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HOW CAN WE RESTORE THE BIODIVERSITY AND ECOSYSTEM SERVICES IN MINING AND INDUSTRIAL SITES?

Growth responses of Scots pine to climatic factors on reclaimed oil shale mined land

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Abstract Afforestation on reclaimed mining areas has high ecological and economic importance. However, ecosystems established on post-mining substrate can become vulnerable due to climate variability. We used tree-ring data and dendrochronological techniques to study the relationship between climate variables and annual growth of Scots pine (*Pinus sylvestris* L.) growing on reclaimed open cast oil shale mining areas in Northeast Estonia. Chronologies for trees of different age classes (50, 40, 30) were developed. Pearson's correlation analysis between radial growth indices and monthly climate variables revealed that precipitation in June–July and higher mean temperatures in spring season enhanced radial growth of pine plantations, while higher than average temperatures in summer months inhibited wood production. Sensitivity of radial increment to climatic factors on post-mining soils was not homogenous among the studied populations. Older trees growing on more developed soils were more sensitive to precipitation deficit in summer, while growth indices of two other stand groups (young and middle-aged) were highly correlated to temperature. High mean temperatures in August were negatively related to annual wood production in all trees, while trees in the youngest stands benefited from warmer temperatures in January. As a response to thinning, mean annual basal area increment increased up to 50 %. By managing tree competition in the closed-canopy stands, through the thinning activities, tree sensitivity and response to climate could be manipulated.

Keywords Reclamation · Post-mining area · Afforestation · Tree-ring · Scots pine · Forest management

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Introduction

Afforestation on reclaimed mining areas has high ecological and economic importance. However, ecosystems established on post-mining substrate can become vulnerable due to climate variability.

Reclamation of oil shale open surface-mined lands in Estonia is mainly done by afforestation with the native Scots pine (*Pinus sylvestris* L). Since the 1960s, when systematic reclamation of post-mining areas started (Korjus et al. 2007), more than 16,000 ha have been afforested (Yearbook Forest 2014). To a large extent, the growth of forest plantations established on such reclaimed areas depends on the physical (e.g., Torbet et al. 1990) and chemical properties (e.g., Hüttl and Weber 2001) of the growth medium where tree roots are concentrated. In general, substrate conditions for plant growth on reclaimed post-mining areas are harsh due to shallow soil, high (60–100 %) content of coarse unweathered rocks (Reintam 2004; Roberts et al. 1988), and low organic matter and nutrient content (especially N). Alkaline soil reaction persists in such substrates for decades (Reintam et al. 2002) and may inhibit natural tree establishment (Pensa et al. 2004) or reduce the survival of planted trees (Kaar 2002). These factors restrict tree species selection and as a result, single-species forest ecosystems of low stability are being established on large areas of degraded land.

Scots pine is able to grow on infertile soils and has been widely used for reclamation of mining areas in Estonia (Kaar 2002) and throughout Europe (Hüttl and Weber 2001; Baumann et al. 2006; Pietrzykowski and Socha 2011). Despite limiting soil conditions, forest plantations on mined sites in Estonia show high productivity (Reintam and Kaar 2002) and are comparable to pine growth on fertile forest sites (Korjus et al. 2007; Kiviste et al. 2010). Plantations on post-mining areas are important for carbon sequestration (Karu et al. 2009) and play a significant ecological role in promoting soil development (Reintam 2001). Besides, these afforested areas are managed generally for timber production.

Previous studies carried out on the reclaimed areas of oil shale excavation have investigated tree species selection (Kaar 2002), tree survival, and biomass production (Kuznetsova et al. 2011) as well as ecosystem restoration possibilities (Laarmann et al. 2015). Growth of the plantations has been extensively studied for young trees (Vaus 1970; Kuznetsova et al. 2011), but only a few studies on growth dynamics and productivity (e.g., Korjus et al. 2007; Kiviste et al. 2010) are based on long-term observations.

Recently, changing climatic conditions have been suggested to have a pronounced effect on forest growth and productivity. Knowledge about climate-growth relationships is essential for the evaluation of possible impact of climate change on the productivity and vitality of pine plantations of reclaimed areas. Several previous studies (Linderholm 2001; Weber et al. 2007; Hökkä et al. 2012) showed that climatic sensitivity of Scots pine greatly depends on local soil properties, while the influence of climate variables (temperature or precipitation) differs along the latitudinal gradient (Helama et al. 2005; Hordo et al. 2011; Henttonen et al. 2014). Pine trees are more sensitive to variation in temperature at high latitude sites, while this relationship changes, moving toward the South, where stronger relationships between growth and precipitation are usually detected. In Estonia, several studies have investigated Scots pine radial growth response to climate variables (e.g., Läänelaid and Eckstein 2003; Hordo et al. 2009) but mainly considered trees growing on forest sites. Some attempts to relate growth of young trees, growing on post-mining areas to precipitation in spring were described by Vaus (1970), but no thorough dendroclimatic assessment of older trees growing on highly degraded soils in Northeast Estonia has ever been conducted.

The aim of the present study was to investigate radial growth variability and climate influence on the growth of pine monocultures on reclaimed areas across several combinations of substrate and stand structural conditions. The specific aims were (a) to identify the main climatic factors driving annual diameter growth of Scots pine established on reclaimed oil shale mining areas, (b) to examine how the relationship to climate variables is affected by soil and forest stand characteristics, and (c) to assess possible effects of climate, site productivity, and changes in stand structure on annual basal area increment.

Material and methods

Study area

The study was carried out in Northeast Estonia (Fig. 1), in Narva (Viivikonna section) oil shale quarry (59° 16′–59° 19′ N, 27° 39′–27° 40′ E, elevation 40–46 m a.s.l.) that is a part of the largest commercially exploited oil shale mining area in Estonia (Raukas and Punning 2009). Lowlands prevail in the surrounding undisturbed landscape, while the topography of post-mining areas has been drastically altered by large-scale surface mining activity and mainly consists of artificial hills (leveled spoil heaps) covered with forest plantations (Sepp et al. 2010).

Although the machinery used in oil shale extraction industry has changed over time, there were no major differences in oil shale extraction and reclamation methods in our sites. The access to commercially valuable layers of oil shale was gained by removing natural ecosystems, and topsoil was stockpiled and used during reclamation. The average oil shale extraction depth was 7.4 m and did not differ significantly among the sites. The remaining surface and rock overburden was removed and underwent mechanical reduction. The oil-bearing shale was excavated and hauled to the processing plant. After oil shale extraction, crushed waste rocks, mainly consisting of limestone (Reintam et al. 2002), were dumped at the bottom of excavated areas, covered with previously removed overburden, and bulldozers leveled the spoils (Pensa et al. 2004). Pine plantations were subsequently established by planting 2–3-year-old Scots pine seedlings with initial planting densities of 5300–6700 stems per hectare (Kaar 2002; Korjus et al. 2007).

Due to drastic land disturbance, post-mining substrates are characterized by locally high spatial variability in physical properties (primarily texture), fertility, and soil water availability. Physical soil conditions restrict tree-rooting depth and water holding in the substrate is low. Additionally, ground water levels are artificially lowered by pumping out the water to avoid flooding in the excavated areas. Furthermore, due to interactions with vegetation, soil-maturing processes produce gradual changes due to rock weathering and organic matter accumulation, resulting in decreased soil reaction (pH) and profile development over the time (Reintam 2001; Reintam 2004).

