Forest Ecology and Management 551 (2024) 121515

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Environment-induced growth changes in forests of Finland revisited - a follow-up using an extended data set from the 1960s to the 2020s

Helena M. Henttonen, Pekka Nöjd, Harri Mäkinen *

Natural Resources Institute Finland (Luke), PO Box 2, FI-00791 Helsinki, Finland

A R T I C L E I N F O

Keywords:
Boreal forests
Forest growth
Forest inventory
Global change
Time series analysis

A B S T R A C T

After a rising trend for 1971 – 2013, during which the annual volume growth of the forests of Finland increased by more than 70 %, a recent reduction has been observed. We analyzed the development of annual growth in the forest of Finland, focusing on the component not explainable by changes in growing stock. The data originate from nine consecutive Finnish National Forest Inventories. In the data, diameter increments were measured from increment cores and tree height increments from standing sample trees in the field. We developed models predicting periodic (5 years) annual volume increment per hectare with properties of the trees and stands as predictor variables. Deviations from model-predicted values were interpreted to be induced by environmental variation. The development was analyzed for all tree species combined and separately for three species groups: Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* (L.) Karst.) and broadleaves. We observed a rising growth trend not solely explainable by increased growing stock. The species groups produced rather a similar pattern in different parts of Finland: from the 1960s to the mid-1990s, the observed volume increment was mainly below the model-predicted level, thereafter above it. During the current century, the difference between observed and predicted annual volume increment has shown a downward trend for Scots pine. For Norway spruce, the difference has continued to increase in southern Finland, but shows little change in the north. For broadleaved species, the difference between measured and predicted increment shows a recent increase as well, though not as large as for Norway spruce. The geographical pattern of the environment-induced increment component was described in more detail via maps using a 75 km × 75 km grid. The changing environment has enhanced forest productivity in Finland over a period of nearly six decades, but recent years have not been favorable for Scots pine, which represents 50 % of the growing stock volume of the forests of Finland.

1. Introduction

At high northern latitudes, where cool climate limits photosynthetic production (e.g., Hari and Kulmala, 2008) and thereby plant growth, global warming could enhance forest growth. As climate change is expected to continue for the next decades (IPCC 2021), the phenomenon could have long-term effects on the productivity of the boreal forests, which cover 30 % of the global forest area (Keenan et al. 2015) and constitute a substantial carbon sink (Tubiello et al. 2021). Northwards advances of the tree line (e.g., Esper and Schweingruber 2004, Hansson et al. 2021, Dial et al. 2022) and spatial shifts of tree species (e.g., Boisvert-Marsh et al. 2014, Fei et al. 2017) provide evidence of an ongoing change.

Warming also effects the hydrological cycle, which could partially counter the positive effects on productivity (Barber et al. 2000, Girardin et al. 2016). Babst et al. (2019) reported a significant decrease in temperature response of tree growth between 1930 and 1960 and 1960 – 1990 at many parts of the boreal zone. Grünzweig et al. (2022) further argue that climate change is likely to induce unprecedented shifts in mechanisms governing ecosystem functioning in historically wetter climatic zones towards mechanisms currently prevalent in dry regions. In time, trees also acclimate (Ainsworth and Long 2005) and even genetically adapt to the changing environment, which could also limit the growth response to warming.

The effects of the continuously rising CO_2 concentration of the air on forests have been in focus in recent years. Using forest inventory data from the United States, Davis et al. (2022) reported a connection between CO_2 fertilization and the increase of woody above-ground biomass. Likewise, in a *meta*-analysis using ecosystem carbon-cycling data from 1,119 experiments, Song et al. (2019) reported an increase

* Corresponding author.
E-mail addresses: helena.m.henttonen@gmail.com (H.M. Henttonen), pekka.nojd@luke.fi (P. Nöjd), harri.makinen@luke.fi (H. Mäkinen).

https://doi.org/10.1016/j.foreco.2023.121515
Received 29 June 2023; Received in revised form 18 September 2023; Accepted 19 October 2023
Available online 10 November 2023

in above-ground volume of ecosystems due to elevated CO_2. However, Cabon et al. (2022) reported wide-spread decoupling between eddy-covariance gross primary production and woody growth using tree-ring data in the proximity of carbon dioxide flux towers. Similarly, an ecosystem-scale Free-Air CO_2 Enrichment (FACE) experiment in a mature forest provided evidence that carbon uptake through gross primary production did increase, but the addition did not lead to increased carbon sequestration at the ecosystem level (Jiang et al. 2020).

Forest surveys have produced evidence of increased forest productivity (Kauppi et al. 1992, Köhl et al. 2015) on a wide scale in developed countries. A large share of the change can be attributed to increased growing stocks and to changes in forest management (Keenan et al. 2015). Observational data has, however, provided evidence of increased tree growth not explainable by these factors. Spiecker et al. (1996) published an extensive report based on growth data from European countries. With few exceptions, rising growth trends deviating from previous growth levels were discovered. Using a similar approach, Kahle et al. (2008) emphasized the role of nitrogen deposition as potential causal factor. Pretzsch et al. (2014) discovered sizable productivity increases on German long-term experimental forest plots, some of which had been monitored and managed in a similar fashion for more than a century.

Statistically representative data from forest inventories offer the option of generalizing the findings to the sampled population. In addition, the sample size is generally large. Inventories also routinely produce plot-level data describing the surrounding stand of sample trees, which means that factors such as stand density can be incorporated into the analysis. Using growth data from the Swedish national forest inventories, Elfving and Tegnhammar (1996) discovered a systematic increase of both basal area and height growth of individual trees over the period 1953 – 1992. Ols et al. (2022) used inventory data from France and Austria to analyze statistical links between growth trends during 1996 – 2016 and various environmental factors.

The annual volume increment of the forests of Finland increased from 57 to 108 mill. $m^3 a^{-1}$ from the 1960s to the 2010s (Official statistics of Finland, 2023a). The most recent NFI results suggest a reduction to 103 million $m^3 a^{-1}$ (Haakana et al. 2023). Similar findings have been observed in the neighboring Sweden (Roberge et al. 2023).

Henttonen et al. (2017) estimated that about one third of the growth increase observed in Finland was not related to increased growing stock. They used sample tree data from the Finnish National Forest Inventories (NFI) for 1971 – 2013. The basic approach was to model periodic (5 years) annual volume increment per hectare (m^3/ha a^{-1}) with properties of the sample trees and the surrounding stand, as well as altitude and long-term temperature sum as predictor variables. Regional deviations from the model were assumed to be mainly related to environmental factors, with warming climate as a strong candidate explanatory variable. Henttonen et al. (2017) discovered no trend from the 1970s to the mid-1990s, and the volume increments were mostly lower than the model-predictions. During the current century, values higher than predicted by the model were systematically observed. Therefore, the component of growth not explainable by the model displayed a rising trend.

Analyzing growth trends in the forests of Finland is simplified by the fact that 80 % of growing stock consist of two species: Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.). The remaining 20 % mainly consists of two birch species (*Betula pubescens* Roth 11.2 %, *Betula pendula* Ehrh. 5.5 %) (Official statistics of Finland, 2023b). This type of situation is very rare, however, and often high variability of site conditions and species composition tends to complicate the task.

We analyzed changes in the annual volume increment from the Finnish NFI data collected between 1964 and 2022. Peatlands, ditched sites and forest with signs of paludification were excluded from the analysis. In a sense, our study is a follow-up to Henttonen et al. (2017). The time series has been extended, not only to cover recent years, but also by adding years from the 1960s. We report the unexplained, presumably environment-induced increment changes separately for Scots pine, Norway spruce and broadleaves. In addition to large-scale estimates, we illustrate the changes using a 75 km × 75 km grid. We also discuss the potential causal factors behind the growth reduction observed in recent years.

2. Material and methods

2.1. National forest inventory (NFI) data

We used data from nine consecutive National Forest Inventories (NFI) of Finland. The oldest data came from the 5th NFI (NFI5), which started in 1964, and the most recent data was collected in 2022 as a part of the ongoing NFI13 (2019 – 2023). The Finnish NFIs have been based on systematic cluster sampling since NFI5. The distance between clusters as well as the number of plots and the distance between plots in a cluster have, however, changed several times since the 1960s (Tomppo et al. 2011, Haakana et al. 2023). Sampling has been more intensive in the southern parts of the country, mainly because of higher variability in land use and forests due to a larger percentage of agricultural and construction land. In NFI9 (1996 – 2003), the country was divided into six sampling regions (Fig. 1) with different sampling intensities. Since the 1990s, a part of the sample plots have been measured as permanent plots without increment corings. The data from permanent plots was not used here, as our approach was based on increment estimation using cored sample trees on the temporary plots. The proportion of permanent plot clusters has increased from 25 % in NFI9 to 80 % in the most recent NFI13.

A fundamental change in the collection of field data took place in 2004. From NFI5 to NFI9 the inventory field work proceeded by regions, i.e., one to three administrative regions were inventoried each year (Fig. 2) and the measurements covering the whole country took from six (NFI6) to nine (NFI8) years. Since NFI10 (2004 – 2008) the entire country (excluding sampling regions 1 and 6, i.e., the southernmost and northernmost region) has been covered by the field measurements each year (Fig. 2) and the inventory cycle has been five years. The details of tree sampling and sample tree measurements are presented in the Supplementary Material.

The borders of the sampling regions have changed over time. Based on their coordinates, each sample plot from the varying inventories was placed to the sampling regions shown in Fig. 1. Data from temporary plots within sampling regions 2, 3, 4 and 5 were used. We didn't go beyond NFI5 (1964 – 1970), since the older inventory data are only

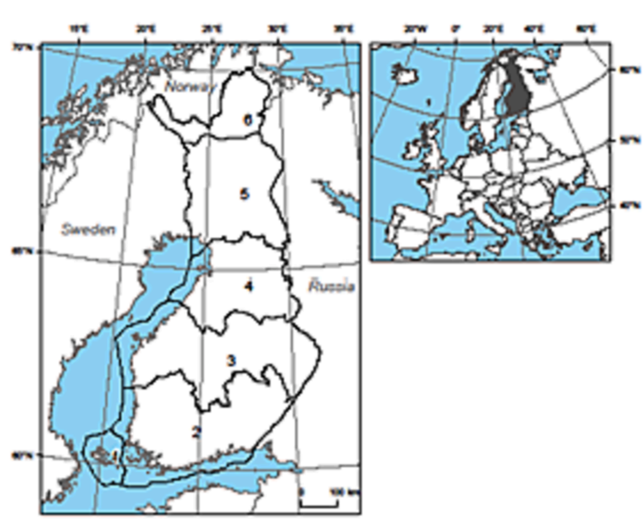

Fig. 1. The inventory regions of the Finnish NFI used in our study. . Reproduced from Henttonen et al. (2017)

