinal transects from the Arctic Circle up to the northern timberline in Finland, a significant effect of the mean July temperature of the previous year on the height growth of Scots pine was found (Salminen and Jalkanen, 2005). Other studies from the temperate forests in central Europe found tree growth to be positively correlated with temperature (Kahle et al., 2008; Pretzsch et al., 2014; Rohner et al., 2018).

Though not evaluated in this study, increased height growth might also be ascribed to the increasing atmospheric CO_2 and nitrogen deposition (which is about 2 kg N ha^{-1} year^{-1} in the north, 5 in the southeast and 10 in the southwest) in Sweden. Temperate and boreal forest soils are mostly deficient in soil nitrogen and hence, tree growth and productivity are limited. Therefore, an increase in nitrogen deposition would potentially enhance tree growth (e.g. Eriksson and Johansson, 1993; Kahle et al., 2008; Solberg et al., 2009; Laubhann et al., 2009;

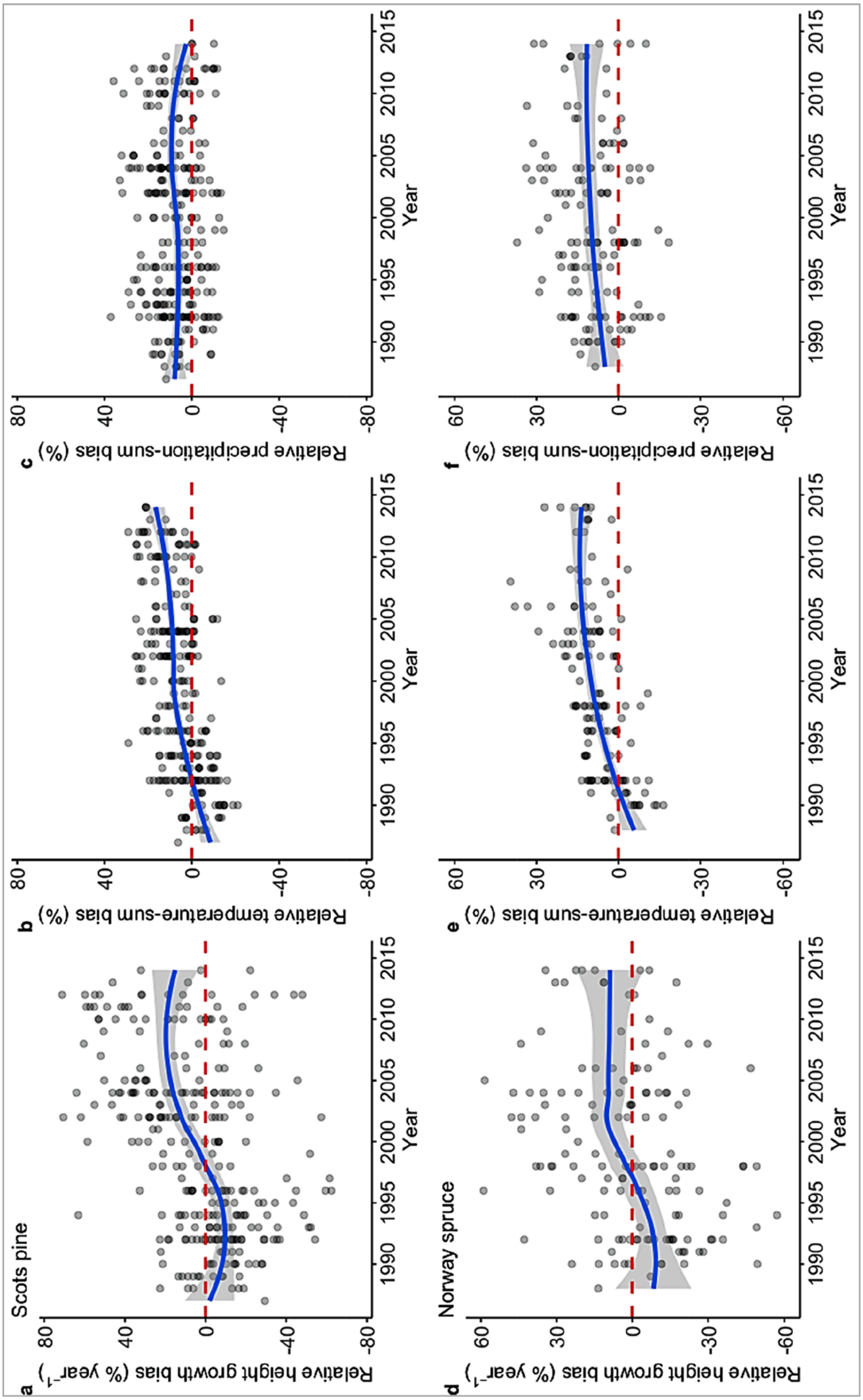

Fig. 4. Trends of annual top height growth, temperature-sum and precipitation-sum of the experimental sites over period of measurements (1986–2014) for Scots pine (a-c) and Norway spruce (d-f) after Eqs. (13) and (16). The horizontal red dashed-lines highlight where the equivalence of the observed and expected top value. Shaded regions are 95% confidence interval. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 5

Relationship between height growth [$\Delta ih_{rel}, \%/year$] and climatic changes for Scots pine and Norway spruce. “SE” denotes standard error.

