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Detecting drainage events and the effect of drainage intensity on tree growth: A case study of Tellissaare raised bog, Estonia

ALAR LÄÄNELAID, KRISTINA SOHAR *, KÄRT ERIKSON AND AIN KULL

Department of Geography, Institute of Ecology and Earth Sciences, University of Tartu, Vanemuise 46, 51003 Tartu, Estonia

* Correspondence:
Kristina Sohar
kristina.sohar@ut.ee

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Abstract

Mires are an important part of northern and boreal landscapes. Many peatlands have been drained in Estonia either for peat extraction, forestry or agricultural purposes. The remaining mires often have drainage ditches in their peripheral area, affecting the hydrology and vegetation. The main objective of this study was to quantify the effect of drainage on the radial growth of trees growing in the mire margin and to assess if a drainage-induced change in the radial growth of Scots pines (*Pinus sylvestris* L.) in a bog can be used as an indicator to determine the width of a buffer zone for the preservation of the natural interior of the mire. Pines growing at different distances from the ditch were sampled by increment borer, and their radial growth was analysed. We found a time lag in the effect of drainage on tree growth towards the interior of the mire. Detecting drainage events is complicated as the effect is mixed with the climate signal which varies also with drainage intensity. Trees growing closer to the ditch were mostly negatively affected by late autumn temperatures of the previous year, while trees in the unaffected area of the mire were more affected by winter temperatures. The positive spring and summer precipitation signal intensified towards the pristine core of the mire. A significant increase in radial increment of pines was observed near the drainage ditch up to 40 metres; however, a weaker effect of drainage was still detected at a distance of 90 metres from the ditch. The drainage effect on the radial growth disappeared at a distance between 190 and 440 metres from the ditch. This indicates that the buffer zone width to protect the mire core from forest encroachment due to anthropogenic drainage should be at least 190 metres wide.

Keywords: dendroecology; climate–growth relationships; disturbance; peatland; *Pinus sylvestris* L.

Introduction

Peatlands with their unique flora and fauna can be considered an important natural resource in the boreal and temperate zone of the Northern Hemisphere. Extensive drainage of mires for agricultural and forestry purposes, and peat excavation have reduced the extent of natural mires. Beside conservation of biodiversity and natural values it is emerging that peatlands are necessary to ensure ecological stability on local, regional as well as global scales (Costanza 1997, Masing et al. 2010, Leibak 2021). Baltic peatlands play a unique role in the assessment of bog hydrology and investigation of Holocene climate variability through multi-millennial proxy records (Edvardsson et al. 2016, Edvardsson et al. 2019).

Estonia has a long history of peatland drainage. First written records of systematic activities with maps are dating back to the end of the 19th century. In 1897, the first Bureau of Land Amelioration in Estonia was established to study, promote and coordinate land amelioration works (Estonian Institute of Agriculture 1960). Between 1897 and 1907, peatland reclamation activities were carried out in the lands of 604 manors and 140 farms. From 1908–1909, the activities extended to 308 manors and 132 farms, and in 1909–1910 additional 335 manors and 48 farms were included. This indicates that land amelioration efforts were considered a high priority by the landowners (Estonian Institute of Agriculture 1960).

The need for peatland protection has arisen and gained common acceptance already for more than half of a century (Joosten and Clarke 2002). In Estonia, the turning point in the views to values of mire took place in the early 1960s, when the Soviet plans of massive mire amelioration were overcome by ideas of ecological values of wetlands (Masing 1976, Ilomets and Kallas 1995, Järvet 2010). Nevertheless, even for a relatively sparsely populated country like Estonia, the area of natural mires decreased drastically.

Large-scale drainage of mires, especially fens and transitional bogs was executed between the 1950s and the 1980s. The area of transitional bogs and wooded transitional bogs together with bogs and bog forests decreased from 608,000 ha in the 1950s to 268,000 ha in the 1990s

(Kimmel et al. 2010), and 584,400 ha of fens were drained for agricultural purposes by 1980 (Paal and Leibak 2013). In the 1950s the total area of (ombrotrophic) raised bogs in Estonia was about 250,000 ha (Laasimer 1965) while, according to the mire inventory, almost 100,000 ha of bogs were destroyed during the following 60 years (Paal and Leibak 2013, Paal et al. 2024).

The main cause of the loss of mires was drainage for forestry, agriculture and peat industry. Today peat extraction continues in limited areas, approximately 2% of all drained peatlands. The forest amelioration was carried out to improve forest growth in waterlogged areas, as depth of water table and waterlogging are the prime regulators of tree growth in peatlands (Linderholm et al. 2002). Lowering the water level increases tree cover and biomass in a mire (Vasander et al. 1993). A number of extensive mires were declared mire protection areas (Masing 1997). However, despite decades-long drastic measures of nature conservation, most of the mires have adjacent drainage systems of various ages in their very vicinity (Paal et al. 2024). Even many of the natural-looking mires may be affected to some extent by functioning drainage and lowered groundwater level at their margins.

Research into peatland pines in the Baltic region has a long history (Läänelaid 1984, Dauškane et al. 2011, Smiljanić et al. 2014). Drainage effect on tree growth is well established (Boggie 1972, Edvardsson et al. 2016), especially in the context of forestry studies (Seppäla 1969, Padari and Kiviste 2005, Päivänen and Hånell 2012a, Potapov et al. 2023). Still, the exact extent of drainage effect toward the mire core area remains unclear (Paal et al. 2024). To protect natural mires, buffer strips must be established around them to limit hydrological effects of neighbouring amelioration systems on the mire ecosystems. Previously the extent of possible influence of mire melioration on various hydrological and ecological parameters, including vegetation was studied in Estonian mires by Paal et al. (2016, 2024). In our study we focused specifically on drainage effect on tree growth. Tellissaare bog in northern Estonia with a well-documented amelioration system was used for that purpose.

We aimed to use the series of tree-ring widths of growing pines (*Pinus sylvestris* L.) to establish: (1) how far in the bog the drainage ditch influences radial tree growth, (2) how long it takes for the drainage effect to appear, and (3) how intensive is the effect of drainage on tree growth. In addition, we assessed the impact of climate on the radial growth of trees in the studied bog to allocate the natural climate effect and the drainage effect.

