Carbon accumulation rate in a raised bog in Latvia, NE Europe, in relation to climate warming

Normunds Stivrins[a,b,c], Merlin Liiv[b], Ilze Ozola[c] and Triin Reitalu[b]

[a] Department of Geography, Faculty of Geography and Earth Sciences, University of Latvia, Jelgavas Street 1, Riga, LV-1004, Latvia; normunds.stivrins@lu.lv
[b] Department of Geology, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia; merlin.liiv@ttu.ee, triin.reitalu@ttu.ee
[c] Lake and Peatland Research Centre, Puikule, Latvia; ilze.ozola@epicentrs.lv

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Abstract. The carbon accumulation rate (CAR) over the last 180 years was estimated by measuring carbon concentrations in 1-cm layers in a fine-resolution dated and analysed peat sequence in Teiči Bog, Latvia, NE Europe. We used the Granger causality test to examine the temporal (lagged) relationships between the CAR and the historical climate variables. Our results showed that the average CAR was 192 g C m^{-2} yr^{-1} during the last 180 years and 169 g C m^{-2} yr^{-1} when excluding the acrotelm where decomposition and the stock of carbon are still not in the balance. The Granger causality test showed significant positive temporal associations between the temperature and the CAR, indicating that the temperature is a likely driver of the CAR in the bog. The overall pattern of the CAR resembles the changes in other peat bogs of Europe and underlines that the bogs in NE Europe most likely accumulate more C with increasing temperatures – that should be considered when addressing the issues of CAR and CO_2 emissions at local and regional climate and policy initiatives.

Key words: C/N ratio, carbon accumulation rate, peatland, *Sphagnum*, Granger causality test.

INTRODUCTION

Peatland ecosystems contain approximately 30% of the global terrestrial soil carbon (C) pool (Limpens et al. 2008). Peatlands are, therefore, one of the key components of the global C cycle. It is estimated that the peatland carbon accumulation rate (CAR) for the Northern Hemisphere alone during the last 11 700 years averaged 23 ± 2 g C $m^{-2}yr^{-1}$ and the atmospheric C stored in peat has served to reduce global temperatures by about 1.5–2 °C (Loisel et al. 2014). Although the bogs dominate the northern temperate and the southern boreal zone, the climate change may cause a shift in the distribution of the bog zone and subsequently changes in the CAR (Väliranta et al. 2017).

Through the photosynthesis, ombrotrophic bog plants take C from carbon dioxide (CO_2) and thereby sequester C as the excess of vegetation production over decay (Chambers et al. 2011). The sequestration of C in peatlands follows from an imbalance between biomass production on the one hand and decomposition and lateral discharge on the other hand, with production exceeding losses (Clymo 1983). Carbon is sequestered in bogs as long as the formation of new peat exceeds decay losses of previously accumulated peat (Clymo 1984) and any visible changes in drainage around a bog reduce peat biomass accumulation and lead to a reduction of the CAR.

Charman et al. (2013) and Loisel et al. (2014) suggest that climate warming leads to an increase in C sequestration due to increased net primary productivity. However, a handful of studies underline that climate warming with drier peatland surfaces enhances the decomposition of organic matter and peat accompanied by C fluxes into the atmosphere (Yu 2012; Kalnina et al. 2015; Willis et al. 2015). Although the sequestration and storage of C provided by ombrotrophic bogs is a natural process, it has become clear that the C balance is strongly influenced by both climate change and human-induced activities (Reichstein et al. 2013; Loisel et al. 2014). Disentangling differences in disturbances of peatland, as well as changes in the peat and CAR influenced by natural and human-induced factors, are challenging (Lamentowicz et al. 2016).

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Considering the significance and large uncertainties in the knowledge about the CAR in different geographical locations, it is necessary to seek a deeper understanding of peatland CAR over a longer timescale, e.g. 200 years instead of one- or two-year estimates. The information on the past CAR can reveal not only a trend but also gives the background of the CAR (natural CAR prior to the distinct anthropogenic impact on bog ecosystem) that can later be used to verify the reliablility of the C and CO_2 models used for bogs. International cooperation uses a selection of activities including emission taxation to slow down C accumulation in the atmosphere (Tahvonen 1994; Victor & Leape 2015; Rogelj et al. 2016; Peters et al. 2017) and the knowledge on the CAR can play an important role in this context. Whilst, by default, CO_2 emissions from drained organic soils including peatlands are set as 2.8 t C ha^{-1} (IPCC 2014; Gancone et al. 2017), the knowledge about the yearly C accumulation and its natural background values still lacks for instance in Latvia where peatland covers nearly 12% (7 514 000 ha) of the territory (Tanneberger et al. 2017).