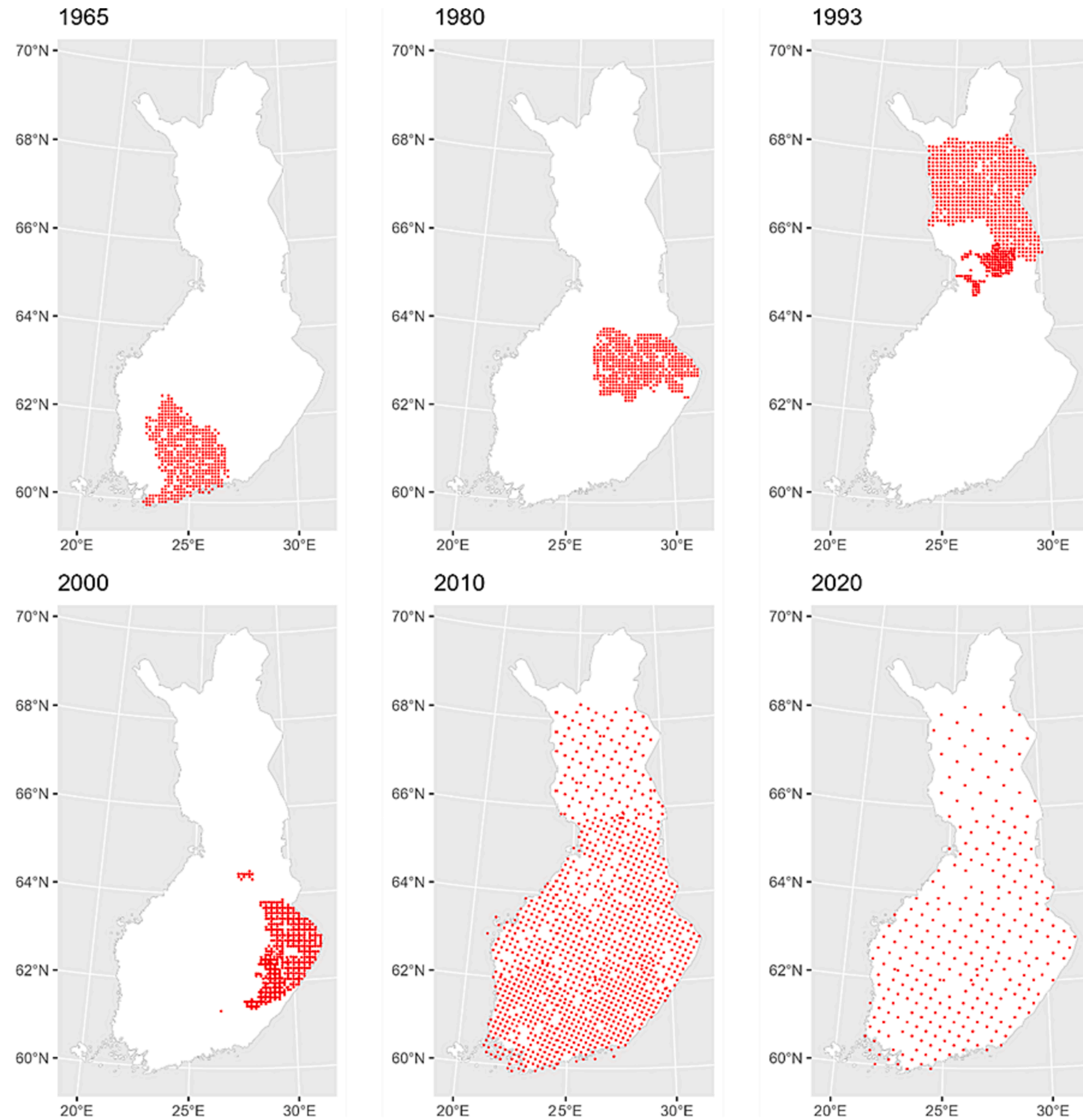

Fig. 2. Examples of the locations of the temporary inventory plots in individual years.

partially available in digital format, except for NFI1 (1921 – 1924). Also, data from NFI5 for sampling region 5 were not available for calculations. Sampling region 1 (southwestern archipelago) has been measured using a different sampling rotation since the early 2000s and the volume increment estimate in NFI12 was small, only 0.4 million m^3 a^{-1}, i.e., 0.38 % of the total volume increment. Sampling region 6 in northernmost Finland has been measured in approximately every 10 years using a sampling scheme differing from the rest of country (double sampling for stratification). Increment corings from northernmost Finland, made as part of the on-going NFI13 in 2022 were not available for our study.

Peatlands and ditched or paludified mineral soils were excluded from our analysis. The ditching of peatlands and paludified mineral soil sites was intensive in the 1960s and 1970s, decreased rapidly in the 1980s and practically ended in the late 1990s (Minkkinen et al. 2002). On ditched sites, the effects of other, possibly time-dependent environmental factors, are therefore difficult to separate from the effects of ditching.

In NFI5 and NFI6, the minimum diameter for sampled trees was 2.5 cm. To ensure comparability, trees with a diameter below that limit were excluded from the study material for NFI7 – NFI13. The total number of increment sample trees used in this study was 272 024. The number of increment sample trees from each inventory is presented in Table 1.

In estimating mean annual volume increment, m^3/ha a^{-1}, we applied the estimators presented in Tomppo et al. (2011). We calculated the mean annual volume increment for the sampling regions and 75 km × 75 km grid cells by tree species groups, assuming tree growth has ended by August 1st. The increments of 5 years preceding the inventory year were used for trees measured before August 1st. For trees measured on or after August 1st, the increment measurement period included the inventory year and the four preceding years. The increments from cored sample trees on temporary sample plots were used. The details of estimation are presented in the Supplementary Material. The increment estimates do not include the increment of drain, i.e., trees that have either been cut or have died during the 5-year calculation period.

2.2. Modelling tree volume increment

We used data from NFI6 (1971 – 1976), NFI7 (1977 – 1984), NFI8 (1986 – 1994), NFI9 (1996 – 2003), NFI10 (2004 – 2008), NFI11 (2009 –

Table 1
Number of increment sample trees ($dbh > 2.5$ cm) by tree species group and NFI rotation. Stands on mineral soils without ditching were included. NFI13 data from years 2019 – 2022.

Region	Species group	NFI 5	6	7	8	9	10	11	12	13
2	Pine	4395	6915	7404	7220	5963	5228	5265	2194	849
	Spruce	4642	7714	8118	7853	6171	5042	5050	2064	809
	Broadleaves	2024	2962	3198	2921	2699	2479	2688	1175	457
	Total	11,061	17,591	18,720	17,994	14,833	12,749	13,003	5433	2115
3	Pine	3903	6020	6034	6296	5046	4357	4930	1903	683
	Spruce	4346	6689	6610	6138	4113	3057	3426	1414	573
	Broadleaves	1917	2674	2937	2476	2313	1931	2208	918	376
	Total	10,166	15,383	15,581	14,910	11,472	9345	10,564	4235	1632
4	Pine	1801	3221	3704	3178	3380	2911	2967	1543	573
	Spruce	1276	2040	2107	1558	1253	1038	1148	614	261
	Broadleaves	606	1038	1024	885	891	783	848	426	123
	Total	3683	6299	6835	5621	5524	4732	4963	2583	957
5	Pine	–	1293	2262	2341	2342	1999	2152	1316	568
	Spruce	–	649	1079	945	785	615	749	500	221
	Broadleaves	–	483	764	698	635	526	579	367	172
	Total		2425	4105	3984	3762	3140	3480	2183	961

2013) and NFI12 (2014 – 2018) to model the effects of tree species, tree size (volume and stem diameter at breast height (*dbh*), average *dbh* within a plot, plot basal area (m^2/ha), cuttings, regeneration method, soil stoniness, altitude and mean effective temperature sum on *iv/g*, where *iv* is the mean annual increment of stem volume over the 5-year increment calculation period (m^3/ha a^{-1}) and *g* is the basal area of the tree (m^2). Variable *iv/g* has fewer extreme values than *iv*, which is useful when applying GAM.

Generalized additive models (GAM) (Hastie and Tibshirani 1986) were applied. GAMs allow a part of the linear predictor to be specified as a sum of smooth functions of predictor variables and provide a flexible way to fit surfaces based on smooths of several variables simultaneously (Wood 2017). We used a gamma location-scale model, where the log of the mean and the log of the scale parameter (see Wood 2023, p. 105 for details) were modelled with additive smooth predictors (Wood et al. 2016).

Separate models were fitted for the regions 2, 3, 4 and 5 (Fig. 1) × inventory rotation (NFI6 to NFI12). Models were not fitted for NFI5 data since data are not available from region 5 and we wanted to have temporally corresponding modelling data from the different sampling regions. The data available from NFI13 was from years 2019 – 2022 (not a complete inventory rotation) and because of the increased proportion of permanent sample plots, where trees are not cored, the number of increment sample trees is much lower than in earlier inventories. NFI13 data was therefore not used in modelling.

We also fitted separate models according to regeneration type (artificial/natural) and the time passed from the most recent cutting, i. e., stands that had been thinned within 10 years of the field measurement were modelled separately. The values of the effective temperature sum (*ets*) were derived for each plot from the grid of the Finnish Meteorological Institute (Venäläinen et al. 2005) and averaged over the years 1991 – 2020. We avoided including variables describing site fertility into models, as there are indications that forest sites in Finland have become more fertile (Mäkipää and Heikkinen 2003, Tomppo et al. 2011). Thus, possible trends in forest growth could be partially hidden. We included, however, a variable describing forest soil stoniness, which is recorded in the field. We also tested models with random cluster and/or plot effects for a part of the data, but these models were not always better (AIC criterion) than simpler models assuming independent tree-level observations (results not shown).

As an example, the model for the mean *iv/g* for trees in naturally regenerated stands with no cuttings within ten years of the measurement was:

$$\log\left(\mathrm{E}\left[\frac{iv_{ijk}}{g_{ijk}}\right]\right) = f_{1,sp_{ijk}}\left(dbh_{ijk}, \overline{dbh}_{i.}, BA_i\right) + f_{2,sp_{ijk}}\left(fh_{ijk}\right) + f_3(alt_i) + \beta_1 \log(ets_i) + \beta_2 sp.1_{ijk} + \beta_3 sp.2_{ijk} + \beta_4 sp.3_{ijk} + \beta_5 birch_{ijk} + \beta_6 (ct4_{ij}) + \beta_7 stone_{ij},$$

$\frac{iv_{ijk}}{g_{ijk}} \sim$ Gamma, (1).

where $\mathrm{E}\left[\frac{iv_{ijk}}{g_{ijk}}\right]$ is the expected value of $\frac{iv_{ijk}}{g_{ijk}}$ of tree k in stand j on plot i,

iv_{ijk} is the mean annual volume increment of the previous five years (m^3 a^{-1}),

dbh_{ijk} is diameter (cm) at 1.3 m and $g_{ijk} = \pi(dbh_{ijk}/200)^2$ is basal area (m^2) of tree k,

$\overline{dbh}_{i.}$ is the basal area weighted mean diameter (cm) on plot i,

$fh_{ijk} = \frac{vol_{ijk}}{g_{ijk}}$ is the form height (m), and vol_{ijk} is the volume (m^3) of tree k,

BA_i is basal area (m^2/ha) of trees on plot i calculated as a weighted sum of trees,

alt_i is the altitude of plot i (m),

ets_i is the mean effective temperature sum (degree days, daily mean T > 5 °C) for the period 1991 – 2020 on plot i,

$stone_{ij}$ is a dummy (0,1) variable, which indicates whether the stand j on plot i was on bedrock or exceptionally stony soil,

sp_{ijk} is tree species group (factor variable with three levels 1 = pine, 2 = spruce, 3 = broadleaved tree species),

$sp.1_{ijk}$, $sp.2_{ijk}$, $sp.3_{ijk}$ are dummy variables for tree species groups,

$birch_{ijk}$ is a dummy variable for tree species 'birch',

$ct4_{ij}$ is a dummy variable for latest cutting 11 – 30 years before inventory measurement.

The model for the log of the shape parameter had similar smooth components to $f_{1,sp}$ and $f_{2,sp}$ in model (1).

$f_{1,sp}$ was included in the model for evaluating the social position and competition between trees. It was smoothed by tree species group as a tensor product between a 2-dimensional smooth (tree *dbh*, mean *dbh* of all trees on the plot) and a 1-dimensional term (*BA*, which is linked to stand density). Tensor product smooths are useful for describing the effects of covariates measured in different units. The smoothing basis was a thin plate regression spline (Wood 2017). The models were fitted using the function gam() in R package mgcv (Wood 2023) (see Supplementary Material).