Material and methods

Study area and tree-ring sampling

Tellissaare bog (59°2’39”N, 25°31’4”E, 76 m a.s.l.) is in Järva County in northern Estonia, within the Kõrvemaa Landscape Reserve (Figure 1). It is a raised bog bordered by the Jägala River and its tributaries from the northeast as well as drainage systems from the south and west. According to the topographic map dating back to 1935, the earliest drainage work (a ditch) in Tellissaare bog took place before 1935 (Republic of Estonia Land and Spatial Development Board 2024). The main ditch of the drainage system was commissioned in 1956. Although the drainage work was carried out on the northwestern side of the bog in 1964, it might have had a minimal effect on the pines at the most distant part of the study area. The extended melioration at the southeastern side of the bog was completed in 1976 (Maa- ja Ruumiamet 2022).

Sample plots were established along a hydrological gradient at fixed distances from the drainage ditch to the pristine interior part of the peatland (Figure 1). By using a transect method it is possible to investigate the buffer zone dimensions to protect the pristine interior mire. In each plot, several measurements of hydrological and soil parameters were made every month and vegetation was studied (for a detailed description, *see* Paal et al. 2024). Vegetation, especially *Sphagnum* cover, has an interactive influence on the tree layer in bogs (Ohlson et al. 2001).

The study transect was established perpendicular to the bordering drainage ditch at the southeastern edge of the bog, stretching to the northwest from the ditch, towards the central part of the bog. Along the transect, seven sample plots were marked with painted poles, starting from the ditch, at the distances of 5, 15, 40, 90, 190, 440 and 718 m. The last plot was located closer to the ditch on the NW side of the bog (Figure 1). The absolute elevation of the ditch near the first plot was 72.0 m, and the elevation of the seventh plot in the middle part of the bog was 75.7 m. As common in Estonian bogs, the slope was covered with small trees of Scots pine (*Pinus sylvestris* L.), whereas the pine cover turned sparser and more stunted towards the centre of the bog. The interior was characteristically open with single dwarf pines only, growing on hummocks. Tree height and canopy cover are dependent of nutrient availability in soil and pore water (Figure 2). The effect of drainage appears on tree growth primarily through the water level (distance from ditch, and microtopography), nutrient availability and mineralization of the soil. Figure 2 shows the effect of drainage on average value of canopy cover, average tree height and nitrogen (N) concentrations. Drainage had a clear positive effect on average canopy cover and tree height up to 90 m from the ditch, being the strongest at 5 m from the ditch. Farther than 90 m the drainage effect on nutrient availability and tree height was no longer significant.

For the dendrochronological study, 12 pine trees per plot were sampled by an increment borer in a zone two metres wide perpendicular to the transect, i.e. parallel to the ditch. Looking towards the centre of the bog, the first six pines were taken to the left from the transect study plot and the other six pines to the right. The samples were taken by inserting the increment borer at the height of 0.5 m from the mire surface in the north-south direction relative to the tree stem so that opposite radii were obtained in one core.

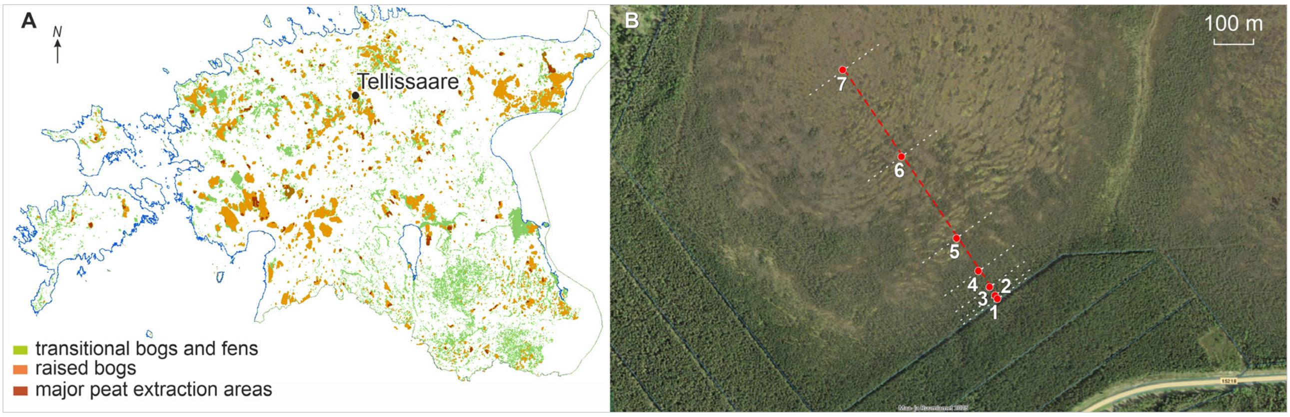

Figure 1. (A) Location of Tellissaare bog in Estonia. (B) Study transect in Tellissaare bog: seven study plots (red dots) starting from the drainage ditch at the SE edge of the bog, with increasing distances between the plots. At each plot, 12 pines (6 on either side) were sampled from a 2 m zone (white dashed lines) perpendicular to the transect (orthophoto by the Republic of Estonia Land and Spatial Development Board 2025)

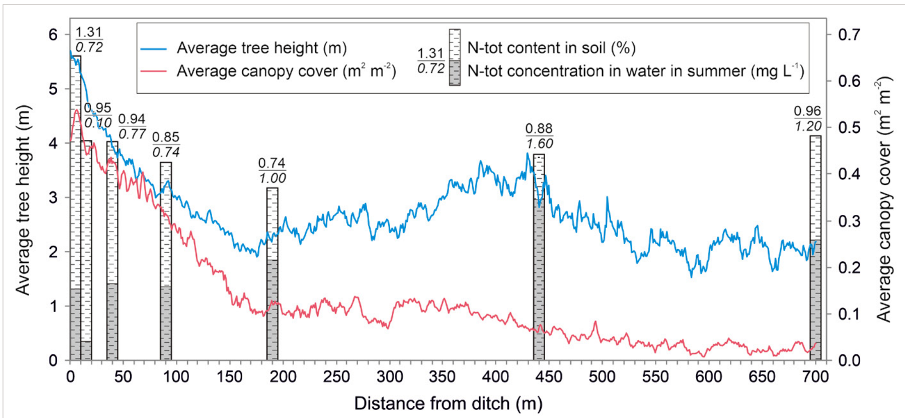

Figure 2. The effect of drainage on total nitrogen content in soil (upper 40 cm) and total nitrogen concentration in pore water (0–100 cm depth) in vegetation period, as well as average tree height and canopy cover in the plots in Tellissaare bog

Bars show total N content in water and soil (total bar length indicates relative N-tot (%, above fraction line) in soil while shaded part of bar indicates relative proportion of average N-tot (mg L–1, below fraction line) in pore water during vegetation period). Note that the total length and shaded part of the bar are not proportional to each other but are proportional individually along the distance.

