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Peatland pines as a proxy for water table fluctuations: Disentangling tree growth, hydrology and possible human influence

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HIGHLIGHTS

- We analyzed growth of Scots pines from peatland in relation to environmental factors.
- Developed an algorithm to identify changes in limiting factors and missing rings
- Distinct growth periods were identified using structural analysis.
- Water table fluctuations were the main drivers of peatland pine growth.
- Tree rings of peatland pines can serve as a proxy variable to water table levels.

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ABSTRACT

Dendrochronological investigations of Scots pine (*Pinus sylvestris* L.) growing on Männikjärve peatland in central Estonia showed that annual tree growth of peatland pines can be used as a proxy for past variations of water table levels. Reconstruction of past water table levels can help us to better understand the dynamics of various ecological processes in peatlands, e.g. the formation of vegetation patterns or carbon and nitrogen cycling. Männikjärve bog has one of the longest water table records in the boreal zone, continuously monitored since 1956. Common uncertainties encountered while working with peatland trees (e.g. narrow, missing and wedging rings) were in our case exacerbated with difficulties related to the instability of the relationship between tree growth and peatland environment. We hypothesized that the instable relationship was mainly due to a significant change of the limiting factor, i.e. the rise of the water table level due to human activity. To test our hypothesis we had to use several novel methods of tree-ring chronology analysis as well as to test explicitly whether undetected missing rings biased our results. Since the hypothesis that the instable relationship between tree growth and environment was caused by a change in limiting factor could not be rejected, we proceeded to find possible significant changes of past water table levels using structural analysis of the tree-ring chronologies. Our main conclusions were that peatland pines can be proxies to water table levels and that there were several shifting periods of high and low water table levels in the past 200 years.

1. Introduction

Peatlands are not only major global carbon stores and contemporary carbon sinks (Gorham, 1991), but also a significant source of methane emissions (Matthews and Fung, 1987; Turetsky et al., 2014). Spatiotemporal dynamics of these carbon fluxes in peatlands are mainly driven by hydrological conditions, expressed by water table level (WTL) (Moore and Knowles, 1989; Freeman et al., 1992; Gažovič et al., 2010; Mitsch et al., 2013). In addition to driving carbon flux, WTLs in peatland ecosystems influence a wide range of environmental processes including but not limited to: formation of peatland vegetation patterns (Glaser et al., 1990; Robroek et al., 2007), nitrogen gas flux (Freeman et al., 1992;

Abbreviations: WTL, water table level; TRI, tree ring index; EPS, expressed population signal; PCA, principal component analysis; PLSR, projection on latent surfaces regression; PCR, principal component regression; MRC, missing ring combination; CLF, change of the limiting factor; RMAV, regression model with all variables; RMSV, regression model with subset of variables.

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Regina et al., 1996) and the chemical composition of water passing through peatlands (Freeman et al., 1993). Consequently, records of WTL variations are required to improve our understanding of the temporal variability of these environmental processes. However, monitoring datasets of WTLs are rare and often limited to the last decades. Consequently, WTL time series are mostly too short for robust statistical inferences.

Estimating past WTLs beyond the time of instrumental record requires reliable proxy variables (Cook and Kairiukstis, 1990; Fritts, 1976). One of the potential proxies in peatlands with established tree populations might be tree growth, i.e. tree-ring widths. In previous studies, peatland trees were used as proxies for various environmental variables (Läänelaid, 1979, 1982; Vaganov and Kachaev, 1992; MacDonald and Yin, 1999; Linderholm et al., 2002; Linderholm and Leine, 2004; Dauskane et al., 2011; Moir, 2012), including peatland hydrology using subfossil pines (Eckstein et al., 2008, 2009, 2010; Moir et al., 2010; Edvardsson et al., 2012). However, whether it is possible to use tree rings for annually resolved reconstructions of WTLs in peatlands, has to our knowledge yet to be considered.

Tree-ring width is a good proxy only for the environmental variables with limiting effect on tree growth (Fritts, 1976). Limiting effects of WTLs on peatland tree growth can be twofold: 1) if WTL is high there is less oxygen available, i.e. the trees suffer from hypoxia or anoxia, and 2) when WTL is low, surface layers of peat dry out and since peatland trees form most of their roots in the top peat layer they might be prone to drought stress (Braekke, 1983; Dang and Lieffers, 1989; Pepin et al., 2002). Therefore, we might expect that the growth of peatland trees might be a good proxy for WTLs as long as the effect of low WTLs on tree ring formation can be differentiated from the effect of high WTLs.