Models similar to model (1) were fitted for trees in naturally regenerated stands with cuttings within 10 years before inventory in regions 2 and 3. In the northern regions 4 and 5, forests are typically dominated by Scots pine and cuttings (thinnings) are not as common as in the south. Therefore, a simpler model was used in which the smooth term $f_{1,speciesgroup_{ijk}}\left(dbh_{ijk}, \overline{dbh}_{i.}, BA_i\right)$ was replaced by two smooth terms $f_{1'}\left(dbh_{ijk}, \overline{dbh}_{i.}\right)$ and $f_{1''}(BA_i)$, common to all tree species groups. For artificially regenerated stands, models similar to model (1) were used in

NFI9 – NFI12. For the older data, simpler formulations were used. Due to their small amount in the earlier inventories, all artificially regenerated stands were combined into the same data set in northern regions 4 and 5. Moreover, the number of trees in artificially regenerated stands in region 4 in NFI6 was only 104 and the smooth terms were excluded from the model.

2.3. Measured and predicted volume increments and their difference

Predicted values of *iv/g* were produced for all sample trees from the fitted GAM models using the predict.gam – function of the R-package mgcv. After the prediction step, we had thus seven predicted values (models for NFI6 – NFI12) for each of the 300 622 sample trees with one measured *iv/g* in NFI5 – NFI13 (data collected 1964 – 2022). We used the average of those seven predictions as the predicted value of *iv/g*.

In the next step, we used the tree data to calculate two different estimates for the mean annual volume increment per hectare (iV, m^3/ha a^{-1}). The first estimate was calculated using increments measured for individual trees ($\widehat{iV}_M$). The second estimate was based on the predicted increments ($\widehat{iV}_P$) (for the calculation of mean increments per area unit, see Supplementary Material).

We estimated $\widehat{iV}_M$ and $\widehat{iV}_P$ and the difference $\widehat{iV}_M - \widehat{iV}_P$ from NFI5 (NFI6 in region 5) to NFI13 for the sampling regions 2 – 5. In addition, these mean increments were produced for 75 × 75 km grid elements in order to study the geographic variation in more detail.

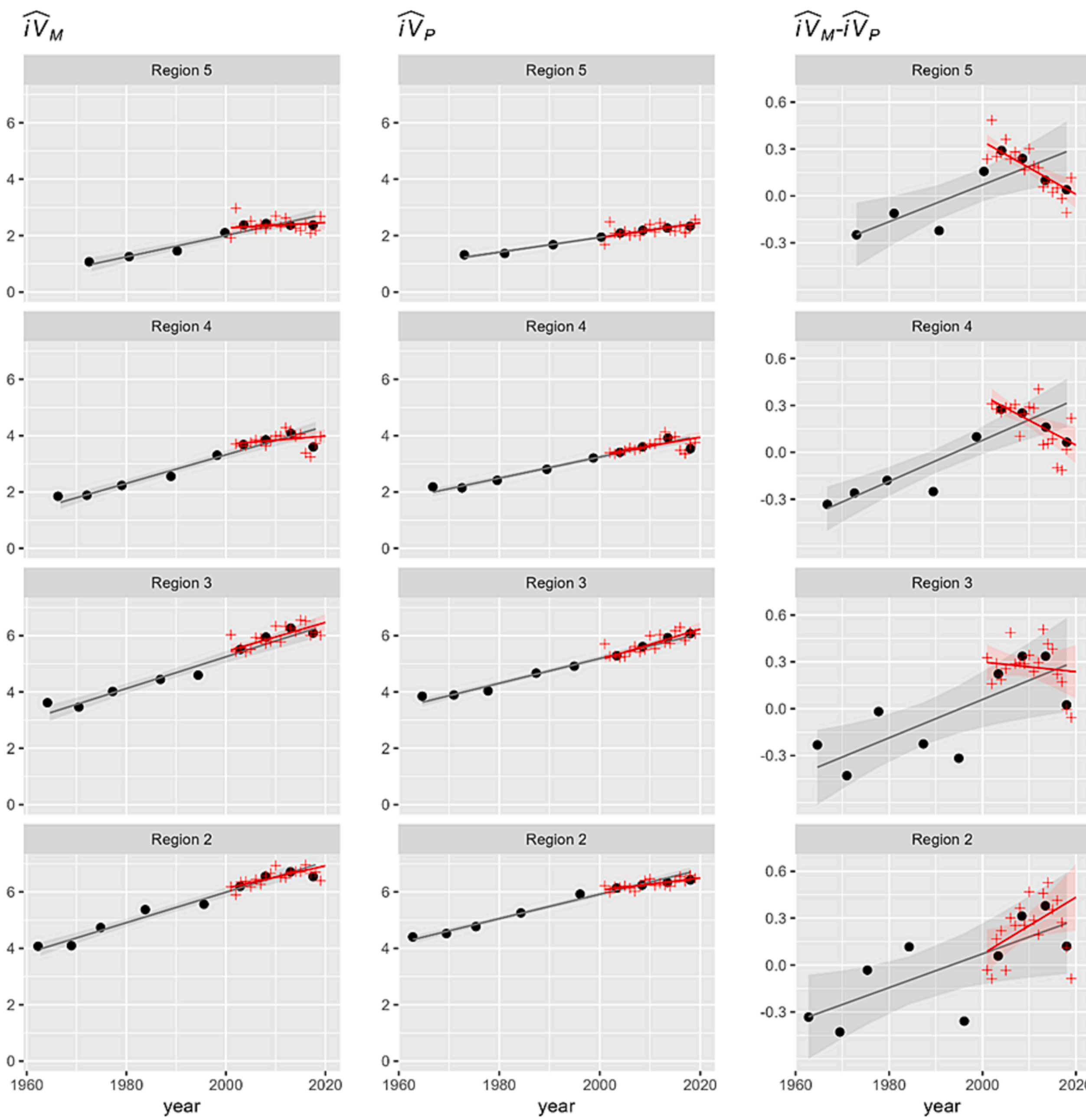

Fig. 3. The measured volume increment (m^3/ha a^{-1}) (left column), the model-predicted increment (middle) and their difference (right) for forests on mineral soils (for regions see Fig. 1). The black dots indicate the means for the increment measurement period of an individual forest inventory (placed at the center year of the inventory period), the red crosses give estimates for data collected during an individual year. For example, data collected before the end of growing season in 2022 is represented by a cross in 2019, the middle-year of the increment measurement period 2017 – 2021. The linear trend line over the whole study period is given with a black line, and the trend over 2001 – 2019 with a red line. The shadowed areas around trend lines indicate 95 % confidence regions.

We also estimated linear trends of $\widehat{iV}_M$, $\widehat{iV}_P$ and $\widehat{iV}_M - \widehat{iV}_P$ over NFI periods for sampling regions and grid cells. The long-term trends and their 95 % confidence regions were estimated by fitting linear trendlines to NFI5 (NFI6 in region 5) – NFI13 increment estimates using R package lm. Since the inventory field work proceeded by regions before year 2004, the increment estimates for regions 2 – 5 do not cover exactly the same years and the beginning year of the increment series is not the same in each region. Since year 2004, all regions have been covered by field measurements each year. For this part of the data, we estimated the increments of the previous five years and trendlines using data collected during an individual year. All increment estimates were derived also for the tree species groups (pine, spruce, broadleaves) separately.

3. Results

The key results include the development of the measured increment ($\widehat{iV}_M$), the predicted increment ($\widehat{iV}_P$) and the difference of these ($\widehat{iV}_M - \widehat{iV}_P$), the difference being interpreted to be mainly induced by changes of the environment. We present these separately for all tree species and for Scots pine, Norway spruce and broadleaves. In addition, results are provided in more geographical detail by using a 75 × 75 km grid.

3.1. Measured vs. Predicted increment, all tree species

The difference in mean increment is very large across the north–south gradient in Finland (Fig. 3). The current increment in region 5 is about one third of the increment in the southernmost region 2. Back in the 1960s the proportional difference was even larger (4.0 m^3/ha a^{-1} vs. 1.0 m^3/ha a^{-1}).

An increment increase from the 1960s to present is evident in each region as indicated by the black trend lines (Fig. 3, left column). The model predictions (middle column) also display rising trends, suggesting that changes in growing stock have had a strong effect on the increased productivity. The measured increment no longer shows an increase between NFI12 (sample tree increments from 2009 to 2018) and NFI 13 (2014 – 2022). Thereagainst, model-predicted values have increased also during recent years, apart from the notable exception of region 4. The latter suggests that forests are mostly still developing into a direction favorable for growth.

The difference of measured and predicted increment (Fig. 3, right column) is interpreted to reflect the effects of the changing environment on growth. The black trend lines indicate a rising trend in each region from the 1960s to present. The estimated trendline slopes in regions 2, 3, 4 and 5 were 0.0108, 0.0123, 0.0131 and 0.0118 (Table 2), and their p values 0.051, 0.026, 0.001 and 0.021, respectively. The results for individual inventories (black dots) show large variation, especially in regions 2 and 3. The measured increment was almost invariably below predicted from the 1960s to the turn of the century in each region.

During the early years of the current century the measured volume increment has been well above the model predictions in each region. During 2001 – 2022 (Fig. 3, right column, red trend lines), a turn towards lower values has occurred in the two northern regions 4 and 5 (the estimated slopes for the red trend lines −0.016 and −0.017, respectively with $p < 0.01$). Region 3 shows a limited, not significant ($p = 0.646$) downward change, but in region 2 the trendline covering the past two decades is a rising one (slope estimate 0.018, $p = 0.042$).

In recent years, the difference of measured and predicted increment has been close to zero in every region, indicating environmental conditions similar to the average of the modelling period (NFI6 – NFI12), which includes sample tree increments from the years 1966 – 2018). Thus, a clear turn towards less favorable environmental conditions seems to have occurred. Note also the low values in recent years (Fig. 3, red crosses).

3.2. Measured vs. Predicted increment for tree species groups

3.2.1. Scots pine

The development of Scots pine differs strongly from the combined results for all species. The measured annual volume increment of pine increased from 1.4 m^3/ha a^{-1} to 2.2 m^3/ha a^{-1} in region 2 during the study period, and in every other region the proportional change has been even larger (Fig. 4). The steep rising trends also in the predicted values suggest that a large share of the development can be attributed to changes in growing stock.

The latest inventory is an exception to the trend, as both measured and predicted values are below the level of the preceding inventories in each region. The mean measured increment of Scots pine has dropped from 2.8 m^3/ha a^{-1} (NFI12) to 2.3 m^3/ha a^{-1} (NFI13) in region 3 and from 2.7 m^3/ha a^{-1} to 2.1 m^3/ha a^{-1} in region 4.

The environment-induced growth component (measured-predicted) shows a long-term rising trend also for Scots pine (Fig. 4, black trendline), which is statistically significant in the northern regions 4 and 5 (trend slope estimates 0.0071 and 0.0072 and p values for estimated trend slopes 0.011 and 0.040, respectively). In the southern regions 2 and 3 the estimated long-term trend slopes are smaller in value (0.0029 and 0.0042) and not statistically significant (p values 0.069 and 0.091). Contrary to that, the red trend-lines, including years 2001 – 2021, indicate a diminishing environmental effect on pine increment during the current century (Fig. 4, right column). This diminishing effect is not statistically significant in the southernmost region 2, where also the long-term increase was low. In regions 3 and 4, the environment-induced growth component shows particularly low recent values.

The difference between measured and predicted values ($\widehat{iV}_M - \widehat{iV}_P$) has been negative during the latest inventory in regions 2, 3 and 4 (Fig. 4, right column, rightmost black dots), indicating that environment has been less favorable for Scots pine in recent years than on average during the modelling period of 1966 – 2018.