The north direction of the cores was fixed, and the samples were stored in numbered plastic straws.

Development of tree-ring chronologies

The cores were air-dried to prevent mould growth. Subsequently, the cores were moistened, their surface was cut with a razor blade and treated with white chalk, and tree-ring widths were measured precisely by Leica S4E stereomicroscope and Lintab measuring device (Rinntech) with accuracy of 0.001 mm (Rinn 2011). The ring-width series graphs of the north and south radius of each tree were visually inspected to detect possible measurement errors and locally missing rings. The corrected opposite radii series were averaged to form a tree-level increment series. The ring-width series of 12 trees from each plot were compared on graphs with the aid of a TSAP-Win software package (Rinn 2011) and additionally using the Cofecha program (Holmes 1983, Grissino-Mayer 2001). Each tree-ring width series was checked visually for sections of wide rings attributed to young age. Consequently, the early part of radial growth was removed from the series. Subsequently, the tree-ring series were averaged into mean curves for each plot. Each mean curve included between 9 and 12 tree-ring-width series. In further analyses, both the chronologies and individual tree-ring series were used.

Disturbance analysis

As tree growth in peatlands is influenced by drainage, the drainage effect can be treated as a forest disturbance. Accordingly, we applied a modified formula of relative radial increment from Nowacki and Abrams (1997), Black and Abrams (2003), and Altman et al. (2013, 2014):

$$GC = \frac{M2 - M1}{M1}, \quad (1)$$

where
GC is the percentage of growth change,
M1 is the average tree-ring width in the preceding period (including the target year), and
M2 is the average tree-ring width in the subsequent period.

The formula has several variations, differing by length of periods (Rubino and McCarthy 2004). Contrary to Black and Abrams (2003), we did not apply a boundary line in the release event calculation because of the specific growth rates of pines growing in bogs. Similarly to Altman et al. (2013), we used the formula for individual trees, and for plot tree-ring chronologies, too. As we investigated known anthropogenic disturbance events and needed to exclude the effect of microtopography (lawn, ridge and hummock) on tree growth, the chronology approach was additionally used. Averaging of growth series across trees smooths out their growth patterns and enhances common signals like external disturbances, e.g. drainage effects. In our study, we tested the method with the M1 periods of 7 and 10 years and the M2 periods of 10 and 15 years. Finally, M1 = 10 and M2 = 10 were used. Instead of an arithmetic average, we used the median of the tree-ring widths. Further on, we determined the year when the relative growth change was maximal. This was calculated within 15 years after the drainage event in 1956 for each tree and plot. As a next step, 10-year median increments before and after the year of maximum growth change were calculated for each tree and chronology. In addition, 10-year median increments before and after the 1956 drainage were determined for individual trees.

Dendroclimatological analysis

To study climate-tree growth relationships, each tree-ring width series was indexed separately (Fritts 1976). For standardisation, we used the program ARSTAN (Cook 1985, Cook and Krusic 2005). Tree-ring series were detrended using a 30-year cubic smoothing spline (Cook and Peters 1981), which preserves 50% of the variance at a wavelength of 30 years. The smoothing spline was the most efficient for removing the tree age-related trend and the low-frequency drainage effect. A curve was fitted individually to each tree-ring width series, and dimensionless indices were derived from the curve by division. Thus, this process also removed the differences in growth rates between the samples. The index series were further pre-whitened to remove persistence due to autocorrelation, and seven residual site chronologies were constructed using a bi-weight robust mean (Cook 1985).

We used monthly mean temperatures and precipitation sums from the nearest weather station in Türi (58°48’31”N, 25°24’33”E, 60 m a.s.l.), located 27 km south of Tellissaare bog. Pearson’s correlation (r) and response function coefficients (r_{res}) were calculated using the DendroClim2002 program (Biondi and Waikul 2004). Response coefficients are multivariate estimates from a principal component regression model (Briffa and Cook 1990). The program uses bootstrapped confidence intervals to estimate the significance of both coefficients ($p < 0.05$). In the calculations, we used a 12-month window from prior October to September of the current year. Since the length of continuous meteorological observations is limited, the common period for the climatic and dendrochronological data was from 1946 to 2012. The stability of relationships was tested using 50-year moving intervals.

Results

Regardless of the distance from the drainage ditch, the annual increment of trees in Tellissaare bog had a similar magnitude and pattern until the 1960s (Figure 3). The major divergence in annual increment between different distances appeared with the temporal delay after the main drainage event in 1956. A significant increase in annual increment was observed closer to the ditch, no effect appeared in the distant parts of the transect.

The investigation of disturbances revealed minor differences in increments between consequent 7- and 10-year, 7- and 15-year, 10- and 10-year and 10- and 15-year periods. Three clearly defined peaks with positive relative growth change appeared in the 1910s, 1930s and 1960s, regardless of the length of time frame (Figure 4). The years of maximum increment difference did not exactly coincide with the documented drainage years in Tellissaare bog (1956, 1964 and 1976). After establishing the main drainage ditch in 1956, the mean radial increment of pines in the three plots closer to the ditch showed a significant growth increase during the following ten years, compared with ten years prior to drainage (Figure 4). The positive effect of the 1956 drainage event on pine growth appeared after a certain time lag and reached maximum of approximately ten years after drainage in 1965. Some temporal

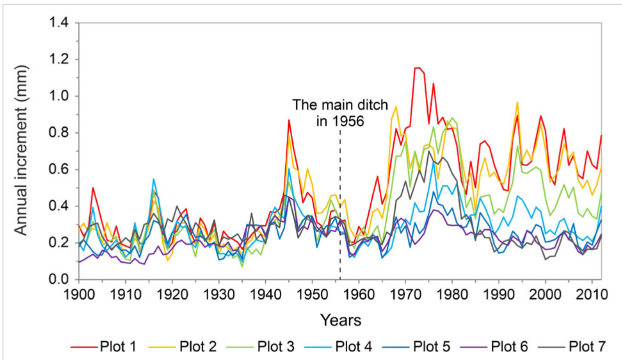

Figure 3. Average pine tree-ring width series in the plots in Tellissaare bog during 1900–2012