Sampling design and stand characteristics

We selected 12 circular permanent sample plots, previously established across the reclaimed area of Narva (Viivikonna section) quarry. The plots were located in small groups at three sites (Fig. 1) and represent varying soil and stand structure conditions of reclaimed areas. Mean stand age decreased southwards, following the progression of excavation activities; stand age in 2010 varied from 44 to 24 years, with around 10 years difference

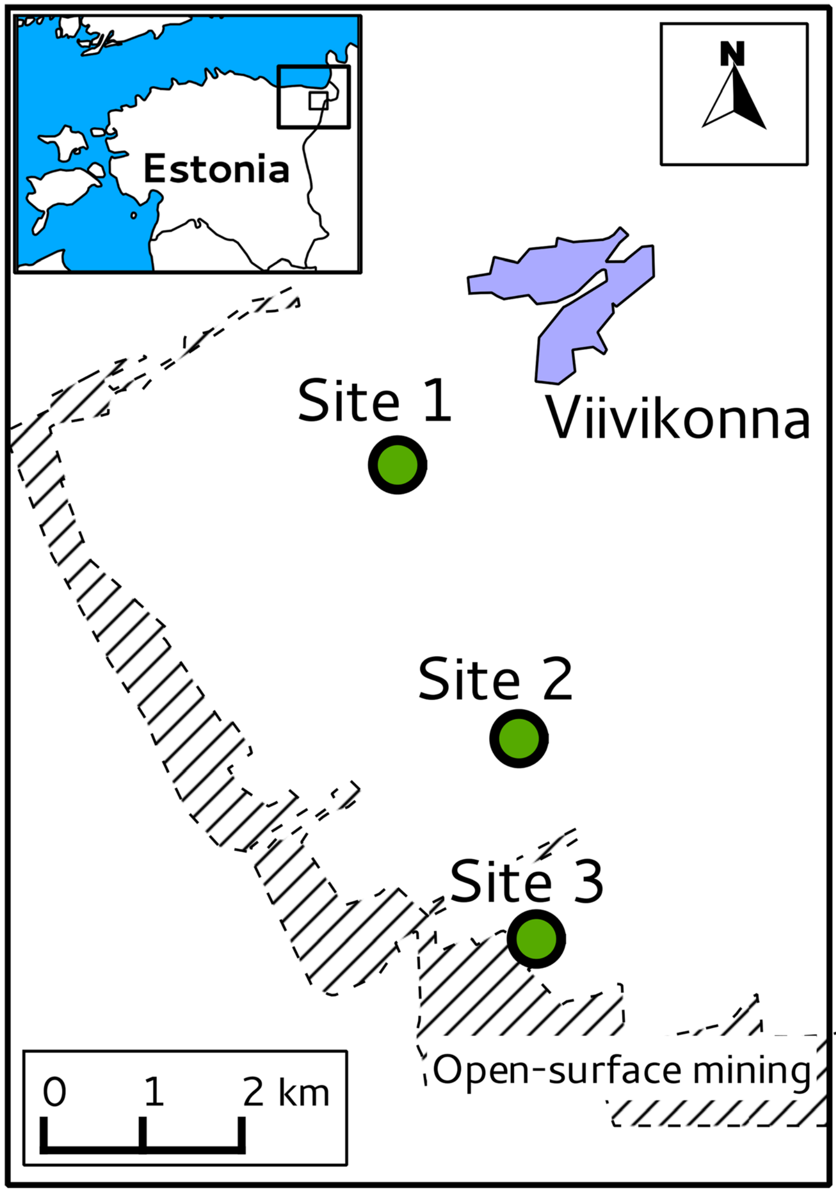

Fig. 1 Location of the study area and sampling sites (*dots*)

between consecutive sites. If our investigated stands grew on forest sites, they would belong to a single age group, but since continuous substrate formation occurs on post-mining areas, we divided trees into three age groups (50 year old, 40-year middle-aged, 30-year young). The oldest trees grew on site 1; the middle-aged trees came from site 2 and the youngest ones were sampled on site 3. Stand dendrometric characteristics were calculated from inventory data in 2010, gathered in circular plots (0.03–0.125 ha) (Kiviste and Hordo 2002). Site index at base age of 50 years (SI_{50}) and relative density were calculated according to equations proposed by Nilson (2014), where space for tree growth is calculated based on average tree size in the stand and mean distances between the trees.

Since plantations on reclaimed areas are grown for wood production, management interventions occurred on two of the sites. Pre-commercial thinning was conducted in 2003 in the young pine populations (site 3) and first commercial thinning in 2008 in the oldest stands (site 1). Middle-aged stands (site 2) were unmanaged, with high tree numbers in the stands. Other dendrometric measurements for this site (Table 1) indicate higher competition levels (exceeding the self-thinning line; RD≈1), as compared to other sites. The oldest stands were the sparsest, with the lowest tree densities and greatest stand basal area. However, quadratic mean diameter in the oldest stands was not significantly different from the youngest ones, where site productivity was higher as indicated by site index (SI_{50}).

Table 1 Dendrometric characteristics of the studied Scots pine stands

Site	Sample plot	Age_{2010} (years)	Tree density (stems ha^{-1})	RD	SI_{50} (m)	D_q (cm)	H (m)	G (m^2 ha^{-1})	V (m^3 ha^{-1})
Site 1	VK-01-01	42	828	0.71	18.8	16.2	15.1	16.7	129.2
	VK-01-02	44	859	0.79	20.7	18.4	17.5	22.7	195.1
	VK-01-03	44	915	0.76	19.5	16.6	16.4	19.8	163.0
	VK-01-04	44	1542	0.88	19.5	14.4	16.4	24.8	205.5
	VK-01-05	41	844	0.66	19.7	14.9	16.6	14.4	120.0
	VK-01-06	43	1249	0.71	16.5	12.0	14.5	14.28	126.6
	Mean±SD	43±1.3	1040±292	0.75±0.08	19.1±1.4	15.4±2.2	16.1±1.1	18.8±4.4	156.6±37.2
Site 2	VK-02-04	33	2674	1.06	20.6	13.0	13.5	31.3	221.2
	VK-02-05	36	2483	1.07	21.3	14.0	15.7	36.8	291.2
	VK-02-06	37	2674	0.99	16.9	11.3	12.2	25.1	166.5
	Mean±SD	35±2.1	2610±110	1.04±0.04	19.6±2.3	12.8±1.3	13.8±1.8	31.1±5.9	226.3±62.5
Site 3	VK-03-04	24	1231	0.75	22.6	14.0	11.7	18.9	119.2
	VK-03-05	24	1218	0.76	22.3	14.4	11.5	19.7	122.3
	VK-03-06	24	1415	0.81	25.0	14.5	13.3	23.4	163.0
	Mean±SD	24±0.0	1288±110	0.77±0.03	23.3±1.5	14.3±0.3	12.2±1.0	20.7±2.4	134.8±24.4

Site 1 50-year-old stands, *site 2* 40-year-old stands, *site 3* 30-year-old stands, Age_{2010} mean stand age in 2010, *RD* relative stand density, SI_{50} site index at base age of 50 years, D_q mean quadratic diameter, *H* mean stand height, *G* mean basal area, *V* mean standing volume

Soil characteristics

To characterize the growth substrates, we sampled soils at each permanent sample plot following procedures described in Laarmann et al. (2015). Skeletal fraction content was assessed using the model developed by Laarmann et al. (2011). According to the results of soil analysis, physical and chemical properties differed among the sites (Table 2). The thickness of the organic layer (O-hor) varied from 2.7 to 6.4 cm and was significantly ($p<0.05$) thicker under the oldest stands as compared to the youngest stands. Depth of the fine soil fraction ranged from 7.1 to 18.0 cm (mean 10.5 cm), but no significant trend were detected along the age gradient. The content of the skeletal fraction did not differ across all sites and averaged 64 %. Clay content increased significantly ($p<0.01$) from the youngest site (site 3) toward the oldest (site 1), whereas soil alkalinity (pH) slightly decreased with stand age and ranged from 7.4 to 7.7 ($p<0.01$) across the sites. Amount of potassium (K) increased with stand age (from 41.1 to 84.9 mg kg^{-1}; $p<0.05$); while lower amounts of phosphorus (P) were detected under old stands (mean range among the three sites 5.4–40.2 mg kg^{-1}; $p<0.05$). Amounts of P depended on fine soil content ($r=0.84$; $p<0.001$), while amounts of K were related to clay ($r=0.87$; $p<0.001$). Soil pH decreased with increasing amount of clay ($r=-0.75$; $p<0.05$).