3.2.2. Norway spruce

The proportional increment increase over time has not been nearly as large for Norway spruce as for Scots pine. An increase of less than 50 % has been observed in regions 2, 3 and 4 from the 1960s to the early 2020s (Fig. 5). Increment has roughly doubled in the northernmost region 5, but in absolute terms the species represents only about one fourth of forest growth in the area. Similarly, predicted values indicate a much less steep trend than for Scots pine.

The long-term development of the environment-induced growth component ($\widehat{iV}_M - \widehat{iV}_P$) shows a long-term rising trend (Fig. 5, right, black trend-line), which is statistically significant in the northern

Table 2
Coefficients of the linear trends in each region (NFI5 – NFI13, all tree species, black lines in Fig. 3) in measured and predicted volume increment, expressed as m^3/ha a^{-1}, the environment-induced growth component (measured-predicted) and its share of the measured trend, expressed as a percentage.

Region	Measured, $\widehat{iV}_M$		Predicted, $\widehat{iV}_P$		Measured-Predicted, $\widehat{iV}_M - \widehat{iV}_P$		Share, %
	Coeff.	Std error	Coeff.	Std error	Coeff.	Std error	
2	0.0541	0.0040	0.0432	0.0023	0.0108	0.0046	20
3	0.0563	0.0051	0.0440	0.0027	0.0123	0.0044	22
4	0.0508	0.0040	0.0376	0.0025	0.0131	0.0025	26
5	0.0380	0.0046	0.0262	0.0015	0.0118	0.0038	31

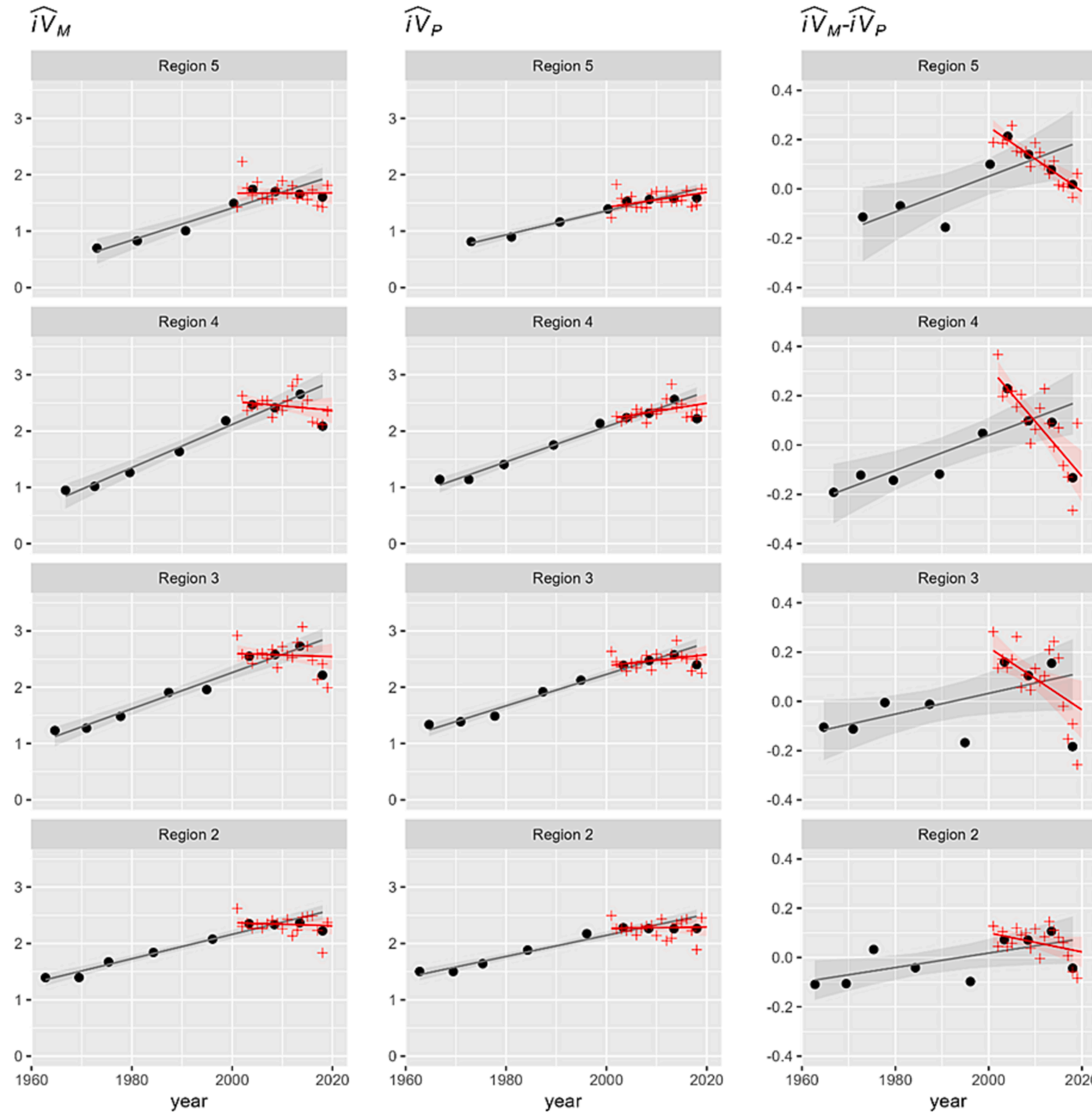

Fig. 4. The measured volume increment (left column) of Scots pine, model-predicted increment (middle) and their difference (right) in regions 2 – 5 (see Fig. 1). The mean increment of the species has been calculated over the total forest area in each region, not only for those forests where Scots pine is dominant. The black dots indicate the mean increment level during increment measurement period of an individual forest inventory. The red crosses are the increment estimates based on measurements during an individual year (data available since 2004). The trend over the whole study period is given with a black line and the trend for 2001 – 2019 with a red line. The shadowed areas around trend lines indicate 95% confidence regions.

regions 4 and 5 (trend slope estimates 0.0054 and 0.0027 and p values for estimated trend slopes 0.001 and 0.020, respectively). In the southern regions 2 and 3 the estimated long-term trend slopes are at the same level (0.0043 and 0.0045), but they are not statistically significant (p values 0.185 and 0.092). The uncertainty in the trend estimates of the southern regions is mainly due to the unfavorable growth years in the 1990s.

The predicted values (Fig. 5, middle column) suggest that forests have not developed into a direction favorable for growth since the mid-1990s in region 2. Thereagainst, volume increment estimates show an increase from 2.4 m^3/ha a^{-1} during the 1990s to the most recent 2.7 m^3/ha a^{-1}.

For region 3, the predicted values suggest that forests have developed favorably and should have induced an increment increase. This was indeed observed, but the increase in measured volume increment has been even larger, as shown by the upward trend in $\widehat{iV}_M - \widehat{iV}_P$ values (Fig. 5, right column). Also, in region 4 the increment increase has been larger than indicated by the model. For region 5 the model suggests steady development, as has indeed been observed.

Overall, the environment-induced increment change ($\widehat{iV}_M - \widehat{iV}_P$) produced a long-term pattern fairly similar to Scots pine: mostly negative values from the mid-1960s to the 1990s, and mainly positive ones during the early years of the current century. The trend for years 2001 – 2019 shows a marked difference: unlike for Scots pine, the environment-induced increment change has stayed close to the level of the preceding inventories in the northern region 5 and increased sharply in regions 2

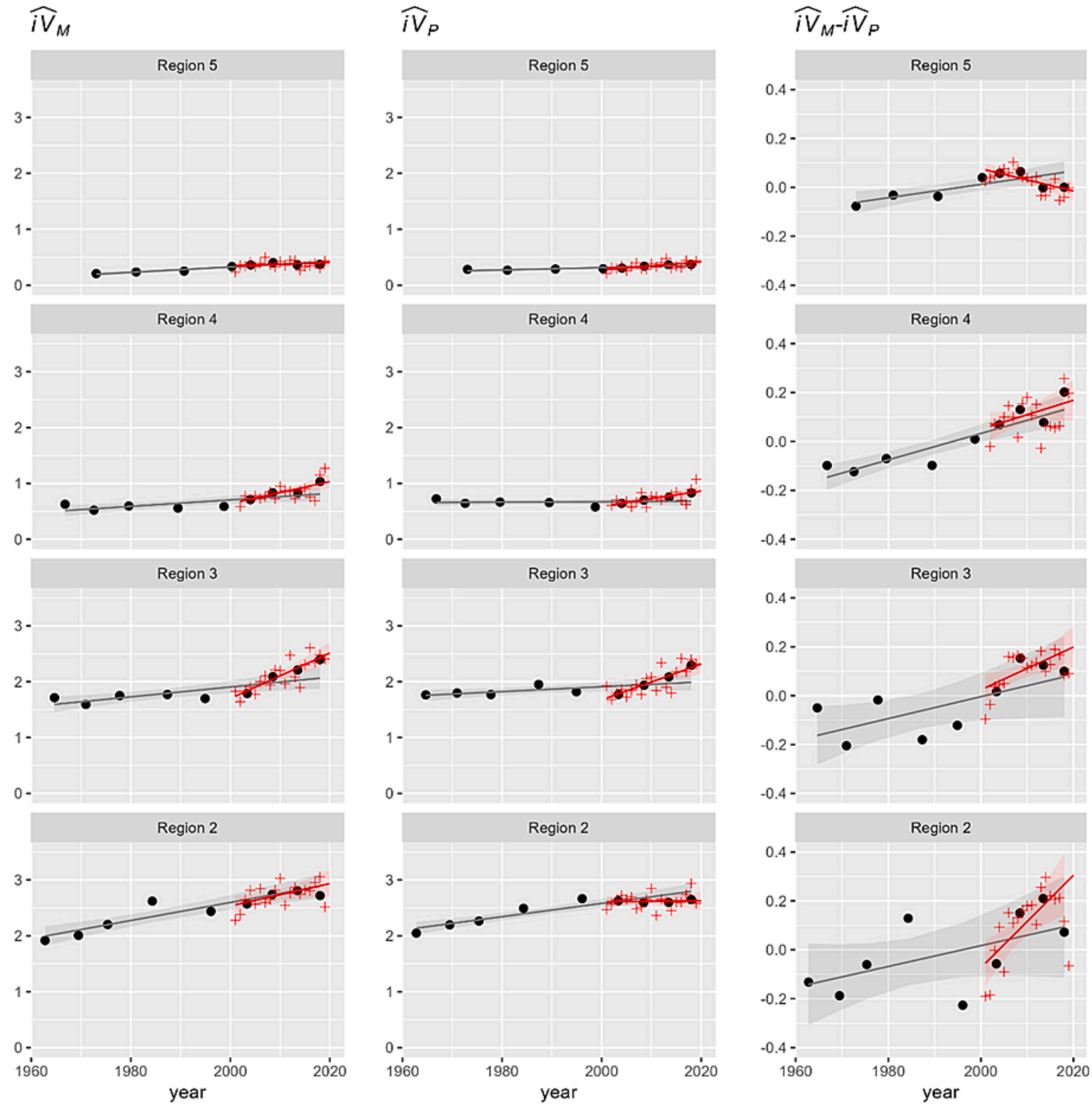

Fig. 5. The measured volume increment (left column) of Norway spruce, model-predicted increment (middle) and their difference (right) in regions 2–5 (see Fig. 1). The mean increment of the species has been calculated over the total forest area in each region, not only for those forests where Norway spruce is dominant. The black dots indicate the mean increment level during increment measurement period of an individual forest inventory. The red crosses are the increment estimates based on measurements during an individual year (data available since 2004). The trend over the whole study period is given with a black line, and the trend for 2001 – 2019 with a red line. The shadowed areas around trend lines indicate 95% confidence regions.

and 3 (Fig. 5, right column, red trend line). Note the very large fluctuations between inventories, including the low level of $\widehat{iV}_M - \widehat{iV}_P$ in the 1990s in region 2. Also, the results for individual years (Fig. 5, right column, red crosses) show large fluctuations, including lower values in regions 2 and 3 in recent years.