Table 1. The first year of positive relative growth change and year of maximum growth release at the plots in Tellissaare bog during three historic drainage episodes

	1st drainage		2nd drainage		3rd drainage	
	First year	Max year	First year	Max year	First year	Max year
Plot 1	1911	1913	1932	1939	1957	1965
Plot 2	1912	1914	1932	1940	1960	1965
Plot 3	1906	1913	1934	1940	1960	1967
Plot 4	1907	1911	1932	1938	1962	1968
Plot 5	1907	1914	1931	1939	1962	1967
Plot 6	1909	1916	1927	1936	1962	1967
Plot 7	1906	1913	1933	1940	1962	1969

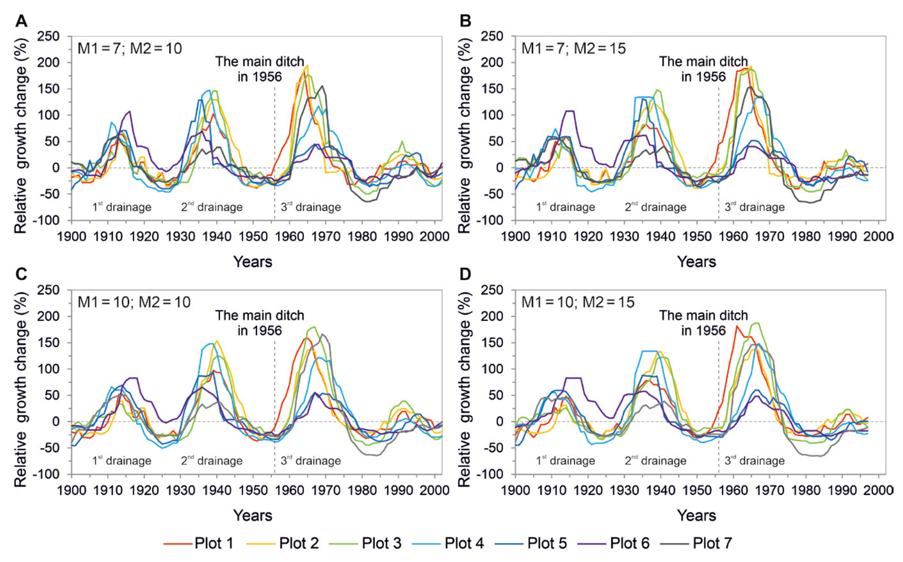

Figure 4. Relative growth releases of pines in the plots in Tellissaare bog. Relative growth change was calculated as running median increment for 7 years prior, and 10 and 15 subsequent years increment (A, B), and median of 10 years prior, and 10 and 15 subsequent years increment (C, D)

shifts happened in the reaction of pines farther from the ditch (Table 1). Different periods did not show significant differences in growth change calculation results. Shorter time frames were slightly more sensitive and showed more abrupt growth changes. Due to a lack of significant difference, the more common 10-year prior and 10-year subsequent time frames were applied.

Spatially there was a significant difference between pre- and after-drainage tree increment only in the four sample plots closer to the ditch, whereas, in the other sample plots the difference was negligible. Nevertheless, as an exception, the most distant sample plot (at 718 m from the ditch) again showed a growth difference between pre-drainage and after-drainage tree increments after 1956 drainage (Figures 4 and 5). This phenomenon is supposed to be unrelated to the main drainage event of 1956 but rather is a result of an additional drainage event in 1964 that affected the opposite NW side of the bog. Despite a statistically significant threefold increase in tree-ring width after drainage, changes in the radial increments of pines were still relatively small. Tree-ring width before drainage ranged from 0.2 to 0.3 mm on average in all sampling plots and did not exceed 1 mm after the drainage. The distance-wise trendlines were statistically significant ($p < 0.01$ and $p < 0.05$), showing that drainage influence diminished towards the centre of the bog (Figure 5). Based on the radial increment of pines, the minimal extent of a buffer strip around an unaffected core area of the mire could be defined as 90 m.

Spatially, there was no significant difference between the 10-year average radial increments before and after drainage in 1956 at the individual tree level (Figure 6). In the space of 10 years after the drainage, average tree growth was equal to or even lower than before the drainage event. In general, in the years coming after 1956, the 10-year median tree ring growth did not exceed 0.5 mm, while for the 10-year-long period before the drainage; there were multiple trees with increment values above 0.5 mm. That indicates the initial shock of trees due to amelioration works. The same pattern could be seen throughout the peatland, from the sample plots nearest to the drainage ditch to the most distant ones but the effect diminished with distance (Figure 6).

The drainage effect on trees lagged both spatially and in time (Figure 7). The trees closer to the drainage ditch achieved maximum growth earlier than the ones growing further away. As a median, the year of maximum growth release for the trees in all studied plots was 1967. The largest number of trees with maximum growth occurred in the years 1965 (9 trees), 1967 (13 trees) and 1971 (15 trees). The reaction to drainage is distance-dependent but the effect was delayed and shaped by individual tree growth.

The dendroclimatic analyses revealed a lack of clear common climatic signals along the transect (Figure 8). However, the bootstrapped correlation (r) and response (r_{res}) functions revealed that the pines growing closer to the ditch were mostly negatively affected by late autumn temperatures of previous year, e.g. in prior November ($r = -0.26$, $p < 0.05$) in plot No. 2 (15 m from the ditch). The trees farther from the ditch and at the unaffected area of the mire were more affected by winter temperatures ($r = -0.24$ in January and $r = -0.26$ in February, $p < 0.05$ in plots No. 3 and 4, respectively; $r_{res} = -0.24$ in December, $r = -0.23$ in January and $r = -0.25$ in February, $p < 0.05$ in plot No. 6). A significant negative correlation was continuous almost throughout the observed period from 1946 to 2012 in three plots closest to the ditch (up to 40 m) and at the unaffected area of the mire (440 m from the ditch). A positive spring and summer precipitation signals intensified towards the pristine core of the mire. For instance, pines from plots No. 3 and 4 reacted positively to precipitation in May ($r = 0.20$ and $r = 0.21$, $p < 0.05$, respectively), but this relationship was unstable. The trees from the centre of the mire also benefitted from precipitation in April ($r = 0.24$ and $r_{res} = 0.22$, $p < 0.05$; 440 m from the ditch) and in May