Climatic conditions

The Estonian Weather Service provided daily weather data from the Jõhvi (59° 21′ 33″ N, 27° 25′ 15″ E) meteorological station, located 15 km from the study area. Mean annual air temperature for the period of 1975–2013 was +4.9 °C (Fig. 2). The warmest month at Jõhvi was July (+16.9 °C), while the coldest month was February (−6.5 °C). Mean annual rainfall is around 720 mm. Melting snow is the main source of water in spring, since long-term mean monthly rainfall in early spring months (February–April) is around 30 mm, increasing in June with a peak in the middle of summer (August, 97 mm $month^{-1}$). The changes in long-term climate conditions were examined via linear regression analysis.

Dendrochronological methods

We sampled 12–15 dominant and co-dominant Scots pine trees outside each permanent sample plot at the end of June 2014. Only trees without visible stem damage or top leader change were selected. We extracted increment cores from two radii at breast height (1.3 m above the ground). Cores from 18 trees with signs of healed moose damage inside the tree stem were excluded from further analysis because disturbance impulses are undesirable in assessing growth-climate relationships (Cook and Kairiukstis 1990). The remaining increment cores were prepared following standard dendrochronological techniques (Pilcher 1990).

Tree-ring widths were measured with the precision of 0.01 mm using a LINTAB® tree-ring measuring table equipped with TSAP-Win™ Scientific Version 0.59 software (Rinn 2003) for graphical and statistical growth pattern matching among trees of the same site. Cross-dating accuracy was examined with the program COFECHA (Holmes 1983) that calculates the correlation between individual ring-width

Table 2 Edaphic characteristics of the studied sites

Site	Sample plot	pH	O-hor (cm)	Skeletal fraction (%)	Fine soil depth (cm)	Sand (%)	Clay (%)	Silt (%)	C_{org} (%)	C (%)	N (%)	P (mg kg^{-1})	K (mg kg^{-1})
Site 1	VK-01-01	7.5	3.1	66	8.5	45.0	17.8	37.2	5.1	7.5	0.10	8.3	113.7
	VK-01-02	7.3	6.2	62	12.8	53.1	14.6	32.3	5.7	7.7	0.18	9.2	103.3
	VK-01-03	7.3	4.7	63	11.3	41.0	20.4	38.6	3.8	5.2	0.17	20.1	98.5
	VK-01-04	7.4	4.9	64	10.2	56.8	12.9	30.3	5.6	7.2	0.10	3.6	61.8
	VK-01-05	7.2	6.2	66	8.6	56.3	11.1	32.6	6.8	9.3	0.18	11.1	78.0
	VK-01-06	7.6	4.4	68	7.1	64.4	9.3	26.2	4.4	7.5	0.07	9.9	54.4
	Mean±SD	7.4±0.14	4.9±1.2	64.8±2.2	9.8±2.1	52.8±8.6	14.4±4.2	32.8±4.5	5.2±1.1	7.4±1.3	0.13±0.05	10.4±5.5	84.9±23.9
Site 2	VK-02-04	7.6	5.2	64	10.7	74.0	5.3	20.7	2.6	6.3	0.10	3.9	27.0
	VK-02-05	7.6	6.4	68	7.2	63.7	6.9	29.5	3.2	5.9	0.10	4.1	37.8
	VK-02-06	7.5	2.7	67	7.9	56.9	11.2	31.9	5.5	13.2	0.10	8.2	64.3
	Mean±SD	7.6±0.07	4.8±1.9	66.3±2.1	8.6±1.8	64.8±8.6	7.8±3.1	27.3±5.9	3.8±1.5	8.5±4.1	0.10±0.00	5.4±2.4	43.1±19.2
Site 3	VK-03-04	7.7	3.3	60	14.2	59.9	0.5	30.5	1.3	1.5	0.05	32.0	46.9
	VK-03-05	7.7	2.7	65	10.0	62.0	5.9	30.0	1.6	2.7	0.04	19.5	40.4
	VK-03-06	7.8	3.2	56	18.0	48.9	4.3	35.8	3.3	4.2	0.04	69.1	36.1
	Mean±SD	7.7±0.09	3.0±0.3	60.3±4.5	14.1±4.0	56.9±7.1	3.6±2.8	32.1±3.2	2.1±1.1	2.8±1.4	0.04±0.00	40.2±25.8	41.1±5.4

pH soil reaction, *O-hor* thickness of organic layer, *Skeletal fraction* content of soil, with particles larger than 2 cm, *Fine soil* mean fine soil thickness, *Sand* content of soil with particle size 0.063–2 mm, *Clay* content of soil with particle size <0.002 mm, *Silt* content of soil with particle size 0.002–0.063 mm, C_{org} content of organic carbon, *C* content of total carbon, *N* content of nitrogen, *P* content of phosphorus, *K* content of potassium

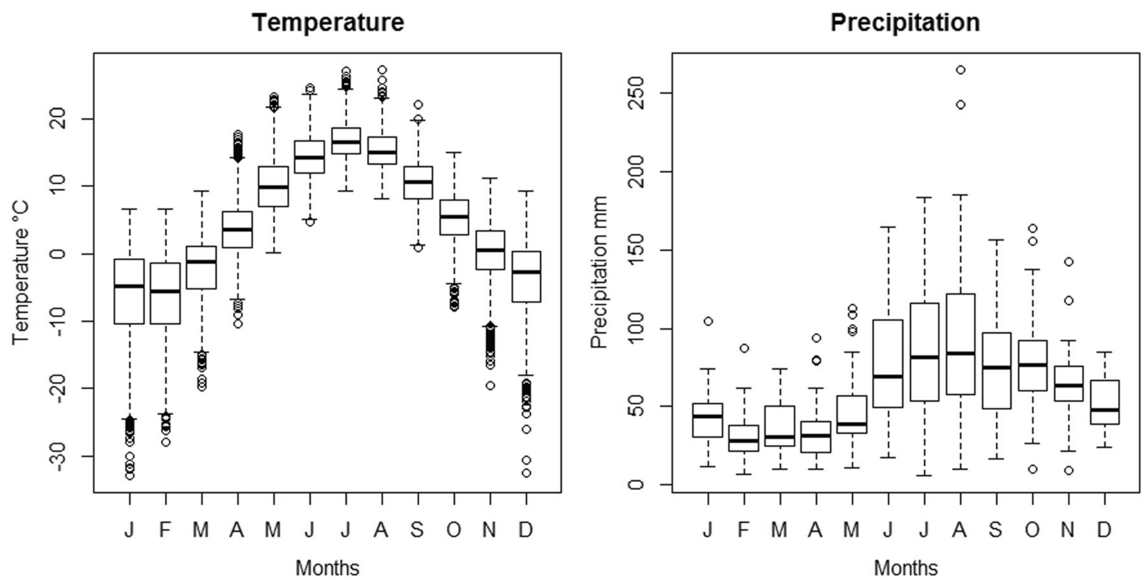

Fig. 2 Mean monthly air temperature (°C) and monthly sum of precipitation (mm), at Jõhvi meteorological station over the period of 1975–2013. The *upper edge of the box* indicates upper and lower quartiles; *line in the box* depicts the median and *whiskers* show limits of inter-quartile range; points are outliers

series and master series (Grissino-Mayer 2001) and identifies mismatching segments. Ring-width series of 21 trees had low correlation with other tree patterns, so they were eliminated. The age-related trend, usually present in ring-width measurement sequences, was removed through the standardization process. We fitted 67 %n smoothing splines with 50 % frequency cut-off on each ring-width measurement series (Cook and Peters 1981; Cook et al. 1990), where n is the series length, and calculated dimensionless tree-ring indices for each tree by dividing the measured radial increment with values of the fitted trend. Detrended ring-width series were pre-whitened to remove autocorrelation and averaged into mean plot-wise and site-wise tree-ring-width chronologies using Tukey's biweight robust mean (Mosteller and Tukey 1977).