3.2.3. Broadleaves

The increment of broadleaves shows a steady development. Increment has more than doubled from the mid-1960s to present (Fig. 6). An exception to this occurred in region 4, where the increment of broadleaves had more than doubled by the mid-2010s, but in the recent years both observed and predicted increment have been well below the preceding ones.

The difference of measured and predicted increment estimates ($\widehat{iV}_M - \widehat{iV}_P$) displayed a similar general pattern for broadleaves as for conifers. The long-term trend in $\widehat{iV}_M - \widehat{iV}_P$ from the 1960s to present is clearly upward in regions 2 and 3, and to a lesser degree also in region 5. No linear trend exists in region 4. For 2001 – 2021, the slopes of the trend lines are not significant (Fig. 6, red line).

3.3. The share of the environment-induced component of the observed increment increase

Like Henttonen et al. (2017), we calculated the share of the unexplained growth component of total measured increment increase (m^3/ha a^{-1}) in each region. The results were rather similar to Henttonen et al.

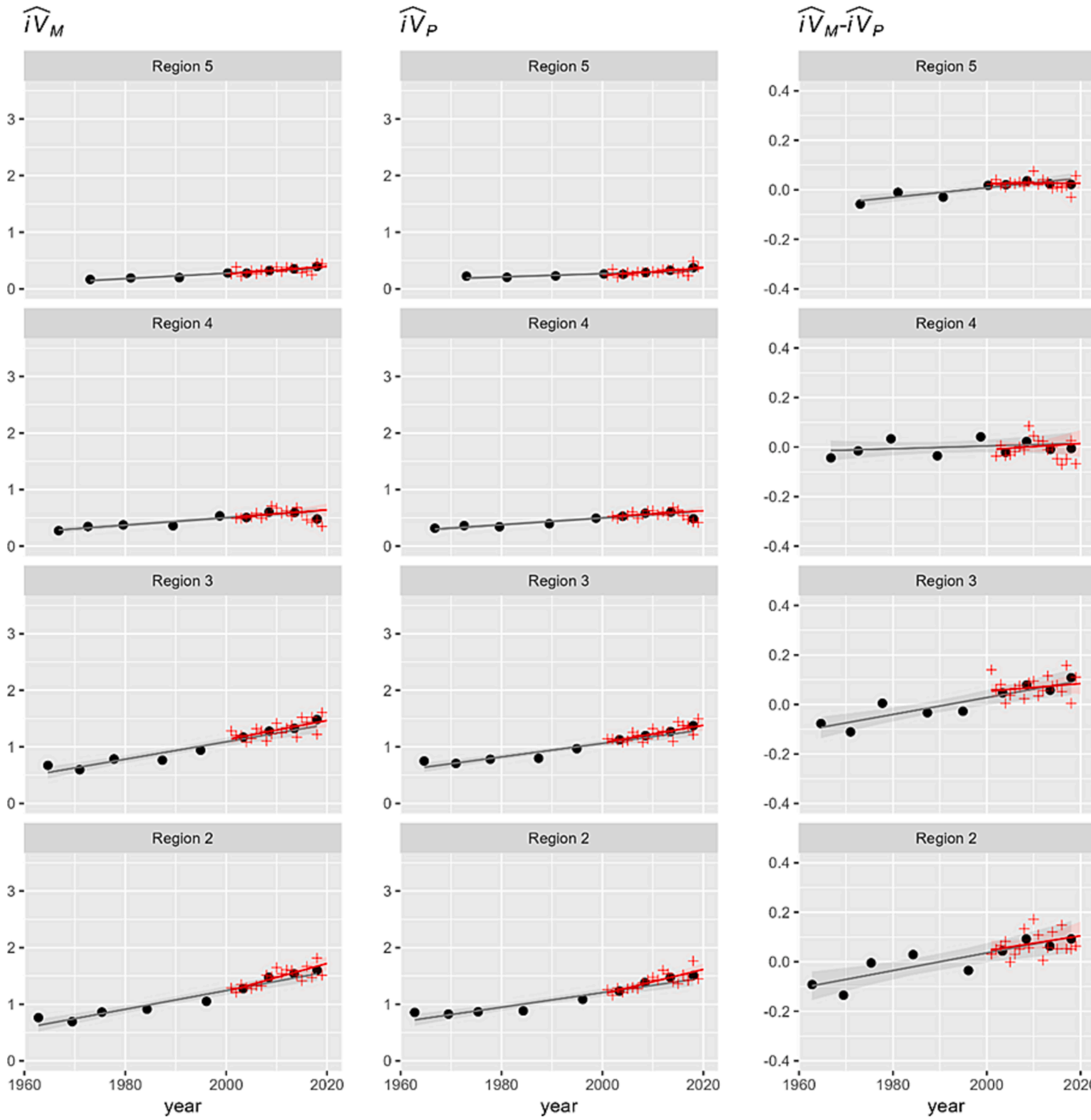

Fig. 6. The measured volume increment of broadleaved trees (left column), the model-predicted increment (middle) and the difference of these (right) in regions 2 – 5 (Fig. 1). Note, that increment of the species group has been calculated for the total forest area of each region, not only for the forest area dominated by broadleaves. The dots indicate the mean increment level during increment measurement period of an individual forest inventory. The crosses indicate the increment estimates based on measurements during an individual year (data available since 2004). The trend over the whole study period given with a black line, and the trend for 2001 – 2021 with a red line.

(2017) in that the share of the unexplained component of growth was larger in the northern regions (31 % in region 5 and 26 % in region 4) than in the south (22 % in region 3 and 20 % in region 2). Unlike Henttonen et al. (2017), the presented figures do not include the accumulated effects, due to the increased growing stock volume, caused by the environmental-induced change in forest growth.

3.4. The spatial distribution of growth trends

How strong have the trends in measured, predicted and measured-predicted volume increment ($\widehat{iV}_M, \widehat{iV}_P$ and $\widehat{iV}_M - \widehat{iV}_P$) been from the 1960s to present at different locations in Finland? Fig. 7 provides the trends in finer geographical detail using 75 × 75 km grid elements.

The grid-map indicates that largest measured increment increases have occurred in south-eastern part of Finland during 1964 – 2022 (Fig. 7). The model predictions indicate that the largest increases indeed should have taken place in the same region. The environment-induced increment component ($\widehat{iV}_M - \widehat{iV}_P$) (Fig. 7) does not yield an equally clear pattern. However, the trend has been positive in almost every grid cell. The largest differences ($\widehat{iV}_M - \widehat{iV}_P$) have been observed in the coastal regions and some eastern grid elements at the middle part of the country. The statistical significance of the trend varies quite a lot, but no clear geographical pattern emerges (Fig. 7).

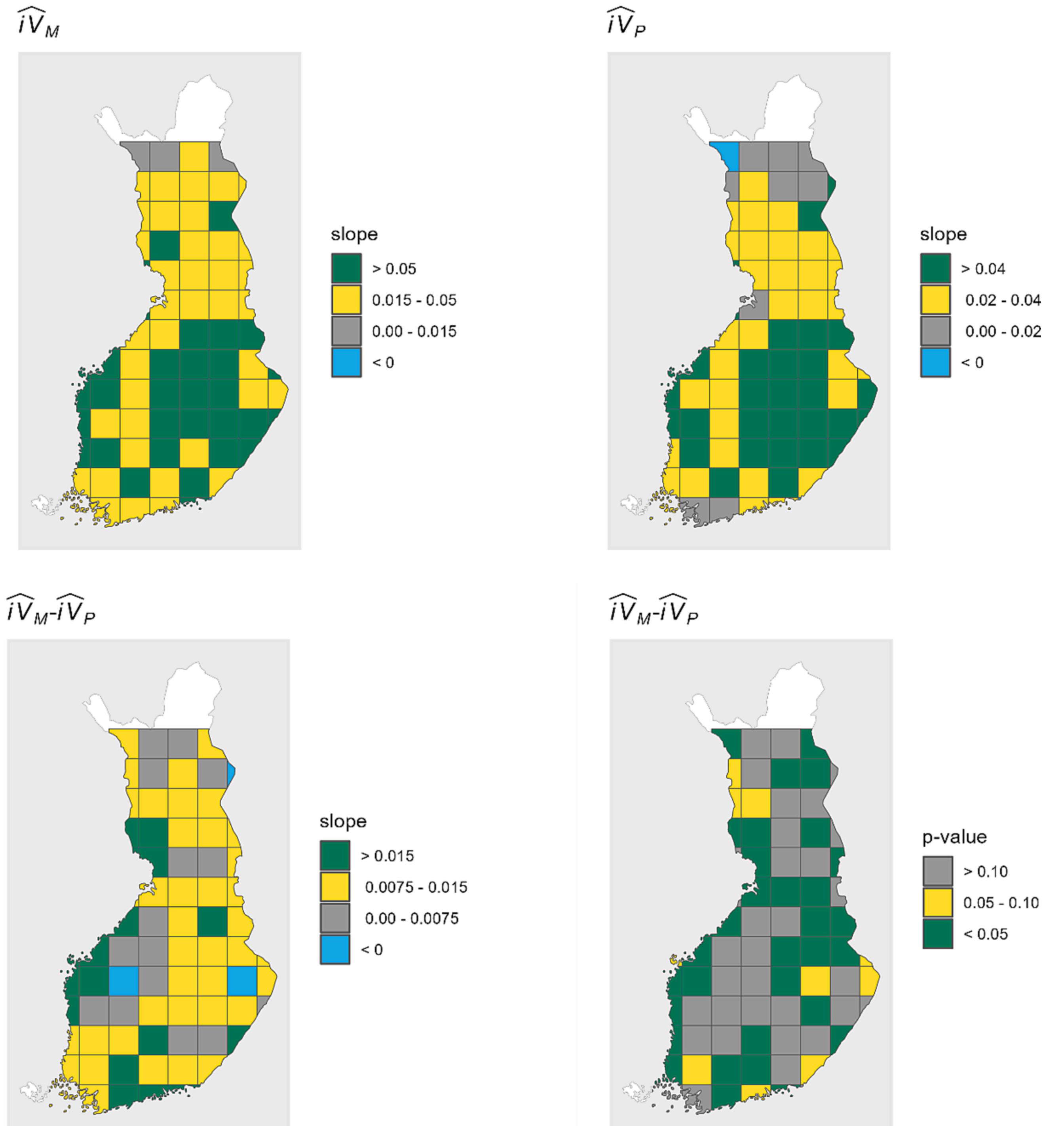

Fig. 7. The trends (m^3/ha a^{-1}) in measured (upper left) and model-predicted (upper right) volume increment for 1964 – 2021, the difference of these two (lower left) and the p-value of the trend estimate (lower right) in a 75 × 75 km grid.

4. Discussion

4.1. The long-term trend

Forest growth shows a long-term rising trend in Finland over the period 1964 – 2022. The increase from the level of 57 million m^3 a^{-1} - representing the start of our study period - to the latest 103 million m^3 a^{-1} has been large (Official statistics of Finland, 2023a). An increase has been observed for all tree species groups over the investigation period as well with pine showing the largest increase, both proportionally and in absolute terms. The area of land available for forestry has shown a slight reduction (26.7 mill. ha -> 26.2 mill. ha) during the same period. The area of productive forest land, assumed to produce on average a minimum of 1 m^3/haa^{-1} of stemwood over a rotation, has increased by 8 %. However, the increase has been solely attributed to the drainage of peatland forests as much as 4.65 mill. ha (Korhonen et al. 2017), which are not part of our study.