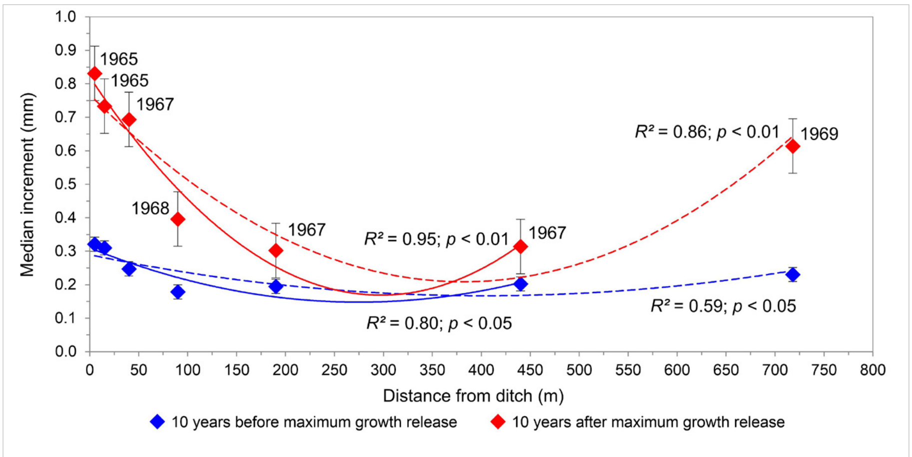

Figure 5. 10-year median increment of pines at different distances from the ditch before and after maximum growth release (years indicated) since the documented main drainage event in Tellissaare bog, 1956

Solid trendlines (second-order polynomial) are based on six plots closest to the ditch. Dashed trendlines are based on all seven plots. Whiskers mark standard error.

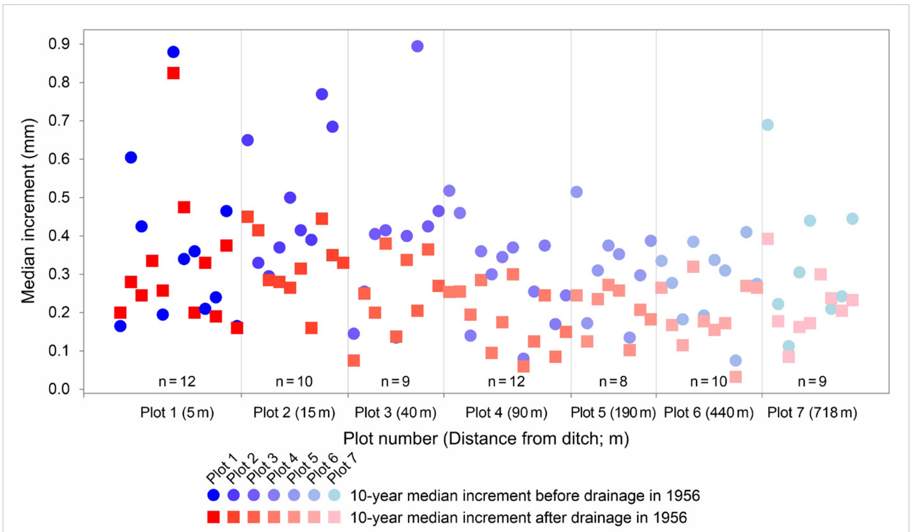

Figure 6. 10-year median tree-ring widths of individual trees at different distances from the ditch before (blue dots) and after (red squares) the drainage event in 1956

Colour intensity indicates distance from the ditch.

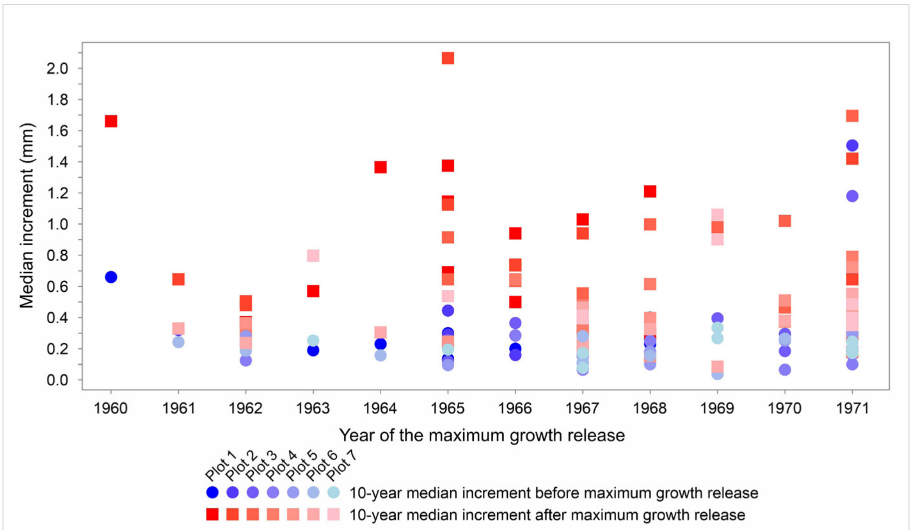

Figure 7. 10-year median tree-ring width variability of individual trees at different distances from the ditch before (blue dots) and after (red squares) maximum growth release within 15 years after the drainage event in 1956