The majority of Latvian peatlands are in a near to semi-natural/natural state with protected peatlands covering approximately 128 000 ha and only a minor proportion (approx. 15 500 ha) is under extraction. The Teiči (hereinafter Teici) Bog complex in eastern Latvia is the largest bog complex in Latvia and has been a nature reserve since 1982. Similarly to most of the bogs in Europe, Teici Bog is affected by drainage activities. Over the last 180 years three distinct time periods of anthropogenic impact on the hydrological regime have been distinguished in Teici Bog: minor drainage (1925–1930s), major drainage (1960–1999), the installation of dams in order to restore the hydrology of the bog since 1999 (Bergmanis et al. 2002; Bergmanis 2004). As its drainage history is known, Teici Bog is a suitable site for estimating the CAR under both natural and anthropogenic disturbances. Here, estimating the CAR from the peat that accumulated under various settings reveals the natural CAR before the distinct human-induced activities and shows how the CAR varies between different time periods of ditching. Furthermore, as historical temperatures show an increasing trend over the last 150 years in the Baltics, it is suitable to test whether the link between climate and the CAR that has been observed elsewhere in the Northern Hemisphere (e.g. Loisel et al. 2014) is also evident in Latvia.

The aim of this study was threefold: (1) to provide the first series of the recent rate of carbon accumulation (CAR; 180 years) estimates for the eastern Baltic region from an ombrotrophic bog in Latvia, (2) to reveal CAR change over the periods ranging from natural to anthropogenic-influenced and (3) to test temporal (lagged) relationships between the CAR and the historical climate variables during the last 180 years. This study is a continuation of a previously published study by Stivrins et al. (2017) where the primary focus was finding drivers of the peat accumulation rate in Teici Bog and some results from this article are used also here.

MATERIAL AND METHODS

Study area

The study area lies within the Teici peat bog complex (14 400 ha) located in eastern Latvia (Fig. 1). There are 15 bog domes in Teici with the elevation from 108 to 114 m a.s.l. Since 1982 Teici Bog has been a Nature Reserve. The most common micro-landscape consists of hummocks and hollows formed by *Sphagnum* species (Namatēva 2012). Scarce shrubs and trees growing in Teici Bog include *Betula nana*, *Betula pubescens* and *Pinus sylvestris*. The surroundings of Teici are predominantly agricultural landscapes with forested patches.

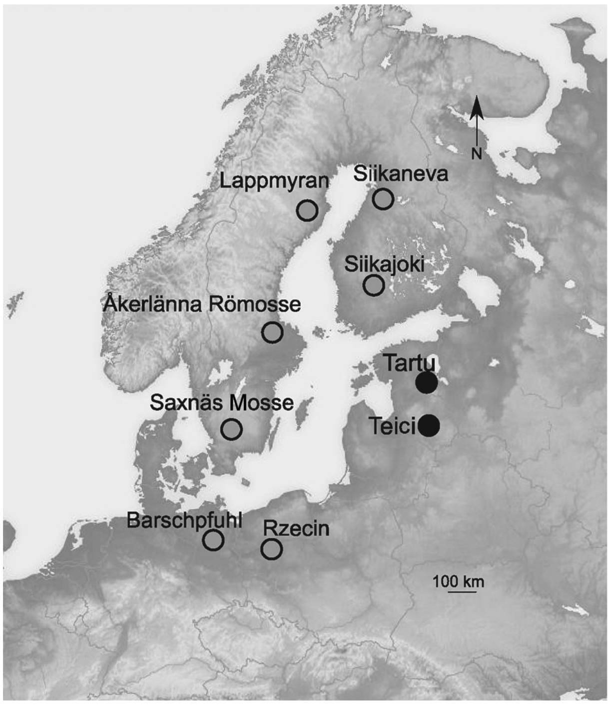

Fig. 1. Location of the study site, Teici Bog, Latvia, the city of Tartu (Estonia) from where the historical climate data come from and a selection of sites discussed in the text: Sweden – Lappmyran, Åkerlänna Römosse and Saxnäs Mosse (van der Linden et al. 2014); Germany – Barschpfuhl (van der Linden et al. 2014); Poland – Rzecin (Milecka et al. 2017); Finland – Siikaneva and Siikajoki (Mathijssen et al. 2016).

The climate in the area is influenced both by the continental climate of Eurasia and the maritime impact of the Atlantic Ocean. The mean annual temperature in the nearest city of Rēzekne (~50 km E of Teici) is +5.2 °C and the mean summer and winter temperatures are +16.9 and –4.1 °C.