Over the period of almost six decades, our models suggest that annual volume increment of forests should have increased strongly, but an even larger increase has actually taken place. The result suggests that also the environment has become more favorable for forest growth in Finland.

Over the past two decades, the models suggest that the combined increment of all species should have increased in every region, but the measured increment has been steady at the two northern regions. Also at region 3, increment has not developed as favorably as predicted, while at region 2 the difference measured-predicted has become larger. As to the latest forest inventory (field measurements in 2019 – 2022), our models suggest an increment increase as well, apart from region 4, but a reduction has occurred in each region, suggesting that the environment has not been as favorable for forest growth as it used to be.

Henttonen et al. (2017) used a rather similar approach for studying the role of the environment behind the measured rather fast increment increase in the forests of Finland. They reported a rising environment-induced increment trend that started from the mid-1990s, the latest observations being from the 5-year period 2009 – 2013. Our results indicate that the rising trend in $\widehat{iV}_M - \widehat{iV}_P$ has at least temporarily ended. Even if climatic warming will induce a long-term growth increase in the boreal forests, one shouldn't expect a monotonously rising trend, as weather variation between years will include less favorable periods, such as the one observed in recent years in Finland.

Over the study period Scots pine shows the largest increase. However, our models suggest a steady or even a decreasing growth development for the species over the past two decades. In each case, an increment reduction has occurred during 2001 – 2019 and $\widehat{iV}_M - \widehat{iV}_P$ has decreased. Thus, in recent years the environmental factors have become less favorable for the Scots pine than during the early years of the ongoing century.

Norway spruce shows a smaller increase, both in absolute terms and proportionately. The difference $\widehat{iV}_M - \widehat{iV}_P$ also shows a positive trend over the study period. Unlike for pine, the models suggest a continuation of the increment increase over 2001 – 2019, except for region 2. The difference of measured and predicted increment has also become gradually larger during the past two decades. However, the most recent results show a drop in the southernmost regions 2 and 3.

For broadleaves, accounting for 20 % of the growing stock, a general increment increase was observed. The difference of measured-predicted has also become continuously larger. This applies even to the latest years, and the difference of measured and predicted increment implies no adverse turn in environmental conditions.

4.2. Reversible variation or a turning point in growth?

The growth estimate for NFI12 (2009 – 2018, 108 million m^3 a^{-1}) was quite a bit larger than for NFI13 (2014 – 2021, 103 million m^3 a^{-1}). The key question is: are we witnessing a turning point of the long increasing growth trend, or are the recent years just a temporary downturn, part of natural variation.

Looking for causal factors behind the growth decline, the question should actually be broken down into two. Can the recent growth reduction in the forests of Finland be explained by natural short-term climatic variation? Secondly, does forest inventory data provide evidence of changes in growing stock that have been detrimental for productivity?

Our study answers the first question by analyzing the difference of measured and predicted increment ($\widehat{iV}_M - \widehat{iV}_P$), termed as the environment-induced growth component. As the variable shows a large drop from NFI12 to NFI13, the results clearly suggest that the environment has played a large role in the recent reduction.

As to question two, the role of changing growing stock behind the decline, our study answers the question using models that predict growth as a function of properties of the sample trees and the surrounding stand, as well as altitude and long-term temperature sum.

The overall results are shown in Fig. 3. For three regions out of four (2, 3 and 5), the result is clear: the models predict rising forest growth, also for recent years. In other words, we should not have expected a recent downturn of forest growth due to detrimental changes in growing stock. The exception is region 4, where the model predicts a notable recent reduction, though not as large as the observed one.

To summarize, our approach provides little support for the theory that the recent growth reduction would have been related to forest management in the form of reduced growing stock that would have resulted in lowered growth. Thereagainst, the difference of measured and predicted growth has become smaller in recent years, suggesting that environmental factors have played a role.

4.3. The spatial pattern of growth changes

The grid maps revealed that the steepest trends in measured increment have occurred in southeastern parts of Finland. Changes in the predicted increment were largest in the same area.

The grid map presenting the difference of measured and predicted increment – the environment-induced growth component – did not yield a consistent pattern. The relative share of the environment-induced growth component was largest in the northern parts of Finland – a finding similar to observations by Henttonen et al. (2017).

4.4. Potential causal factors behind the recent decline

While we did not attempt to analyze the causes of the two-fold growth development, one can elaborate potential causes on a qualitative level. Our model did not suggest a growth reduction due changes in growing stock, but it is of interest to take a look at factors that do have potential for weakening forest growth.

The history of silviculture offers a potential reason for differences between the two coniferous species. During a period from the 1960s to the 1980s Scots pine was favored in artificial regeneration and previous spruce forests were turned into pine-dominated stands on a large scale via planting and seeding (e.g., Tomppo et al. 2011). This is reflected in the very large increase of observed Scots pine growth during 1964 – 2022 (Fig. 4, left column). The silvicultural trend was reversed during the 1990s (Official statistics of Finland, 2023b), mainly because pine plantations were frequently damaged by a large moose population. The species rarely feeds on spruce seedlings. Pine plantations on fertile soils also suffered from poor timber quality (Niinemets and Lukjanova 2003, Huuskonen et al. 2014). Today up to 80 % of forests planted annually in Finland are spruce stands. The Scots pine stands regenerated from the 1960s to the 1980s have through aging reached a phase of slower growth on a large scale, and the model predictions for Scots pine growth have indeed levelled off and even turned downwards in recent years. One should note, however, that even though tree age is not included in the predictor variables of the model, tree diameter is, and as the latter is correlated with tree age, some of the aging effect is at least partly accounted by the model.

Large areas of spruce plantations have just reached or are soon reaching their phase of fastest growth. This has been reflected in the recent upward development of the model-predicted spruce growth. Should a study of this type to be repeated a decade or two later, one would still expect higher levels of spruce growth.

In elaborating the effects of age structure on forest growth, one should note that the recent reduction, observed for Scots pine, has occurred during a short period of time. One would expect growth changes related to aging to be more gradual.

In summarizing the latest NFI findings, Haakana et al. (2023) noted changes in cutting methods. Regeneration of forest stands at a younger phase than what used to be the norm and unusually heavy thinning intensities were brought up as potential causes of the observed reduction in forest growth. This could have taxed the growing stock in stands that are in a phase of fast growth. The Finnish legislation regulating forest management was renewed in 2014, leaving more freedom to forest owners for selecting management methods that best meet their goals and preferences. As roughly 10 % of the population of Finland are forest owners, the group is bound to be heterogenous. It is plausible, that some owners value immediate monetary rewards at the cost of lower future revenues.

Apart from large-scale forest damage, major structural changes over large forest areas usually require time. The recent decline in Scots pine growth has occurred rather quickly. Could it be explainable by damage? Several types of forest damage are in fact species-specific. In addition, as fertile sites are generally occupied by spruce or broadleaves and infertile sites by pine, the damage could be specific to site type.

Truly large-scale forest damage have not been reported in recent years in Finland (Nuorteva et al. 2022). Fairly extensive crown breakage by snow have occurred in recent years covering an area of 1,6 mill. hectares (Nuorteva et al. 2022). Severely affected stands have been treated with salvation cuttings. It is, however, difficult to assess the cumulative effects of the snow-damage on forest growth at areal level. In any case, a growth reduction of Scots pine has also occurred in the south, where extensive snow damage have not been reported.

At national level, the difference of annual growth and drain has been strongly positive since the early 1970s in Finland. This still is the case, even though increased cuttings have narrowed the gap in recent years (Natural Resources Institute Finland, 2023). Continuously elevating growing stock suggests increasing growth as well, but the opposite has happened in recent years. Growth has remained stable in southern Finland (regions 2 and 3) and declined in the north (regions 4 and 5) (Official statistics of Finland, 2023a).

Spiecker et al. (1996) observed rising growth trends in a number of European countries and emphasized the role of nitrogen deposition as a likely causal factor. Kahle et al. (2008) arrived at a similar conclusion. Nitrogen deposition peaked in Finland roughly three decades ago (Vuorenmaa 2004), but the mobilization of the nitrogen accumulated into soil is a slow process.

Recent forest research has focused on the effects of the continuously increasing CO_2 in the atmosphere. Using NFI data, Davis et al. (2022) reported a strong and consistently positive effect of CO_2 on wood volume in temperate forests of the United States. However, Cabon et al. (2022) reported that gross primary production - measured by eddy covariance techniques - and wood growth display a strong decoupling, especially in regions where cold temperatures or dryness limit growth. The finding could offer a potential explanation for our observations of continuously rapid Norway spruce growth but reduced Scots pine growth, the latter species being common on drought-sensitive sites. There are also indications that while young forests display a strong growth response to CO_2 fertilization, in old forests CO_2 fertilization has increased the carbon uptake of trees, but this has not been reflected in volume growth (Jiang et al. 2020). Again, CO_2 fertilization is a slowly accumulating process, and one would expect resulting growth changes to be gradual as well.

The factors listed above include structural changes in forests, as well as some environmental changes, possibly contributing to the observed forest growth in Finland. However, none of them appears to convincingly explain the recent reduction. Therefore, the phenomenon may well be related to natural climatic growth variation, which can be quite strong in the boreal zone. This possibility is further suggested by the fact that the gap between measured growth and the level suggested by our models has narrowed in recent years.

To be more exact, our data suggests that the environment-induced growth component has been less favorable for Scots pine, but not for Norway spruce or the broadleaved trees. As annual variation of Scots pine and Norway spruce growth have been shown to follow rather different patterns in Finland (Mäkinen et al. 2002, Henttonen et al. 2014), it is entirely possible that recent climatic variation has been favorable for spruce but not for pine. Mäkinen et al. (2022) analyzed the causes of the recent reduction of pine growth in northern Finland. They brought up individual dry summers of 2018 and 2019, which occurred simultaneously with formation of narrow tree-rings, but also emphasized the role of abundant flowering that uses tree reserves, leaving less resources for growth. A simultaneous growth reduction, also interpreted to be associated with a dry summer, occurred in the neighboring Sweden (Roberge et al. 2023).

Girardin et al. (2016) suggested that tree growth at the boreal zone is generally linked to the hydroclimatic cycle. Dendroclimatic studies using data from Finland have generally not arrived to conclusions of this type. Scots pine growth has been linked to July temperatures (Mikola 1950, Korpela et al. 2011, Henttonen et al. 2014). Norway spruce growth has correlated more strongly with temperatures during an earlier phase of the growing season (Mäkinen et al. 2002, Henttonen et al. 2014). Weakening of the temperature signal in tree growth, reported for many parts of the boreal zone by Babst et al. (2019), indicates that deductions of this type should be treated with caution, however.

If high July temperatures promote Scots pine growth in Finland, and low growth of the species has been observed in recent years, have the July temperatures been low in those years? Generally, no. The temperatures have been closer to the other extreme (Finnish Meteorological Institute 2023). A superficial comparison of this type does not yield a straight-forward explanation. Henttonen et al. (2017) discovered similarities with the unexplained growth components and temperate sums using data that extended to 2010, but the growth of individual species was not analyzed.

Theoretically, our findings for recent years could reflect a weakening of the climatic signal in tree-rings, termed divergence (e.g., Briffa et al. 1998, Piao et al. 2014). The phenomenon could be explained by acclimation to a changed environment (e.g., Ainsworth and Long 2005), but it is extremely difficult to verify such a gradual physiological process.