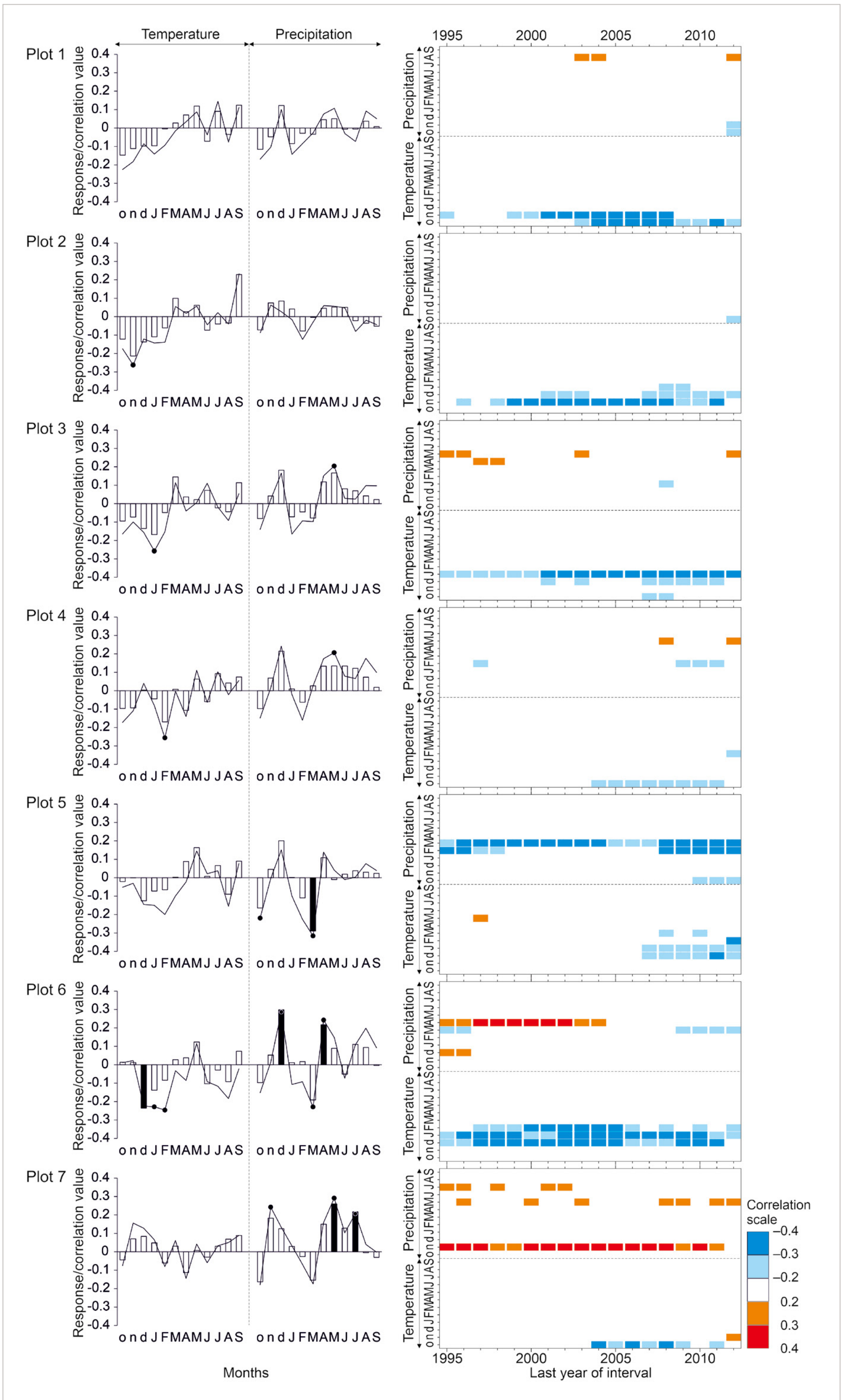

Figure 8. *Left panel*: correlation coefficients (lines) and response values (bars) between tree-ring widths and monthly temperature and precipitation of previous (lower case letters) and current year (capital letters) during 1946–2012 in the plots in Tellissaare bog; statistically significant relationships ($p < 0.05$) are indicated by dots on lines and by filled bars, respectively. *Right panel*: correlation coefficients ($p < 0.05$) between tree-ring widths and monthly meteorological variables of previous (lower case letters) and current year (capital letters) in the 50-year moving interval

($r = 0.29$ and $r_{res} = 0.26$, $p < 0.05$) and in July ($r = 0.21$ and $r_{res} = 0.22$, $p < 0.05$) in plot No. 7 (718 m from the ditch). There was also a positive effect of precipitation in November ($r = 0.24$, $p < 0.05$) and December ($r = 0.29$ and $r_{res} = 0.30$, $p < 0.05$) in plots No. 7 and 6, respectively. On the contrary, the pines in plot No. 5 (190 m from the ditch) showed a stable negative response to March precipitation ($r = –0.32$ and $r_{res} = –0.29$, $p < 0.05$). The same feature occurred in plot No. 6 (440 m from the ditch; $r = –0.23$, $p < 0.05$), but the relationship was unstable.

Discussion

Northern peatlands have been influenced by drainage for a long period. The drainage effect has several ecological consequences dependent on its duration after the amelioration. Particular drainage events are often not documented, and dendrochronology could implicitly help to date the events. Here we apply the dendrogeomorphological approach of event–response dating using tree-ring patterns (Solomina 2002). The special feature in this case is that the disturbances were anthropogenic; their effects are spatially spread in the study area and assumedly have a certain temporal pattern. In reliance on the conceptual aggregate model of tree growth (Cook 1990), we search for external disturbances.

Investigation of ecological disturbances is a classic task in dendroecology (Schweingruber 1996). We have not found any similar use of a transect-based approach along a hydrology gradient in the peatlands of the Baltic region. However, there are works on groundwater monitoring-related transects to study the effect of water level from a North American wetland (Elmes et al. 2024) and Poland (Nowakowska et al. 2021).

According to Banks (1992), the drainage effect can be classified as a multi-seasonal geomorphic disturbance of trees. Drainage changes the natural conditions in the peatland and causes peat subsidence (Eggelsmann 1986). However, it is reported that the annual runoff from a peat bog in SE Finland settled down to the pre-drainage level within 15–20 years (Seuna 1981) while Ivanov (1953) found a long-lasting effect. There is certain knowledge of how forests behave in the changing climate conditions in Europe (Lindner et al. 2010). Trees growing in peatlands respond differently to temperature and precipitation fluctuations than those growing on mineral soils due to higher water retention capacity, thermal resistance and lower organic matter turnover rate. It has been established that lowering the water table in peatlands can significantly alter the carbon and nitrogen cycling in the ecosystem (Choi et al. 2007, Palviainen 2024). Besides, a lowered water table by drainage results in effective litter decomposition in the aerated surface zone (Pitkänen et al. 2012).