However, peatland trees also have certain properties that complicate dendrochronological studies. Peatland environments, characterized by not only high water table, but also poor soil aeration, often low nutrient availability and cold substrate (Botch and Masing, 1979; Ohlson, 1995; MacDonald and Yin, 1999; Kimmel et al., 2010; Masing et al., 2010), can cause trees to have shorter lifespans than trees growing on dry sites (Moir et al., 2010), to form extremely narrow tree rings or to skip forming rings entirely or partially (Läänelaid, 1984, 1988; Linderholm et al., 2002; Moir et al., 2010; Wilmking et al., 2012). Consequently, establishing exactly dated chronologies, which is a prerequisite for reconstructing past environmental variation, might be problematic. We have tried to overcome these difficulties by using some novel methods of tree-ring time series analysis.

The aims of this study were 1) to investigate whether radial growth of peatland pines could be a potential proxy for WTLs and/or regional climate conditions, and 2) to develop a conceptual model of how to test peatland pine potential for reconstructing environmental variables, accounting for the complex interplay of tree growth, natural and human environment in a peatland ecosystem.

2. Materials and methods

2.1. Study site

The site selected for this study was Männikjärve, a 1.5 km^2 raised bog located in Central Estonia (58°52′N 26°15′E; Map). It is a part of the Endla Nature Reserve, a 101 km^2 protected area around lake Endla (Ramsar Secretariat, 2014), which is located about 3.5 km southwest from our study site (Map). Endla lake level has been significantly changed in the recent past due to human activity: 1) it was lowered two times (1872 and 1950) with the construction of a channel connecting lakes Endla and Sinijärv to the river Põltsamaa (Map) and 2) in 1968 local fishermen blocked the channel and water level of both lakes rose again (Endla Nature Center, 2014). The regional climate is classified as humid continental (Dfb climate type) according to the Koeppen–Geiger climate classification system (Peel et al., 2007). Mean monthly temperature and precipitation data originated from the Jõgeva and Tooma climate stations, located approximately 15 km and 2 km from the study site, respectively. Mean annual temperature between 1950 and 2000 was 4.6 °C. On average, the coldest and warmest months were February (−6.8 °C) and July (16.3 °C), respectively. The average annual precipitation sum for the same period was 659 mm. The driest and wettest months were March (32 mm) and August (82 mm), respectively. Männikjärve WTL has been recorded since 1956 (Valgma, 1998), resulting in one of the longest WTL records available in the boreal zone. Since the WTLs is the shortest environmental series, it defines our study period (1956–2003). Average annual WTL fluctuations over the whole period of record were 16.3 cm, with 1991 and 1998 having the lowest WTL fluctuation (6 cm) and 1970 having the highest WTL fluctuation (30 cm). WTL was mainly influenced by precipitation in the previous 3 months and air temperature of the current month (Supplemental Figs. 1 and 2).

2.2. Site chronologies

Sixty-six Scots pine trees (*Pinus sylvestris* L.) were sampled with seventy penetrating cores in August 2005. Cores were taken as near to the peat surface as possible. The transverse planes of the samples were sanded with sand paper of increasingly finer grit until tree rings and cellular structures became clearly visible. Two radii per sample were then measured with a resolution of 0.001 mm using a Lintab 5 measuring stage and TSAPWin software (Rinn, 2003).

Individual tree-ring width series were visually and statistically crossdated with TSAPWin and COFECHA (Holmes, 1983), while ARSTAN (Cook, 1985) was used to build local site chronologies from reliably crossdated series (25 out of 66 trees). Trends related to age, individual tree variations and auto-correlation were removed with a negative exponential function, robust mean indexing and autoregressive modeling, respectively. We thus obtained three chronologies: the raw ring width chronology, a standardized, detrended chronology (standard chronology) and a residual chronology with removed autocorrelations. Reliability of the chronologies and the common variance of the single series were evaluated with the expressed population signal (EPS) (Wigley et al., 1984) and running r_{bar} (Briffa and Jones, 1990), respectively. The resulting site chronologies were absolutely dated by referencing them with an already established regional chronology (Läänelaid, unpublished results).

2.3. Proxy potential of the peatland pines

To estimate the proxy potential of peatland pines, we designed an algorithm (Fig. 1) that first determined whether the relationship between tree growth and environmental variables was stable through time (Section 2.3.1). If it was unstable, the algorithm estimated whether the instability was due to a possible change in limiting factor and if undetected missing rings might bias the results (Section 2.3.2). Based on the results of the previous steps, the algorithm leads to a decision, whether it was possible to reconstruct environmental variables (Section 2.3.3). Finally, regression analysis was used to determine which environmental variables were dominant drivers of tree growth (Section 2.4).

2.3.1. Strength and stability of the tree growth–environment relationship

Pearson correlation analysis was used to estimate the strength of the linear relationship between the residual site chronology and monthly series of the environmental variables, i.e. WTLs, temperature and precipitation, over our study period. A preliminary time series analysis of the WTL series, using the *stats* package for R 2.14.2 (R Development Core Team, 2012), showed moderate to high significant autocorrelations with a two-year lag. Consequently, the site chronology was correlated with monthly environmental data between September of the current year and January from three years ago. Central moving window