Of the 167 trees we sampled, ring-width series from 128 trees were used for chronology building (Table 3). Three mean site tree-ring-width chronologies covered different periods (Table 3; Fig. 3), but shared a common period of 1993–2013 (21 years). The residual chronology for the oldest stands was based on 64 trees and covered the period of 1976–2013. The chronology of growth indices for the middle-aged group was compiled from annual growth increments of 31 trees and spanned the period 1985-2013. The shortest residual chronology, covering the period of 1993–2013, was built for the 30-year-old trees from site 3. It included data from 33 trees.

Several statistics used in dendrochronology studies (Briffa and Jones 1990) were calculated for un-standardized tree-ring series and for each site chronology to assess tree responsiveness to climate and to evaluate the suitability of the chronologies for climate-growth quantification. Mean sensitivity, standard deviation in tree-ring widths, and first-order autocorrelation were calculated for raw ring-width series (Table 3). Mean sensitivity is a measure of mean relative change between adjacent ring widths (Biondi and Qeadan 2008) and standard deviation accounts for variability. First-order autocorrelation quantifies the influence of the previous year growth conditions on the current year's growth. Signal strength for each chronology was estimated by signal-to-noise ratio (SNR) and by inter-correlation of indices series. The confidence of the chronologies was estimated with expressed population signal (EPS).

Table 3 Dendrochronological statistics (mean values) of tree-ring measurements and residual chronologies for three sites

	Site 1	Site 2	Site 3
Ring measurements			
Mean tree age in 2014 (years)	47	39	28
Number of trees/cores	64/128	31/62	33/66
Mean TRW (mm)	2.50	2.66	3.86
Mean BAI (cm^2 $year^{-1}$)	6.84	6.01	9.60
Standard deviation	1.18	1.08	1.48
First-order autocorrelation	0.77	0.75	0.68
Mean sensitivity	0.18	0.17	0.19
Residual chronologies			
Time span	1976–2013	1985–2013	1993–2013
Chronology length [years]	38	29	21
EPS	0.967	0.944	0.987
SNR	29.1	16.8	78.1
Series inter-correlation	0.600	0.632	0.768

TRW tree-ring width, *BAI* basal area increment, *EPS* expressed population signal, *SNR* signal-to-noise ratio

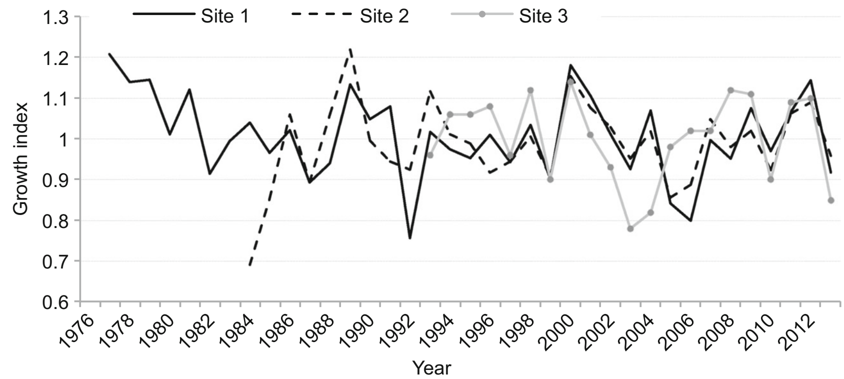

Fig. 3 Tree-ring-width residual chronologies for three sites

The rate of annual increment, expressed as annual basal area increments (BAIs), were used to model effects of site, competition, and climate on growth rates. To avoid bias when growth rates of different size trees are compared (Biondi 1999), tree size has to be considered; thus we calculated annual BAI from mean tree-wise ring-width measurements, assuming that rings were concentric (Biondi and Qeadan 2008). Annual BAI was calculated from the bark to the pith for each tree, according to the formula: $BAI_t = \pi \cdot (R_t^2 - R_{t-1}^2)$, where R is tree radius and t is the year of ring formation. Subsequently, mean arithmetic BAI series were computed for each of the three studied sites.

Statistical data analysis

Dendroclimatic data analyses were performed using the R software (R Core Team 2014) and the packages *dplR* (Bunn 2008; Bunn 2010), *detrendeR* (Campelo et al. 2012), and *bootRes* (Zang and Biondi 2012). Climate-growth relationships were considered significant at the 95 % confidence level.

Growth-climate relationships were established between indices and climate factors and BAI in the nonlinear model. We used bootstrapped correlation analysis (Biondi 1999; Guiot 1991) to study the relationship between climate and radial growth. Residual chronologies were compared against climate variables. Considering that ring formation may take place from May through August (Jyske et al. 2014), the calculations were performed using a time window from the previous year's September to current year's August. Climatic conditions of the previous autumn and winter seasons were considered, since in autumn of the prior year, trees allocate carbohydrates that will be used in the spring to initiate the growth flush. Restricting analysis to the period relevant for ring formation reduces the risk of statistically significant correlations arising by chance, when numerous correlations are calculated. Climate variables used were monthly mean temperature and monthly rainfall sums, seasonal (autumn: September–October–November; winter: December–January–February; spring: March–April–May; summer: June–July–August) and mean annual climate variables. Mean annual temperature and total precipitation were calculated for the time window (previous September to current August) and vegetation period, defined from April to September.

Climate-growth correlations were calculated for the common growth period of 1993–2013 (21 years) in order to maintain the same weather conditions. Correlation relationships were further validated via linear regression analysis. To investigate how a particular climate-growth relationship was influenced by stand or soil characteristics, we also calculated climate-growth relationships for the common growth period between 12 plot-wise chronologies and climate variables. Furthermore, the obtained correlation coefficients were used in Pearson's correlation analysis, where relations' strength and significance were established between correlation coefficients and stand/soil data available for each studied plot.

Modeling response of basal area increment

We used nonlinear modeling to investigate the factors affecting basal area growth of individual trees. Nonlinear models are suitable to test the relationships among the variables, when data are unbalanced (number of observations are not equally distributed among the groups) or when the relationship cannot be linearized (Crawley 2007). Annual basal area increment (*iba*) was used as the dependent variable. According to Burkhart (2003), growth models should be as parsimonious as possible, to avoid over parameterization. At the same time, important predictors for basal area growth should be considered. Thus, three components were considered: basic growth function, effect of thinning, and weather effect. Each component was described with a sub-model and compiled into one general prediction equation of multiplicative structure expressed as follows:

$$\text{iba} = f_1(t) \cdot f_2(th) \cdot f_3(av) + \varepsilon \quad (1)$$

where *iba* is the annual basal area increment (cm^2/year) of dominant and co-dominant trees, $f_1(t)$ is a basic growth function showing basal area growth dynamics in unmanaged stands, f_2 (th) is a function describing individual tree response to changes in competition (stand density reduction), and f_3 (av) is a function expressing annual growth variation, depending on weather conditions during the growing period; ε is the error term.

Basic basal area increment model $f_1(t)$ was compiled considering that basal area growth of individual trees follows asymptotic pattern. We chose Weber growth function (cf. Kiviste et al. 2002) to describe basal area growth trend in unmanaged stands:

$$f_1(t) = p_{tree} \cdot (1 - \exp(-p_{site} \cdot A)) \quad (2)$$

where p_{tree} is the parameter indicating potential growth of the tree and also defining the magnitude of asymptote. This parameter was related to current tree diameter at breast height (cm); p_{site} is the parameter indicating site fertility; A is the tree breast height age (years).

Response to thinning of individual trees was modeled in a similar manner as proposed by Hynynen (1995). Since we did not have information about stand basal area before the thinning, years since thinning were used to describe changes in stand densities. Studies have shown that thinning effect decreases with increasing time since thinning. We assumed that the thinning effect would last for the same period and response would have an asymptotic shape as suggested by Hynynen (1995). We adjusted the equation to the available variables as follows:

$$f_2(th) = 1 + p_{th} \left(\frac{th}{b}\right)^c \cdot \exp\left(-\frac{th^c}{b}\right) \quad (3)$$

where th is the time elapsed since thinning; b and c are the estimates of parameters, b=13.8 and c=1.58, as proposed by Hynynen (1995); and p_{th} is the thinning intensity parameter to be estimated.