Species		Coefficient	SE	t-value	P-value
Scots pine	Intercept	1.155	1.842	0.627	0.531
	Temperature-sum bias	0.497	0.153	3.251	0.0013
Norway spruce	Intercept	−3.732	2.547	−1.465	0.145
	Temperature-sum bias	0.601	0.193	3.121	0.0022

Kauppi et al., 2014; Etzold et al., 2020).

It has often been difficult to separate the factors responsible for forest growth or decline, especially in the context of management and climate. In Sweden, earlier studies by Elfving and Tegnhammar (1996) found an increase (of the magnitude 0.5–0.8%) in annual basal area and mean height growth of Norway spruce and Scots pine in the 1953–1992 time period. A number of reasons were cited as possible factors behind the increased growth trends, for example, the extensive shift from selective harvesting, target diameter cutting and thinning from above to clear felling, thinning from below and improved regeneration methods in the 1950s have contributed greatly to the growth increase in the Swedish forests. We acknowledge that, improved silviculture, genetics and management may also have brought about the observed changes in top height growth during the two studied periods.

A key issue to highlight here is the effect of measurement errors on height growth trajectories. Measuring heights of standing trees has considerable uncertainties (often overestimation), especially for taller trees with bigger crowns, and this gives higher site indices (Elfving and Tegnhammar, 1996; Elfving and Kiviste 1997). A change in tree height measurement device can also be a source of measurement errors (Elfving and Tegnhammar, 1996; Henttonen et al., 2017). For instance, in the early 1990s of the Swedish NFI, Suunto hypsometers were replaced with the Haglöf Vertex hypsometer, which had a relatively higher precision compared to the former. From 2002 to 2007, the Suunto was used to measure tree heights only on a small portion of the sample plots in combination with the Haglöf Vertex hypsometer. The outcome was the presence of a systematic bias of 30 cm lower with the Suunto hypsometer. Hence, the Haglöf Vertex was recommended for measuring tree heights in all sample plots of subsequent NFIs. Height estimation via controlled inventory showed the measurement error was less than 3% in the Swedish NFI (Fridman et al., 2019). Therefore, in this study, we cannot rule out the effect of measurement errors in the observed top height growth trends.

Since top height growth is positively correlated with volume production (Eichhorn, 1902; Skovsgaard and Vanclay, 2008), the increase in annual top height growth may suggest increased volume production, forest value, site productivity, biomass production, and carbon sequestration within the studied period. This provides a suitable window to compare the growth rate and productivity of tree species in varying site conditions. Additionally, the results indicate future rotation periods can be shorter now than before as the length of the growing season becomes longer in northern Europe. This offers significant inputs into the development of new silvicultural methods and the overall contribution to sustainable boreal forest management.

5. Conclusion

This study has shown that top height growth of Norway spruce and Scots pine increased during the last 30 years in the Swedish forests. The increase in growth was more pronounced after the millennium. Temperature showed positive correlation with the increased growth. We acknowledge that other factors such as atmospheric nitrogen deposition, increased atmospheric CO_2, improved genotypes from tree breeding and improved silvicultural systems may have contributed to the observed growth changes in Sweden, but that climate changes that occurred between the two periods studied are at least possible contributors. The higher growth patterns may result in reductions in the rotation periods for both species in the future. Significant correlations between changes in climate and growth increases suggests that climate-sensitive growth models are required for characterising boreal forest growth under warming climates in the higher latitudes. In the future, we anticipate climatic conditions may influence the height growth either positively or negatively, depending on the severity and frequency of extreme biotic and abiotic conditions.

CRediT authorship contribution statement

Alex Appiah Mensah: Conceptualization, Methodology, Formal analysis. **Emma Holmström:** Conceptualization, Methodology. **Hans Petersson:** Methodology, Funding acquisition. **Kenneth Nyström:** . **Euan G. Mason:** Conceptualization, Methodology. **Urban Nilsson:** Conceptualization, Methodology.

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.

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Declaration of Competing Interest statement

The authors declare no competing interest.

Data availability statement

The data material used in this study is available upon request from the authors.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2020.118727.

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