4.5. Previous results from studies using forest inventory data

Inventory-based studies from the neighboring Sweden, representing on average a milder climate, have yielded varying results. Elfving and Tegnhammar (1996) observed a clear rising trend in both basal area and height growth of individual Scots pines and Norway spruces during 1953 – 1992. Thereagainst, Mensah et al. (2023) observed a rising trend in height growth, but not in basal area growth of individual trees during 1983 – 2020. We analyzed changes in volume growth per hectare, a parameter not directly comparable to height or basal area growth of single trees. It is worth noting that the data used by Mensah et al. (2023) did include a sizable recent reduction in basal area growth after 2015. Without it, a statistically significant rising trend would most likely have been observed in basal area growth as well.

4.6. Methodological aspects

We used data from almost the whole study period (1966 – 2018) for calibrating the models. Thus, the predicted growth level does not correspond to the level calculated by Henttonen et al. (2017), who calibrated their models based on the NFI data during 1986 – 2008.

The models were separately fitted for the regions and inventory rotations, and their predictions were then averaged. Thus, the models were used to estimate volume increment level, assuming trees would have been growing as on average in NFI6 – NFI12. This is the reference level, which was calculated in the same way for all trees in the dataset. There is naturally a large random variation around the models, which is affected by both model errors and measurement errors (e.g., McRoberts and Westfall 2014). By including several inventories, we attempted to reduce the effect of model errors on the average estimate. The primary interest was how deviations from the reference level change over time and in different regions. We also tested an alternative where the models were fitted only to the NFI9, NFI10 and NFI11 data, and the results were almost the same as presented here. The key question is whether the models include all essential independent variables, i.e., can the difference between the measured and modeled increment be caused by some essential process that is not described by the independent variables of the models, or is it primarily related to changing environment, as we assume.

A reservation regarding the sample size is appropriate. The number of sample trees cored as part of the Finnish NFI has dropped, especially during 2019 – 2022, as the increment estimation in NFI has been based on repeated measurements on permanent plots since 2014. The accuracy of the presented estimates is thus lower for recent years. The low recent growth in region 4 could at least partly be a result of this. A reduction of mean increment of about 0.5 m^3/ha a^{-1} was reported for both measured and predicted growth. Natural growth variation could well cause a temporary drop of that size. It is, however, hard to explain, how forest structure would have developed in this fashion during a period of less than ten years.

The small number of cored NFI sample trees could also have an especially notable effect on the results on the growth of broadleaves, which constitute only 20 % of the cubic volume of the forests of Finland.

The limited sample size for recent years is also reflected in trend estimation for Figs. 2 – 5. In calculating the linear trends of the environment-induced growth component for 1964 – 2022 and for 2003 – 2022 each observation has had the same weight. Therefore, recent years have received less weight than they would have, if the sample size had remained balanced over the years.

When a decades-long time series is used, measurement techniques and possibly also definitions applied have usually changed over time. An example are the devices used for measuring tree height in the Finnish NFIs, which have changed from Suunto hypsometer to Forester Vertex. The possible effects of the change were discussed in detail by Henttonen et al. (2017).

4.7. Final remarks

The use of forests is facing unforeseen challenges in Finland. The traditional utilization of raw wood by forest industries has reached record-high levels in recent years (Natural Resources Institute Finland, 2023) and on-going investments will bring additional demand for raw wood. Import of raw wood from Russia used to provide an essential share of the raw wood supply of forest industries in Finland, a source not available for the time being.

At the same time, a sizable difference between annual growth and drain still exists, and higher cutting levels still would be required for turning the balance negative. Forests have played a key role in the national carbon balance by providing a large majority of the existing carbon sinks in Finland (Official statistice of Finland, 2023b). In fact, while forests still are a significant carbon sink, recent results indicate that the land use sector turned into a carbon source in 2021, first time for decades (Haakana et al. 2023).

Regulation by the EU on the land use, land use change and forestry sector (LULUCF) seeks to improve natural carbon sinks to make the EU the first climate-neutral continent by 2050. The regulation will produce additional - legally binding - requirements towards protection of land areas and will probably substantially reduce the forest area available for wood production. In early 2023, the LULUCF regulation was revised by replacing former targets with more strict ones, with the aim of improving natural carbon sinks and improving biodiversity in line with the European Green Deal. (European Commission 2023). In 2021, 30 % of annual energy consumption in Finland came from wood. Note, though, that more than half of it consisted of waste of forest industries (Statistics Finland 2023).

The key question is: will the recent growth reduction turn out to be temporary, part of natural variation, or are we witnessing a turning point, followed by permanently lower growth levels. Increasing forest growth would facilitate the compromises needed between competing forms of forest use. A diminishing growth trend could involve severe economic consequences, either in the form of reduced profits from forest-based industries or compensations for the shrinking carbon sink of forests.

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.

Acknowledgements

The study was conducted in the Natural Resources Institute Finland (Luke) and supported by a grant from the Academy of Finland (No. 315495).

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.foreco.2023.121515.

References

Ainsworth, E.A., Long, S.P., 2005. What have we learned from 15 years of free-air CO2 enrichment (FACE)? A meta-analytic review of the responses of photosynthesis, canopy properties and plant production to rising CO2. The New Phytologist 165, 351–372. https://doi.org/10.1111/j.1469-8137.2004.01224.x.

Babst, F., Bouriaud, O., Poulter, B., Trouet, V., Girardin, P., Frank, D.C., 2019. Twentieth century redistribution in climatic drivers of global tree growth. Science Advances 5, eaat4313. https://doi.org/10.1126/sciadv.aat4313.

Barber, V.A., Juday, G.P., Finney, B.P., 2000. Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. Nature 405, 668. https://doi.org/10.1038/35015049.

Boisvert-Marsh, L., Périé, C., de Blois, S., 2014. Shifting with climate? Evidence for recent changes in tree species distribution at high latitudes. Ecosphere 5 (7), 1–33. https://doi.org/10.1890/ES14-00111.1.

Briffa, K.R., Schweingruber, F.H., Jones, P.D., Osborn, T.J., Harris, I.C., Shiyatov, S.G., Vaganov, E.A., Grudd, H., 1998. Trees tell of past climates: but are they speaking less clearly today? Phil. Trans. r. Soc. Lond. b. 353 (1365), 65–73. https://doi.org/10.1098/rstb.1998.0191.

Cabon, A., Kannenberg, S.A., Arain, A., Babst, F., Baldocchi, D., Belmecheri, S., Delpierre, N., Guerrieri, R., Maxwell, J.T., McKenzie, S., Meinzer, F.C., Moore, D.J. P., Pappas, C., Rocha, A.V., Szejner, P., Ueyama, M., Ulrich, D., Vincke, C., Voelker, S.L., Wei, J., Woodruff, D., Anderegg, W.R.L., 2022. Cross-biome synthesis of source vs. sink limits to tree growth. Science 376, 758–761. https://doi.org/10.1126/science.abm4875.

European Commission. 2023. Parliament adopts new carbon sinks goal that increases EU 2030 climate ambition. Press Releases, 14-03-2023 - 12:23 [Referenced: 16.8.2023]. Access method: https://www.europarl.europa.eu/news/en/press-room/20230310IPR77223/parliament-adopts-new-carbon-sinks-goal-that-increases-eu-2030-climate-ambition.

Davis, E.C., Sohngen, B., Lewis, D.J., 2022. The effect of carbon fertilization on naturally regenerated and planted US forest. Nature Communications 13, 549. https://doi.org/10.1038/s41467-022-33196-x.

Dial, R.J., Maher, C.T., Hewitt, R.E., Sullivan, P.F., 2022. Sufficient conditions for rapid range expansion of a boreal conifer. Nature 608, 546–551. https://doi.org/10.1038/s41586-022-05093-2.

Elfving, B., Tegnhammar, L., 1996. Trends of tree growth in Swedish Forests 1953–1992: an analysis based on sample trees from the national forest inventory. Scandinavian Journal of Forest Research 11, 26–27. https://doi.org/10.1080/02827589609382909.

Esper, J., Schweingruber, F., 2004. Large-scale treeline changes recorded in Siberia. Geophysical Research Letters 31, L06202. https://doi.org/10.1029/2003GL019178.

Fei, S., Desprez, J.M., Potter, K.M., Jo, I., Knott, J.A., Oswalt, C.M., 2017. Divergence of species responses to climate change. Science Advances 3, e1603055.

Finnish Meteorological Institute, 2023. Climate Statistics. https://en.ilmatieteenlaitos.fi/climate-statistics.

Girardin, M.P., Bouriaud, O., Hogg, E.H., Bhatti, J. 2016. No growth stimulation of Canada's boreal forest under half-century of combined warming and CO_2 fertilization. PNAS 113(52): E8406-E8414. https://doi.org/10.1073/pnas.1610156113.

Grünzweig, J.M., De Boeck, H.J., Rey, A., et al., 2022. Dryland mechanisms could widely control ecosystem functioning in a drier and warmer world. Nature Ecology & Evolution 6, 1064–1076. https://doi.org/10.1038/s41559-022-01779-y.

Haakana, M., Haikarainen, S., Henttonen, H.M., Hirvelä, H., Hynynen, J., Korhonen, K. T., Launiainen, S., Mehtätalo, L., Miettinen, A., Mutanen, A., Mäkinen, H., Ollila, P., Pitkänen, J., Räty, M., Salminen, H., Tikkasalo, O.-P., Tuomainen, T., Viitanen, J., Vikfors, S., 2023. Suomen LULUCF-sektorin 2021–2025 velvoitteen toteutuminen.