Annual growth variation f_3 (av) was accounted for by including growth indices. Stepwise inclusion of model components was used to estimate the parameters and to investigate the effects of possible radial growth predictors. Root of the mean squared error (RMSE) and Akaike's Information Criterion (AIC) (Burnham and Anderson 2002) were used to evaluate model improvements. We also calculated the model efficiency or pseudo-R^2, which describes the proportion of variance explained by factors included in the model.

Several candidate models were compiled (Table 5) and iteratively compared with the previously compiled model for significant improvement. First, we fitted basic growth function with one parameter p_{tree} (M_1) on our data set, and proceeded with inclusion of a second parameter p_{site} (M_2). In the following steps, either maximum tree diameter (M_3) or SI_{50} (M_4) was related to the asymptote. The model with the lowest AIC and RMSE was used further in the analysis. Since maximum tree diameters (D_{max}) better described the associated parameter p_{tree}, we used it further in the model and tested variables of site productivity—SI_{50} (M_5) and thickness of fine soil (M_6). Thinning effect (M_7) was evaluated after defining the best parameters to describe basic BAI growth functions. Finally, radial increment indices (M_8–M_{10}) were added to assess the climate effect on BAI growth. We tested if there were any effects of using more generalized indices to avoid more laborious population-level sampling. For that purpose, first, we included general growth indices into model (M_8), then replaced them by site mean chronologies (M_9) and finally tested if model fit improved by including plot-level mean chronologies (M_{10}). Statistics of each of the extended models were compared, and the model with the lowest RMSE and AIC and the greatest explained variance (pseudo-R^2) was selected as the final model.

After comparing observed and predicted mean BAI patterns by sites, we observed that the model was not able to predict a smaller growth peak in growth pattern of site 3. We hypothesized that it could be caused by one earlier management intervention (spacing), which was not recorded. To test that hypothesis, we included a hypothetical thinning in 1996 (M_{11}–M_{14}). Nonlinear modeling was performed using nonlinear least squares (*nls*) function in the R environment (R Core Team 2014).

Results

Changes in long-term climate conditions

Linear regression results revealed several temporal trends in long-term mean climate conditions for the period of 1975–2013. Total precipitation increased for May (8.7 mm decade^{-1}; $p<0.05$). Mean monthly temperature has steadily increased each decade: in April (0.5 °C; $p<0.05$), July (0.8 °C; $p<0.001$), August (0.5 °C; $p<0.05$), and September (0.4 °C; $p<0.05$).

Characteristics of tree-rings and chronologies

The widest tree-rings (TRW=3.86 mm year^{-1}) were formed in the trees growing on the youngest site and decreased with stand age. Overall, year-to-year variation was not high in studied stands (0.17–0.19), which is characteristic for complacent growth (Table 3). First-order autocorrelation ranged from 0.68 to 0.77, and was slightly higher in the oldest trees (site 1), suggesting that the weather of the preceding year had a pronounced effect on the diameter growth for these trees. The most homogeneous tree-ring patterns were present in the youngest trees (site 3) where series inter-correlation among indices was high (0.768). Considerably, lower similarities among patterns were found in the middle-aged tree group on site 2 (0.632), and the lowest (0.600) were among the oldest trees (site 1). Signal-to-noise ratio ranged from 16.8 to 78.1 and was more than two times higher in the young trees than in old trees and more than four times higher than in the middle-aged tree growth patterns. Expressed population signal in all chronologies was high, surpassing the recommended confidence threshold of 0.85 (Wigley et al. 1984), suggesting that chronologies are reliable for examining tree growth-climate relationships.

Climate-growth relationships

Correlation analysis indicated that variation in both precipitation and temperature had a strong relationship to Scots pine radial growth on reclaimed mining areas (Fig. 4). High precipitation in the June–July period was significantly positively related to higher radial growth in all studied age groups, while there was opposite relationship between high mean temperatures in summer, especially in August and annual wood production. Importance of precipitation in June–July period decreased with decreasing age ($p<0.01$).

The strongest significant relationship between radial growth and rainfall over June–July period was detected for the oldest age group ($r=0.66$), with precipitation in June being more important ($r=0.63$) than in July ($r=0.55$). This age group also benefited from higher rainfall in October of the previous year ($r=0.45$). Weaker correlation coefficients were found between chronology of the oldest trees and monthly temperatures. Higher mean temperatures in spring season ($r=0.50$) were positively related to tree-ring width, while high mean temperatures in June ($r=-0.38$) inhibited radial growth of the oldest age group.

Similar relationship patterns (as for site 1) between precipitation in June–July and radial growth were found for middle-aged group (site 2): $r=0.55$ (June–July), $r=0.55$ (June), and $r=0.50$ (July). However, growth of this age group seemed to be controlled more by variation in temperature, as indicated by a greater number of significant correlations between indices and temperature variables. Wood production on this site was related mostly to higher mean temperatures in spring ($r=0.69$), whereas temperatures in March had a pronounced effect ($r=0.49$). Warm winters ($r=0.38$), and especially warmer weather conditions in January ($r=0.39$), were positively associated to pine radial growth on site 2. Growth indices of middle-aged group were also positively correlated with mean annual temperature ($r=0.40$). Mean summer temperatures were not significant for wood production on site 2, contrary to the other two age groups. Negative relationship between growth indices and current August temperatures was slightly stronger for the middle-aged site ($r=-0.43$) than for other two groups ($r=-0.35$).

The least number of significant correlations was found for the youngest age group (site 3). Radial growth relationship to precipitation in June–July was significant but moderate ($r=0.39$), and there was no significant association with monthly rainfall in June or July. The dominant climatic factor controlling Scots pine radial growth in this age group was January temperature ($r=0.56$). High mean temperatures in summer ($r=-0.45$) were negatively related to radial growth on site 3, with mean temperatures in July ($r=-0.39$) and August ($r=-0.35$) being the most influential.

The greatest amount of variance ($R^2=0.28$; $p<0.05$) present in radial increment of the oldest age group was associated

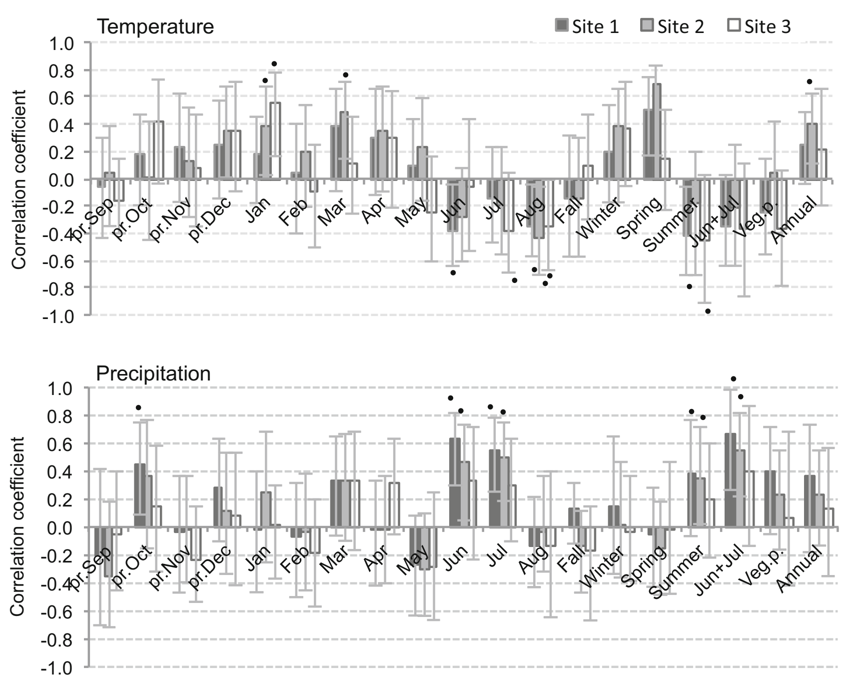

Fig. 4 Pearson's correlation coefficients between tree-ring-width indices of three sites and mean monthly, seasonal, annual, and vegetation period (Veg.p.) temperatures and precipitation; *pr.* denotes months previous to vegetation period, *bars* show medians of correlation coefficients, and *whiskers* indicate 95 % confidence intervals. Statistically significant correlations ($p<0.05$) are marked with *dot*