Although research of mires has long traditions in the Baltic region (Masing et al. 2010), dendrochronology has become a more widely used method for their investigations only in recent decades (e.g. Läänelaid 1976, 1982, 1984, Dauškane et al. 2011, Smiljanić et al. 2014, Tamkevičiūtė et al. 2018, Potapov et al. 2019, 2023). The tree-ring width of peatland pines in northern Poland reacts mainly to changes in the groundwater level (Cedro and Lamentowicz 2011). However, an optimum groundwater level and water regime for tree growth in general has not been specified (Päivänen and Hånell 2012a). As groundwater level is influenced by atmospheric precipitation, the amount of rain in previous June and current July is the main climate variable negatively correlated with diameter growth of pines in the Finnish peatlands (Hökkä et al. 2012, 2025), whilst Edvardsson and Hansson (2015) did not establish clear correlation of tree growth with monthly precipitation in the bogs of southern Sweden. Instead, multiannual precipitation and streamflow showed a significant negative correlation with tree growth, while spring and early summer temperatures had a positive effect (Ibid.). Moreover, it was shown that pines growing on peat soil in Lithuania were unsuitable for high-frequency climate reconstruction but had a potential for reconstructing multi-annual hydrological fluctuations (Edvardsson et al. 2015). Tamkevičiūtė et al. (2018) and Potapov et al. (2019) showed the same for the potential of tree growth for climate reconstruction. Smiljanić et al. (2014) demonstrated that higher water table levels during several years before and warmer and wetter winters before the current growing season harm the radial growth of peatland pines in Estonia. A similar negative winter temperature signal was detected in the present study. Previous year autumn temperatures negatively affected tree growth close to the ditch, while the trees in the pristine part of the peatland were more influenced by winter temperatures. Contrary to Dauškane et al. (2011), summer temperature did not influence tree growth in Tellissaare bog. As in the cases described by Cedro and Lamentowicz (2011), precipitation during the growing season had a beneficial impact on tree growth in Tellissaare, but only in the less disturbed areas (40 to 719 metres from the ditch). Conversely, pines on mineral soils in Estonia have been demonstrated to mostly benefit from winter-spring temperatures (Läänelaid and Eckstein 2003, Hordo et al. 2009, Pärn 2009). The same has been noted in other Baltic regions (Vitas 2004, Elferts 2007, Edvardsson et al. 2015, Rimkus et al. 2018).

A few separate trees in the bog may have been impacted by other disturbances such as fertilisation by nesting birds, which ensures exceptional growth (Masing 1988), or moose damage reducing growth. The series averaging levels out these kinds of outliers to a certain extent. The transect method seems appropriate as the drainage (ditch) is a well-defined linear element within nature, and its effect presumably diminishes towards the centre of a bog. In addition, we see that the influence of drainage is strongest near the ditch.

Although various growth reactions occur in pines such as gradual stem burial, tilting of stems and reaction wood (Wimmer 2002, Stoffel and Bollschweiler 2008), we focus on radial increment disturbances in this study. Various methods have been proposed to investigate disturbances in tree growth (Rubino and McCarthy 2004). We used the averaging method of radial growth (Nowacki and Abrams 1997, Black and Abrams 2003, Stan and Daniels 2010, Altman et al. 2013). However, we altered it and tested different lengths of the pre-event and post-event (*see* target year in Altman et al. 2013) periods. Normally, 10-year periods work well on disturbance effects over decades. In the case of Tellissaare bog, we assumed repeated drainage events in consequence. If the effect of an earlier drainage is evident less than ten years before the next drainage effect, a shorter prior period would help to avoid overlapping with the post-drainage effect of the following event. We tested 10-year and 15-year post-event and 7-year and 10-year pre-event periods. The results differed negligibly. Overall, the shorter length was slightly more sensitive to changes in growth release values. Therefore, the 10-year pre-and post-event period was considered appropriate and used for Equation (1). The increment time series indicates that that as a rule, the drainage effect on tree growth lasts longer than ten years (Figure 3). The growth change Equation (1) does not reflect the length of drainage effect but rather the time of maximum growth change after the disturbance, e.g. drainage.

Figure 4 shows three pronounced peaks of growth release. The first peak of growth release occurred around 1915, the second around the 1940s and the third between the 1960s and 1970s. Long term dendrochronological records were investigated for the intensity and extent of the growth releases to distinguish the possible climatic and anthropogenic (drainage) components of the growth releases. The release predominantly caused by climatic factors tended to be more gradual and could be observed throughout the peatland regardless of distance from the ditch. The anthropogenic growth release is expected to occur more abruptly with varying intensity throughout the peatland, i.e. stronger near the source of the disturbance, and with delay in growth release further away from the source of disturbance.

Analysing the radial growth patterns of pines at the transect plots (Figure 3), we see that after the documented drainage in 1956, growth remained slow or decreased for several years. Increment at plot No. 1 (at 5 m from the ditch) increased only in 1964, followed by a growth increase at plot No. 2 (15 m from the ditch) in 1967 and plot No. 3 (40 m from the ditch) in 1968. A slight increase of increment at plot No. 4 (90 m from the ditch) started later and reached its maximum in 1976. The higher increment of pines at plot No. 7 after 1968 can be explained by the location of this plot closer to the NW edge of the bog, where drainage in 1964 could have affected the trees. Pines at plot No. 5 (190 m from the ditch) also showed a local growth maximum in 1976, whereas trees at plot No. 6 (440 m from the ditch) showed relatively small increment increase in 1976. We do not expect the drainage effect to extend to the centre of bog massif; there may be other factors behind the enhancement of pine increment. For comparison, tree ring growth of black spruce in central Alberta, Canada, reached its maximum only 13 to 19 years after drainage (Dang and Lieffers 1989). On the contrary, Linderholm (1999) claims that drainage causes instant increase in annual tree growth of Scots pine lasting for approximately ten years in a raised bog in south-central Sweden.

The modified simple formula from Altman et al. (2013) was applied to reveal disturbances in tree-ring series. A similar formula was used by Stravinskiene et al. (2013), where instead of the first period the increment was compared with trees in the control stand. Relative increment difference between two periods – ten years before and ten years after the disturbance event – revealed three pronounced maxima in the running growth changes from Equation (1) (Figure 4). The later maximum around 1965–1969 presumably refers to the drainage work in 1956, with a 9–13-year lag (Table 1). This peak marks the year when the tree increment reached the maximum level concerning the prior ten years' increment. Growth releases of several consequent years could be similar which makes it complicated to pinpoint a particular year of disturbance (drainage). The maximum growth may be achieved even a decade later because melioration can affect bog tree growth in many ways. Although a raised bog has the shape of a convex lens, often rising higher than the surrounding mineral surface, its peat is wet like a sponge (Masing et al. 2010, Päivänen and Hånell 2012b). The surface water table fluctuates in the high range, limiting tree growth through the anaerobic environment for tree roots below the water level. Lowering the water level by drainage has little or no immediate effect on tree growth or is limited because better aeration does not immediately mean an increase in nutrients until mineralisation releases them. Oligotrophic raised bog peat is poor in nutrients and decomposer microorganisms. As the water level drops, decomposition in aerated peat increases and more nutrients are released. This takes time, and the growth of trees on it accelerates only after several years. That explains the shift in the effect of pine increment after drainage. Nevertheless, the amount of soil nutrients remains low, and accordingly, the annual increment of trees is low. Figure 3 shows that tree-ring widths of pines fluctuate mostly below 0.5 mm, raising slightly over 1 mm only after the drainage. Even after drainage, the radial growth of studied pines is not comparable with the growth rates of forest pines on mineral soil. The average ring width of pines in the Estonian pine chronology, based on forest trees, from 1900 to 2000 was 1.14 mm (Läänelaid and Eckstein 2003). Therefore, expecting pine increment increase after drainage to match the growth level of forest trees would be too optimistic.