Natural Resources Institute Finland. https://www.luke.fi/fi/documents/suomen-lulucfsektorin-20212025-velvoitteen-toteutuminen.
Hansson, A., Dargusch, P., Shulmaister, J., 2021. A review of modern treeline migration, the factors controlling it and the implications for carbon storage. Journal of Mountain Science 18, 291–306. https://doi.org/10.2747/0272-3646.24.6.520.
Hari, P., Kulmala, L. (Eds.). 2008. Boreal Forest and Climate Change, Springer, 582 p.
Hastie, T., Tibshirani, R., 1986. Generalized additive models (with discussion). Statistical Science 1 (3), 297–318. https://www.jstor.org/stable/2245459.
Henttonen, H.M., Mäkinen, H., Heiskanen, J., Peltoniemi, M., Laurén, A., Hordo, M., 2014. Response of radial increment variation of Scots pine to temperature, precipitation and soil water content along a latitudinal gradient across Finland and Estonia. Agr. Forest Meteorol. 198–199, 294–308. https://doi.org/10.1016/j.agrformet.2014.09.004.
Henttonen, H.M., Nöjd, P., Mäkinen, H., 2017. Environment-induced growth changes in the Finnish forests during 1971–2010 – An analysis based on National Forest Inventory. Forest Ecol. Manag. 386, 22–36. https://doi.org/10.1016/j.foreco.2016.11.044.
Huuskonen, S., Hakala, S., Mäkinen, H., Hynynen, J., Varmola, M., 2014. Factors influencing the branchiness of young Scots pine trees. Forestry 87, 257–265. https://doi.org/10.1093/forestry/cpt057.
IPCC 2021. Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. [Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekci, O., Yu R., Zhou, B. (eds.)] Cambridge University Press. https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_FrontMatter.pdf.
Jiang, M., Medlyn, B.E., Drake, J.E., Duursma, R.A., Anderson, I., Barton, C.V.M., Boer, M.M., Carrillo, Y., Castañeda-Gómez, L., Collins, L., Crous, K.Y., De Kauwe, M. G., dos Santos, B.M., Emmerson, K.M., Facey, S.L., Gherlenda, A.N., Gimeno, T.E., Hasegawa, S., Johnson, S.N., Kännaste, A., Macdonald, C.A., Mahmud, K., Moore, B. D., Nazaries, L., Neilson, E.H.J., Nielsen, U.N., Niinemets, Ü., Noh, N.J., Ochoa-Hueso, R., Pathare, V.S., Pendall, E., Pihlblad, J., Piñeiro, J., Powell, J.R., Power, S. A., Reich, P.B., Renchon, A.A., Riegler, M., Rinnan, R., Rymer, P.D., Salomón, R.L., Singh, B.K., Smith, B., Tjoelker, M.G., Walker, J.K.M., Wujeska-Klause, A., Yang, J., Zaehle, S., Ellsworth, D.S., 2020. The fate of carbon in a mature forest under carbon dioxide enrichment. Nature 580, 227–231. https://doi.org/10.1038/s41586-020-2128-9.
Kahle, H.-P., Karjalainen, T., Schuck, A., Ågren, G.I., Kellomäki, S., Mellert, K., Priezel, J., Rehfuess, K.E., Spiecker, H. 2008. Causes and consequences of forest growth trends in Europe. Results of the RECOGNITION project. European Forest Research Institute, Research Report 21, Brill, Leiden, 261 p.
Kauppi, P.E., Mielikäinen, K., Kuusela, K., 1992. Biomass and carbon budget of European forests, 1971–1990. Science 256 (5053), 70–74. https://doi.org/10.1126/science.256.5053.70.
Keenan, R.J., Reams, G.A., Achard, F., de Freitas, J.V., Grainger, A., Lindquist, E., 2015. Dynamics of global forest area: Results from the FAO Global Forest Resources Assessment 2015. Forest Ecol. Manag. 352, 9–20. https://doi.org/10.1016/j.foreco.2015.06.014.
Köhl, M., Lasco, R., Cifuentes, M., Jonsson, Ö., Korhonen, K.T., Mundhenk, P., de Jesus, J., Stinson, G., 2015. Changes in forest production, biomass and carbon: Results from the 2015 UN FAO Global Forest Resource Assessment. Forest Ecol. Manag. 352, 21–34. https://doi.org/10.1016/j.foreco.2015.05.036.
Korhonen, K.T., Ihalainen, A., Ahola, A., Heikkinen, J., Henttonen, H.M., Hotanen, J.-P., Nevalainen, S., Pitkänen, J., Strandström, M., Viiri, H. 2017. Suomen metsät ja niiden kehitys 1921-2013. Luonnonvara- ja biotalouden tutkimus 59/2017. Luonnonvarakeskus, Helsinki. 86 p. http://urn.fi/URN:ISBN:978-952-326-467-0.
Korpela, M., Nöjd, P., Hollmén, J., Mäkinen, H., Sulkava, M., Hari, P., 2011. Photosynthesis, temperature and radial growth of Scots pine in northern Finland – identifying the influential time intervals. Trees 25, 323–332. https://doi.org/10.1007/s00468-010-0508-8.
Mäkinen, H., Nöjd, P., Kahle, H.-P., Neumann, U., Tveite, B., Mielikäinen, K., Röhle, H., Spiecker, H., 2002. Climatic response of radial growth of Norway spruce (Picea abies (L.) Karst.) across latitudinal and altitudinal gradients in central and northern Europe. Forest Ecol. Manag. 171, 243–259. https://doi.org/10.1016/S0378-1127(01)00786-1.
Mäkinen, H., Nöjd, P., Helama, S., 2022. Recent unexpected decline of forest growth in North Finland: examining tree-ring, climatic and reproduction data. Silva Fenn. 56, 10769. https://doi.org/10.14214/sf.10769.
Mäkipää, R., Heikkinen, J., 2003. Large-scale changes in abundance of terricolous bryophytes and macrolichens in Finland. Journal of Vegetation Science 14, 497–508. https://doi.org/10.1111/j.1654-1103.2003.tb02176.x.
McRoberts, R.E., Westfall, J.A., 2014. Effects of uncertainty in model predictions of individual tree volume on large area volume estimates. Forest Science 60, 34–42. https://doi.org/10.5849/forsci.12-141.
Mensah, A.A., Petersson, H., Dahlgren, J., Elfving, B., 2023. Taller and slenderer trees in Swedish forests according to data from the National Forest Inventory. Forest Ecol. Manag. 527, 120605 https://doi.org/10.1016/j.foreco.2022.120605.
Mikola, P., 1950. Puiden kasvun vaihteluista ja niiden merkityksestä kasvututkimuksissa. Summary in English: On variations in tree growth and their significance on growth studies. Commun. Inst. for. Fenn. 38 (5), 1–131. http://urn.fi/URN:NBN:fi-metla-201207171070.
Minkkinen, K., Korhonen, R., Savolainen, I., Laine, J., 2002. Carbon balance and radiative forcing of Finnish peatlands 1900–2100 - the impact of forestry drainage. Global Change Biology 8, 785–799. https://doi.org/10.1046/j.1365-2486.2002.00504.x.
Natural Resources Institute Finland (2023): Industrial roundwood removals by year [online publication, referred 28.6.2023]. Access method: https://statdb.luke.fi/PxWeb/pxweb/en/LUKE/LUKE_04%20Metsa_02%20Rakenne%20ja%20tuotanto_06%20Puun%20markkinahakkuut_04%20Vuositilastot/03_Teollisuuspuun_hakkuut_v_koko_maa.px/.
Niinemets, Ü., Lukjanova, A., 2003. Needle longevity, shoot growth and branching frequency in relation to site fertility and within-canopy light conditions in *Pinus sylvestris*. Annals of Forest Science 30, 195–208. https://doi.org/10.1046/j.1469-8137.2003.00712.x.
Nuorteva, H., Kytö, M., Aarnio, L., Hamberg, L., Hantula, J., Henttonen, H., Huitu, O., Kaitera, J., Koivula, M., Korhonen, K.T., Kuitunen, P., Lehti, P., Luoranen, J., Melin, M., Niemimaa, J., Piri, T., Poimala, A., Poteri, M., Strandström, M., Terhonen, E., Tikkanen, O.-P., Uimari, A., Vainio, E., Valtonen, A., Velmala, S., Vuorinen, M., Ylioja, T. 2022. Metsätuhot vuonna 2020. Luonnonvara- ja biotalouden tutkimus. Natural Resources Institute Finland. 2/2022. 72 p. http://urn.fi/URN:ISBN:978-952-380-350-3.
Official Statistics of Finland (OSF), 2023a. Annual increment of growing stock on forest land and on poorly productive forest land by inventory, region and tree species online publication]. Helsinki: Natural Resources Institute Finland [referred: 28.6.2023]. Access method: https://statdb.luke.fi/PXWeb/pxweb/en/LUKE/LUKE_04%20Metsa_06%20Metsavarat/1.24_Puuston_vuotuinen_kasvu_metsa_ja_kitu.px/.
Official Statistics of Finland (OSF), 2023b. Growing stock volume on forest land and poorly productive forest land by tree species [online publication]. Helsinki: Natural Resources Institute Finland [referred: 28.6.2023]. Access method: http://statdb.luke.fi/PXWeb/pxweb/en/LUKE/LUKE_04%20Metsa_06%20Metsavarat/1.17_Puuston_tilavuus_metsa_ja_kitumaan_kan.px/table/tableViewLayout2/.
Ols, C., Gschwantner, T., Schadauer, K., Bontems, J.-D., 2022. Unexpected negative effect of available water capacity detected on recent conifer forest growth trends across wide environmental gradients. Ecosystems 25, 404–421. https://doi.org/10.1007/s10021-021-00663-3.
Piao, S., Nan, H., Huntingford, C., Ciais, C., Friedlingstein, P., Sitch, S., Peng, S., Ahlström, A., Canadell, J.G., Cong, N., Levis, S., Levy, P.E., Liu, L., Lomas, M.R., Mao, J., Myneni, R.B., Peylin, P., Poulter, B., Shi, X., Yin, G., Viovy, N., Wang, T., Wang, X., Zaehle, S., Zeng, N., Zeng, Z., Chen, A., 2014. Evidence for a weakening relationship between interannual temperature variability and northern vegetation activity. Nature Communications 5, 5018. https://doi.org/10.1038/ncomms6018.
Pretzsch, H., Biber, P., Schütze, G., Uhl, E., Rötzer, T., 2014. Forest stand growth dynamics in Central Europe have accelerated since 1870. Nature Communications 5, 4967. https://doi.org/10.1038/ncomms5967.
Roberge, C., Nilsson, P., Wikberg, P.-E., Fridman, J. 2023. Skogsdata (Official Forest Statistics of Sweden). Umeå. Swedish University of Agricultural Sciences. (In Swedish with English summary). 166 p.
Song, J., Wan, S., Piao, S., Knapp, A.K., Classen, A.T., Vicca, S., Ciais, P., Hovenden, M.J., Leuzinger, S., Beier, C., Kardol, P., Xia, J., Liu, Q. Ru, J., Zhou, Z., Luo, Y., Guo, D., Adam L.J., Zscheischler, J., Dukes, J.S., Tang, J., Chen, J., Hofmockel, K.S., Kueppers, L.M., Rustad, L., Liu, L., Smith, M.D. Templer, P.H., Quinn, T.R., Norby, R. J., Phillips, R.P., Niu, S., Fatichi, S., Wang, Y., Shao, P., Han, H., Wang, D., Lei, L., Wang, J., Li, X., Zhang, Q., Li, X., Su, F., Liu, B., Yang, F., Ma, G., Li, G., Liu, Y., Liu, Y., Yang, Z., Zhang, K., Miao, Y., Hu, M., Yan, C., Zhang, A., Zhong, M., Hui, Y., Li, Y., Zheng, M. 2019. A meta-analysis of 1,119 manipulative experiments on terrestrial carbon-cycling responses to global change. Nat. Ecol. Evol. 3: 1309–1320. https://doi.org/10.1038.
Spiecker, H., Mielikäinen, K., Köhl, M., Skovsgaard, J.P. (Eds.). 1996. Growth Trends in European Forests, Springer, Berlin, Heidelberg, New York.
Statistics Finland, 2023. Total energy consumption by energy source. Statistics Finland, Helsinki [online publication, referenced 28.6.2023] Access method:
Tomppo, E., Heikkinen, J., Henttonen, H.M., Ihalainen, A., Katila, M., Mäkelä, H., Tuomainen, T., Vainikainen, N. 2011. Designing and Conducting a Forest Inventory – Case: 9th National Forest Inventory of Finland. Managing Forest Ecosystems 21. Springer, Heidelberg, Dordrecht, London, New York, 270 p.
Tubiello, F.N., Conchedda, G., Wanner, N., Federici, S., Rossi, S., Grassi, G., 2021. Carbon emissions and removals from forests: new estimates, 1990–2020. Earth System Science Data 13 (4), 1681–1691. https://doi.org/10.5194/essd-13-1681-2021.
Venäläinen, A., Tuomenvirta, H., Drebs, A., 2005. A Basic Finnish Climate Data Set 1961–2000 – Description and Illustrations. Finnish Meteorological Institute, Reports 2005. 27 p. https://doi.org/10.13140/RG.2.2.24473.62567.
Vuorenmaa, J., 2004. Long-term changes of acidifying deposition in Finland. Environmental Pollution 128, 351–362. https://doi.org/10.1016/j.envpol.2003.09.014.
Wood, S.N., 2017. Generalized Additive Models: An Introduction with R, (2nd edition). Chapman.
Wood, S.N., Pya, N., Säfken, B., 2016. Smoothing parameter and model selection for general smooth models. Journal of the American Statistical Association 111 (516), 1548–1563. https://doi.org/10.1080/01621459.2016.1180986.
Wood, S.N. 2023. Mixed GAM Computation Vehicle with Automatic Smoothness Estimation. Version 1.8-42. 332 p.