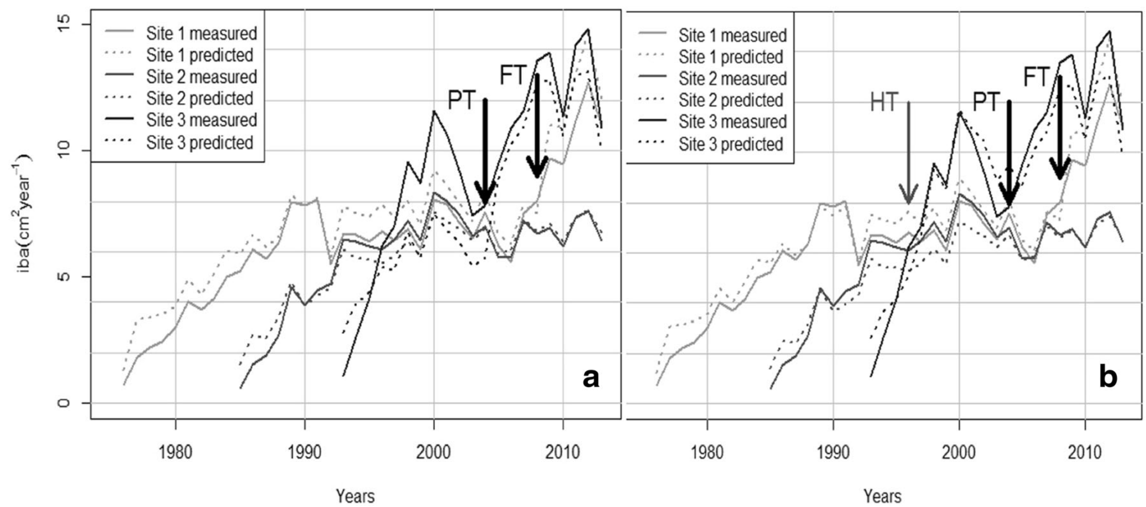

Fig. 5 Observed and predicted basal increment growth patterns of pine trees on three sites: **a** prediction without hypothetical thinning; **b** prediction with included hypothetical thinning. *Arrows* indicate time of management activity, *PT* pre-commercial thinning, *FT* first thinning, and *HT* hypothetical thinning

with the variability in June–July precipitation, while fluctuations in mean spring temperature were responsible for 47 % ($p<0.001$) in annual ring-width variation at site 2. Temperatures in January accounted for 29 % ($p<0.05$) of variability in growth patterns from site 3.

Growth patterns

Mean annual basal area increment was greatest in the youngest age group trees (site 3, BAI=9.60 cm^2 $year^{-1}$) and the smallest in unmanaged stands (site 2, BAI=6.01 cm^2 $year^{-1}$). Sudden increases in BAI followed the pre-commercial thinning at site 3 in 2004, and first commercial thinning in the oldest stands (site 1) in 2008 demonstrated the effect of lowered competition (Fig. 5). After the thinning, mean annual BAI of dominant trees increased 58 and 3 % in old and young trees, respectively, considering 5-year periods before and after the intervention.

Standardized growth patterns were quite synchronous among all chronologies for the period of 1993–2004, but diverged in the youngest age group for the period of 2005–2009, just after the pre-commercial thinning (Fig. 5). A sharp decrease in radial growth in the youngest age group (site 3) is evident for 2002–2003, while growth depression in the same period for the two other sites was considerably lower. Two-year growth depression in 2005–2006 is present in the growth patterns of sites 1 and 2, but not for site 3. Very low growth indices for site 2 were observed in 1984 and for site 1 in 1992.

Correlation analysis suggested that the patterns of indices differed slightly. The strongest correlation ($r=0.74$; $p<0.001$) for common pair-wise length was between chronologies of sites 1 and 2. Coefficients of the other two pair-wise correlations between site 1 vs. site 3 and site 2 vs. site 3 were not statistically significant.

Effects of soil and stand characteristics on tree response to climate

Tree responsiveness to monthly temperature regimes to a large extent was influenced by stand characteristics, while sensitivity to precipitation seemed to increase with growing tree dimensions but also depended on soil characteristics (Table 4). Moderately strong relationships ($r=0.58$–0.68) between sensitivity to spring temperatures (particularly in March) and stand density (expressed in stand volume, relative density, and basal area) were established. Thicker layers of O-hor tended to mitigate negative influence of temperatures in August, as indicated by significant negative correlation. Growth sensitivity to mean temperatures in January was related to stand age and increased with site productivity (SI_{50}). The decrease in pH inversely influenced radial growth response to precipitation in June.

Thinning, site and climate effects on radial growth

An individual tree basal area increment model (Eq. 1) for dominant and co-dominant Scots pine trees on reclaimed oil shale areas was compiled and fitted on the data set, consisting of more than 3600 annual basal increment records. The fit statistics from nonlinear procedure used to estimate annual growth rate with alternative models (M_1–M_{14}) are presented in Table 5.

The compiled growth model was logically consistent. Predicted tree basal area increment patterns followed the observed ones (Fig. 5a, b). Model prediction accuracy improved each time, after new variable was included, as indicated by lower RMSE and decreasing AIC (Table 5). At the same time, model prediction ability remained

Table 4 Correlation coefficients between growth-climate relationships and soil/stand characteristics. Statistically significant ($p<0.05$) correlations are presented in italic

Growth-climate relationship	Stand characteristics						Soil characteristics								
	Age	H	D_q	SI_{50}	G	RD	V	pH	O-hor	Fine soil	Clay	C	C_{org}	N	K
T1	*−0.71*	−045	−0.27	*0.63*	0.57	0.52	0.33	0.45	−0.06	0.30	*−0.66*	−0.17	−0.37	−0.35	*−0.70*
T3	0.51	0.48	0.19	−0.23	*0.58*	*0.60*	*0.68*	−0.34	0.38	−0.11	0.50	0.48	0.37	0.48	0.23
T8	−0.39	−0.39	0.16	0.26	−0.41	−0.39	−0.56	0.29	*−0.75*	0.47	0.06	−0.13	−0.07	−0.37	0.16
Tspring	0.51	0.43	0.13	−0.29	*0.61*	*0.65*	*0.70*	−0.33	0.37	−0.18	0.45	0.48	0.33	0.45	0.24
Tsummer	0.05	−0.42	*−0.66*	−0.51	0.09	0.37	−0.03	0.25	−0.50	−0.19	0.04	0.50	0.05	−0.27	−0.15
Tannual	−0.57	*−0.70*	−0.41	0.10	−0.34	−0.29	−0.51	0.04	0.13	0.11	−0.12	0.23	0.01	0.09	−0.26
P6	*0.60*	*0.80*	*0.62*	−0.10	−0.18	−0.33	0.08	*−0.70*	0.57	−0.14	0.55	0.05	0.49	*0.65*	*0.62*
P7	*0.72*	*0.68*	0.19	−0.47	−0.14	−0.20	0.14	−0.55	0.40	−0.42	0.54	0.41	0.67	0.44	*0.52*
P10	*0.81*	*0.64*	0.01	*−0.68*	−0.27	−0.22	0.01	−0.56	0.33	*−0.62*	*0.60*	*0.58*	*0.78*	0.41	0.49