The earlier abrupt growth increase around 1940 refers to an earlier drainage event. Similarly to the 1956 drainage work with maximum effect in the mid-1960s, we assess that drainage took place at the beginning of the 1930s. Although there is a temporal shift in the maximum effect of this drainage event in the first three plots (1939 and 1940, respectively), the highest relative effect of drainage appeared in plots Nos. 2, 3 and 4 (Figure 4). An earlier drainage ditch is marked on the topographic map of Tellissaare bog dated 1935. The first growth release (Figure 4) occurred around 1915. Assuming a similar time lagging, the potential drainage event could be dated around

1905. Unfortunately, we do not possess documents about this drainage event. However, it is known that in that period, the region saw significant small-scale drainage works and straightening of minor streams to lower the general groundwater level, mainly to increase the share of agricultural land (Estonian Institute of Agriculture 1960). The growth release values around that peak are considerably smaller than the following peaks after the drainage events, and these coincide with other growth release events in Estonia and Belarus (Potapov et al. 2019). Since the values of this growth release event are not unlike throughout the bog and correspond with other growth release events in the region, the event is probably linked to favourable climatic conditions for pines growing in bogs.

A minor disturbance event with a target year happened around 1991 (Figure 4). It can be attributed to the more favourable climatic conditions and high long-range transboundary atmospheric nitrogen transport in the 1980s (Davuliene et al. 2021, Gauss et al. 2021). As indicated by Figures 2 and 4, the supposed nitrogen deposition and mineralisation from soil organic matter affect pine growth differently across the bog. The effect was most pronounced in plot No. 3, where surface water movement increases with increasing bog slope gradient, and was not pronounced at all in plots Nos. 6 and 7 in the middle of the bog.

The assumed drainage around the 1930s (Republic of Estonia Land and Spatial Development Board 2024) and documented drainage of 1956 (Maa- ja Ruumiamet 2022) significantly affected the radial growth of pines (Figure 4). However, pine tree rings after the 1956 event were much wider than those after drainage in the 1930s (Figure 3). Schweingruber (1996) explains growth release by a cumulative effect of repeated drainage. However, the co-effect of favourable climate conditions on tree growth in this period cannot be excluded, and the second release peak (around 1931–1940) somewhat coincides with growth releases of other documented release events in Estonia and Belarus (Potapov et al. 2019). The growth release event as a co-effect of drainage and favourable climatic conditions is supported by the drainage effect visible in the centre of the peatland and around the edge (Figure 4), and the evidence of a drainage event on an old map. There are similar phenomena described as a dry climatic period in the first part of the 20th century coinciding with the drainage effect triggering vegetation changes in ombrotrophic mires in Canada (Pellerin and Lavoie 2003).

To assess the spatial extent of maximal radial growth increase after drainage, we compared tree-ring width median values within ten years prior (including the target year) and ten years after the 1956 drainage event (Figures 5–7). A significant difference appeared between the pre-drainage and post-drainage increments of pine in the first three plots whilst an insignificant difference was farther than plot No. 4 (90 m from the ditch). This is in good agreement with the results of Paal et al. (2024) covering a wider set of indicators in Estonian bogs however the extent of a significant drainage effect (0–90 m) was narrower in our study. The increased increment was also observed in plots Nos. 4 and 5. Pines in plot No. 6 (440 m from the ditch) grew in the uninfluenced central part of the bog. However, they slightly reacted to the 1956 drainage, probably due to a climatic effect. The highest increment difference after the 1956 drainage was observed from 1965 to 1967 in the first three plots (Table 1). The maximum increment differences in the next plots occurred in the same period or a few years later, according to the spread of the water table lowering over the bog. In comparison, in Finland, the average annual diameter growth of pines in drained peatland is nearly levelled within 5 m from the ditch (Hökkä et al. 2012). However, forestry drainage in Finnish peatlands is mostly shallow compared to Estonian forestry drains (Palviainen et al. 2024). Paal et al. (2016, 2024) reported a similar drainage effects on canopy coverage and tree height – up to 200 m from the drainage ditch. Those drainage effects on canopy coverage and average height could be seen up to 350–400 m (Paal et al. 2016, 2024). Our study indicates that the drainage effect on canopy coverage and tree height up to 150 m from the drainage ditch. However, observed drainage influence on tree-ring width was significant up to 90 m from the ditch and a weaker effect was detected up to 190 m from the drainage ditch.

Conclusions

1. Drainage increased the radial growth of pines in Tellissaare bog with delays of up to eight years. The lag increased with distance from the ditch due to slow propagation of the lowering bog water level.
2. A significant increase in the radial growth of the pines occurred only in the four closest plots to the ditch, i.e. up to 90 m. A smaller drainage effect on tree growth was detected farther, up to 190 m from the ditch.
3. A cumulative effect of repeated drainage could be seen. Increased increment peaked and then gradually declined over a dozen years. A secondary (delayed) influence on tree growth could be determined by the additional nutrient release through mineralisation in the layer of aerated peat.
4. However, drainage only increased radial growth to about 1 mm in the ombrotrophic bog pines. This growth rate does not compete with drained shallow peatlands forest or with trees growing on mineral soils.
5. Trees growing closer to the drainage ditch were mainly negatively affected by the late autumn temperatures of the previous year, whilst trees in the undisturbed part of the bog were more affected by winter temperatures. The positive signal of spring and summer precipitation intensified towards the more natural interior of the bog.

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