T temperature, *P* precipitation, numbers *1–10* denote calendar months, *1* January, *2* February etc.; *Age* mean stand age (years), *H* mean stand height (m), D_q mean quadratic diameter (cm), SI_{50} site index at base age of 50 years (m), *G* mean stand basal area ($m^2\ ha^{-1}$), *RD* relative density related to average tree size and distances between trees, *V* mean standing volume ($m^3\ ha^{-1}$), *O-hor* thickness of organic layer (cm), *pH* soil reaction, *Fine soil* mean fine soil thickness (cm), *Clay* content of clay (%), *C* content of carbon (%), C_{org} content of organic carbon (%), *N* content of nitrogen (%), *P* content of phosphorus ($mg\ kg^{-1}$), *K* content of potassium ($mg\ kg^{-1}$)

Table 5 Parameter estimates and fit statistics from the nonlinear regressions of annual basal area increment

Model	Components	Parameters						RMSE	AIC	pseudo-R^2
		p_{tree}		p_{site}		p_{th}				
		Estimate	SE	Estimate	SE	Estimate	SE			
M_1	$f_1(A)$,p_{tree}	8.59999	0.0728	–	–	–	–	3.813	19916.40	0.186
M_2	$f_1(A)$,p_{tree}, p_{site}	8.45432	0.0945	0.22339	0.0111	–	–	3.811	19913.33	0.187
M_3	$f_1(A)$,p_{tree}-D_{max}, p_{site}	0.42745	0.0039	0.23345	0.0100	–	–	3.306	18887.63	0.388
M_4	$f_1(A)$,p_{tree}-SI_{50}, p_{site}	0.43119	0.0047	0.20900	0.0097	–	–	3.673	19646.96	0.245
M_5	$f_1(A)$,p_{tree}-D_{max}, p_{site} -SI_{50}	0.43690	0.0042	1.02682	0.0420	–	–	3.255	18774.91	0.407
M_6	$f_1(A)$,p_{tree}-D_{max}, p_{site} -*fine soil*	0.43969	0.0042	2.00520	0.0806	–	–	3.250	18762.74	0.409
M_7	$f_1(A)$,p_{tree}-D_{max}, p_{site} - *fine soil* * $f_2(th)$	0.37288	0.0035	3.02980	0.1398	1.56969	0.0543	2.824	17749.38	0.553
M_8	$f_1(A)$,p_{tree}-D_{max}, p_{site} -*fine soil** $f_2(th)$*$f_3(av)$-*general chron*	0.37808	0.0034	2.93839	0.1284	1.46564	0.0514	2.746	17547.97	0.578
M_9	$f_1(A)$,p_{tree}-D_{max}, p_{site} -*fine soil** $f_2(th)$*$f_3(av)$-*site chron*	0.38345	0.0037	2.73189	0.1159	1.07318	0.0482	2.804	17697.97	0.559
M_{10}	$f_1(A)$,p_{tree}-D_{max}, p_{site} -*fine soil** $f_2(th)$*$f_3(av)$-*plot chron*	*0.38019*	*0.0034*	*2.89446*	*0.1233*	*1.38587*	*0.0501*	*2.723*	*17485.93*	*0.585*
M_{11}	$f_1(A)$,p_{tree}-D_{max}, p_{site} -*fine soil** $f_2(hth)$	0.36497	0.0035	2.74465	0.1130	1.50165	0.0475	2.746	17113.90	0.578
M_{12}	$f_1(A)$,p_{tree}-D_{max}, p_{site} -*fine soil** $f_2(hth)$*$f_3(av)$-*general chron*	0.37002	0.0034	2.67500	0.1043	1.41983	0.0449	2.663	17326.93	0.603
M_{13}	$f_1(A)$,p_{tree}-D_{max}, p_{site} -*fine soil** $f_2(hth)$*$f_3(av)$-*site chron*	0.36948	0.0032	2.68756	0.1035	1.23886	0.0438	2.664	17326.93	0.603
M_{14}	$f_1(A)$,p_{tree}-D_{max}, p_{site} -*fine soil** $f_2(hth)$*$f_3(av)$-*plot chron*	*0.36890*	*0.0033*	*2.72059*	*0.1029*	*1.45914*	*0.0443*	*2.586*	*17329.42*	*0.626*

Parameters: p_{tree} tree size parameter, depending on maximum tree diameter (diameter when trees were sampled); p_{th} response to thinning parameter, described as years since thinning; p_{site} site productivity parameter described by either SI_{50} or fine soil thickness (cm); $f_1(A)$ basic grow function, $f_2(th)$ response to thinning function, $f_3(av)$ function describing annual variation related to climate; $f_2(hth)$ response to thinning function with included hypothetical thinning. The best models are marked in italic: M_{10} without hypothetical thinning and M_{14} with hypothetical thinning considered; *RMSE* root mean square error, *AIC* Akaike's information criterion, *pseudo-R^2* shows total explained variance considerably stable, with low variation in parameter standard errors. All the parameter estimates were logical and highly significant ($p<0.001$).

The basic models (M_3–M_6), where site fertility and tree size were used as predictor variables, explained 39–41 % of the total variation in the observed basal area increments. Fine soil thickness was a better predictor than SI_{50}. Inclusion of response function to thinning (M_7) increased pseudo-R^2 up to 55 %, with a reduction in RMSE and AIC. After including climate effects (M_8–M_{10}), the fit statistics (RMSE, AIC) showed improvement, and maximum explained common variance increased up to 59 %. The greatest effect on radial growth, according to our model, had site properties and thinning, while climatic variation was significant, but it improved model predictions only slightly.

Mean plot chronologies were slightly better predictors of basal area increment than mean site or mean general chronology, proving that response to climatic factor among the sites are not the same.

After inclusion of a hypothetical thinning into the data set, model predictions improved as indicated by lower RMSE and AIC. Percentage of maximum explained common variance (pseudo-R^2) increased up to 63 % (M_{14}). No evidence of dependencies was observed in bi-plots of residuals against predicted values (data not presented).

Discussion

Climate effects on radial growth

Dendrochronological studies in Baltic countries report that Scots pine, growing on dry and infertile sites, is sensitive to cold winters (Elferts 2007; Vitas 2004; Vitas and Erlickyte 2007) and benefits from higher temperatures in winter and early spring (Hordo et al. 2009; Läänelaid and Eckstein 2003). Erlickyte and Vitas (2008) found in Lithuania that due to changes in long-term climate trends, the influence of winter cold on Scots pine annual diameter growth decreased, while sensitivity to rainfall in springtime and summer became more important. Our results show that Scots pine radial growth on the reclaimed areas is limited by water deficit in summer, apparently as a result of low precipitation and high temperatures in June to August. The main water source for tree growth is precipitation and extended dry and warm periods may cause water deficiency in the area (Vaus 1970). Läänelaid and Eckstein (2003) reported that rainfall in June is the main climatic factor driving radial growth in Norway spruce in Estonia. Spruce sensitivity to precipitation is usually explained by close-to-surface root system, which could be the same reason for pine trees growing on reclaimed areas where rooting depth is confined by the rocky substrate. Root penetration into deeper layers is restricted by physical soil conditions and water holding in the substrate is low. Additionally, ground water levels are artificially lowered by pumping out the water to avoid flooding in the excavated areas. Because of this drainage, the water table can be too deep to supply the moisture for roots by capillary action. Besides that, microbial activity is also dependent on soil water availability. Microbial activity decreases with lower soil water availability, and microbial metabolism may become totally inhibited during extended drought events (Borken and Matzner 2009), therefore suspending uptake of nutrients. In Estonia, severe meteorological summer droughts, when precipitation was absent or was low for longer than 20-day period, were observed in 2002 and 2006, with exceptionally dry summers in 1983, 1992, and 1999 (Tarand et al. 2013). These dates coincide with years of extremely low radial increment in our studied plots. In general, Scots pine is tolerant to drought, and its sensitivity to precipitation and water deficit is more characteristic of dry regions (Allen and Breshears 1998). However, Scots pine trees become more sensitive to climate dryness, in the areas where water deficit becomes more frequent or lasts for an extended time, eventually leading to tree mortality (Hereş et al. 2012).

Temperature governs physiological processes, including photosynthesis and carbon sequestration, in the tree and determines the rate at which water evaporates from the soil (Fritts 1976). Formation of a permanent forest floor enhances moisture retention, and may also influence tree response to climate (Drobyshev et al. 2010). Our results suggest that thicker layers of the organic horizon, which develops on reclaimed sites as vegetation develops, reduced the negative influence of temperature in August. Pine sensitivity to precipitation in October could be explained as due to formation of new roots (Ostonen et al. 2006) during this time. The presence of higher amounts of carbon and organic carbon increased tree sensitivity to precipitation in October (Table 4). With a better-developed root system, water and nutrient uptake could have been enhanced, which might be advantageous during the ring-formation time.

Mean temperatures in July and August are steadily increasing, suggesting that evaporative demand will be increasing and growth stress induced by high temperatures is likely to increase in the future. This could be especially significant for older trees, as we found a positive relationship between precipitation in June and July and increasing tree size. Tree density reduction through thinning has been suggested as a way to mitigate water stress effects (Giuggiola et al. 2013). Basal area increment patterns did not show growth decline, but rather was flat for dense stands and increased sharply as a response to reduced competition.

We also found that trees of different age, growing in close vicinity and under the same climatic conditions, responded to climate differently. Radial growth patterns were similar within the sites (Table 3), but less coherent between the sites, confirming spatial variability of growth response to environmental factors. Variation in tree responsiveness to climatic variables has been previously observed between the tree species on the same site and in the trees of a species between the sites (Fritts 1976). Furthermore, correlation coefficients, established during our study between growth indices and climatic variables, were higher than the ones reported for Scots pine, growing on forest sites (e.g., Läänelaid and Eckstein 2003; Hordo et al. 2009, 2011) in the region. Apparently, Scots pine growing on reclaimed areas is more sensitive to weather variability than pine trees growing on forest sites.

Greater growth rates were detected on the youngest site as compared to other two groups. Similar results were observed for pine growing on fertile forest sites in Estonia, where younger tree cohorts had enhanced growth as compared to the older ones (Metslaid et al. 2011). For pine trees growing on the mined areas, the greater BAI growth could be a result of more fertile soil conditions, as defined by thicker fine soil layer and more intensive management. The youngest Scots pine generation was more sensitive to temperature, suggesting that their water needs were satisfied, possibly due to greater amount of fine soil present in the substrate. The fine soil had a higher water holding capacity, which means that moisture could have been stored for longer periods. Growth sensitivity to mean temperatures in spring was related to stand density. Soil under forest cover tends to be cooler in the summer and warmer in the winter, than in the clear-felling areas (Aussenac 2000). Already during the sampling occasion, we noticed that ground vegetation under theses stands was sparse, indicating lack of sunlight in these stands. It was darker, because of full canopy shading and the temperature felt also cooler, than at the other two sites. Due to delayed snowmelt in spring, onset of the growing season in denser stands could have started later, having considerable influence on tree annual productivity (Vaganov et al. 1999; Helama et al. 2013). The greater canopy cover in the middle-aged stands could explain the positive correlation to annual temperature (longer time span) and lower sensitivity to temperatures in summer months as compared to managed stands. However, relation to temperatures in August for middle-age group was stronger as compared to the other two groups, suggesting that there could be delay in ring formation processes due to later onset in spring. Ring formation can be continuing in these trees, while growth processes are about to cease in more sparse stands.

Modeling basal area increment

The basal area increment model developed during this study included three main components, which described site properties and accounted for climatic variation and tree response to changes in competition. These variables are commonly used in basal area models (Wykoff 1990; Keyser and Brown 2014; Mehtätalo et al. 2014). By applying a nonlinear modeling approach, we avoided many assumptions that are necessary for using linear modeling (Zuur et al. 2009; Eastaugh et al. 2013). As a result, our model was able to predict basal area increment in managed and unmanaged Scots pine plantations growing on reclaimed areas. For simplicity, and because we were not interested in tree-level effects, we used tree maximum diameter to describe potential tree growth (asymptote) on particular sites.

According to our model, site properties and thinning had the greatest effect on the radial growth (Table 5). Our results (Fig. 5) show that thinning on these sites reduced competition between trees resulting in a positive effect on radial growth, with trees responding immediately after treatment.

The first thinning increased the basal area increment of dominant trees up to 50 %. This corresponds to the results of Mäkinen and Hynynen (2014) who found that intensive thinning on mineral soils can increase the basal area increment of remaining trees ~50 %. Thinning on reclaimed sites has positive effect on radial growth of dominant trees reducing the competition between trees after canopy closure. Individual tree response to changes in stand density was modeled as time elapsed since thinning, because stand basal area before and after thinning was not available. In practice, changes in basal area are rarely recorded, and inclusion of a variable describing time since thinning is more convenient. It was a surprising finding that with a model assistance, we were able to detect one more thinning (on site 3), presumably a cleaning (Fig. 5b), since it was carried out at an early stand development stage. We refer to this management activity as hypothetical, because management activities are not well recorded for these areas, and we could not detect any proof for this activity. However, model prediction was improved significantly after including a thinning in 1996 for that site. Thus, our finding suggests that trees on reclaimed areas are highly responsive even to minor changes in stand structure. It should be noted that only dominant and co-dominant trees were investigated in this study, since these trees are expected to be crop trees, growing for many years on that site. Trees with other social status (intermediate or suppressed) might have been responding differently to increased space, since radial growth is size-mediated (e.g., Gavin et al. 2008); therefore, all the findings in this study apply only for the largest trees in the stand (trees with crowns extending above general level and from the general level).

To evaluate the effect of site productivity on radial growth, we tested traditionally used site index. Fine soil depth was included because it showed high correlation to site index (SI_{50}) and because previously similar variables have been used (e.g., Schröder et al. 2002) as a direct indicator of site productivity. For our data set, fine soil depth was a better predictor than site index. Besides, it is easy to measure in the field. Site productivity is an important variable in basal area growth modeling, describing differences in trees growing under the same climate conditions, but on different soils (Subedi and Sharma 2013). Annual basal area increment data, expanding over the period of 1976–2013 (37 years), was used to fit the model. Therefore, growth predictions may be used to predict long-term growth on reclaimed areas and predictions are climate sensitive.

Mitigating effects of climate change

Dry and warmer than average climatic conditions in summer, especially in June and July, were negatively related to diameter growth of the Scots pine trees on reclaimed oil shale mined areas in Northeast Estonia. This relationship grew stronger with increasing tree dimensions, i.e., as stands developed. Water stress, caused by lack of rainfall in summer, when active ring formation takes place, was expressed among the trees unevenly and was associated to physical characteristics of the substrate (e.g., soil texture and the amount of fine soil fraction, and the depth of organic matter accumulation) and stand density that influenced microclimate in the understory due to shading. Thicker organic matter reduced the negative effects of temperature especially in August. In general, organic matter accumulation on reclaimed mined sites is correlated with litter production, meaning that quickly attaining full site occupancy and high productivity are necessary for rapid accumulation (Mandre and Kuznetsova 2004). Positive relationship between growth and mean spring temperatures indicated that greater annual wood production could be expected during early and warm springs. Trees growing in dense stands, however, are subject to competition-induced mortality (Laarmann et al. 2009) and older managed stands are sensitive to moisture stress. Thinning in young stands may retard soil formation and organic layer accumulation as well as stability on mined sites and first thinning often is delayed.

The relationships among climate variables and soil and stand characteristics established in this study can be used to guide management of reclaimed oil shale mined sites under altered future climate. As suggested by Giuggiola et al. (2013) and D'Amato et al. (2013), managing tree competition in closed-canopy stands by thinning can be an adaptation to climate change-induced drought stress. Thinning young and old stands on reclaimed sites positively influenced growth rates, with immediate response of the dominant and co-dominant trees. Temperatures in January controlled radial growth in the youngest stands. Responsiveness to lower temperatures in January grew weaker with age, although higher productivity sites (expressed as SI_{50}) retained sensitivity to temperature. As climate changes toward warmer winter temperatures, increased growth rates on reclaimed mining sites may accelerate stand development and necessitate earlier thinning to avoid competition-induced mortality and moisture stress.

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