Sampling

The Siksalas dome was selected for this study after careful evaluation of all possible domes, as the one that was most likely to provide a representative estimate of average peat growth for the entire Teici Bog area. The selection criteria were the shape of the dome with clear margins and dome plateau, location in the middle of the bog massif, similar distances from the centre of the dome to the closest ditches in two opposite directions, dome with no large bog pool(s), and ombrotrophic peatland dominated by *Sphagnum* communities (Stivrins et al. 2017). The peat profile of the uppermost 78 cm was retrieved with a Wardenaar corer (Wardenaar 1987) from the Siksalas dome of Teici Bog (56°37′20.67″N, 26°26′26.91″E) in autumn 2013 (Fig. 1). The peat profile was described in the field, wrapped in plastic film, placed horizontally in a wooden box and transported to the Department of Geology, Tallinn University of Technology, where it was stored in a cold-room at a constant temperature of 4 °C.

Chronology

The chronology of the peat profile was established by ^{14}C AMS dating (12 samples of *Sphagnum* stems), spheroidal carbonaceous particles, radionuclide dating using naturally occurring ^{210}Pb and tephrochronology. A chronology of the peat sequence was produced by using Bayesian age–depth modelling software Bacon 2.2 (Blaauw & Christen 2011). Individual ^{14}C calibration was carried out by using the IntCal13 calibration dataset (Reimer et al. 2013) with a 2σ (95.4%) of confidence level. All this was performed in the R environment (version 3.0.3) (R Core Team 2015). Detailed descriptions, input data and results of these dating methods are published in Stivrins et al. (2016, 2017).

Loss on ignition

The dry weights of consecutive 1-cm samples were determined after oven drying to constant weight (12 h at 105 °C). The organic matter content of the peat was determined by loss on ignition analysis, by combusting the dried samples in a furnace at 550 °C for 4 h. The bulk density (g cm^{-3}) was calculated on the basis of loss on ignition for all samples. The methods and the results of loss on ignition are published in Stivrins et al. (2017).

C/N ratio measurements and carbon accumulation rates

Seventy-five consecutive 1-cm samples (missing 3 cm at the bottom) were analysed for total organic carbon (C) and total nitrogen (N) content through combustion in the FLASH 2000 Organic Elemental Analyzer. Freeze-dried samples were ground to a powder and homogenized. For the measurements, BBOT ($C_{26}H_{26}N_2O_2S$) as a standard (ThermoFisher Scientific) and algae *Spirulina* as reference material (IVA Analysentechnik e. K) were used. Analyses were done in triplicate. The TOC/TN (C/N) values are expressed as atomic ratios (Meyers & Teranes 2001).

The CAR was calculated for each sample depth since a fine-resolution chronology and detailed bulk density and C concentration measurements were available. The CARs (g C m^{-2} yr^{-1}) were calculated using the following equation (van der Linden et al. 2014):

$$\mathrm{CAR} = r \cdot C \cdot \rho,$$

where r – each 1-cm layer from the peat growth rate (m yr^{-1}), C – concentration (g C g^{-1}) and ρ – bulk density (g m^{-3}).

Data analysis

We used analysis of variance (ANOVA) followed by Tukey's honest significant difference test to detect significant differences in the CAR, water table depth and vegetation composition between the periods of natural conditions (1835–1925), minor ditching (1925–1960), major ditching (1960–1999) and after the installation of dams with the aim of restoring water level (1999–2013).

The upper part of the sediment core that includes the living parts of *Sphagnum* mosses has different characteristics and should be interpreted with caution (Swindles et al. 2015; Stivrins et al. 2017). As noted by van der Linden et al. (2014), the CAR on recent timescales (the recent rate of carbon accumulation) has higher values than the long-term CAR (the long-term apparent rate of carbon accumulation), because of the larger contribution of the acrotelm in which still growing moss and less decomposed peat is present. The C currently contained in the acrotelm will eventually be incorporated into long-term storage within the catotelm (Anderson 2002). The boundary between the acrotelm and catotelm in the study site of Teici Bog was previously set at the year 1999 (11 cm from the bog surface, Stivrins et al. 2017).

The Granger causality test (Granger 1969) was used to check for temporal (lagged) relationships between the CAR and the climate variables. The method was developed for econometric analyses but has been successfully used in studies of (palaeo)climate change (Stern & Kaufmann 2014; Davidson et al. 2016) and has the potential for palaeoecological studies. Information about local water table depth changes was obtained from previously published subfossil testate amoebae-based reconstructions from the same sediment sequence that is used in the current study (Teici-1 core, Stivrins et al. 2017). Instrumental records of monthly air temperature and precipitation over the last 150 years (1866–2013) from the city of Tartu in southern Estonia (190 km from the study area) were obtained from the Estonian Institute of Hydrology and Meteorology (published in Stivrins et al. 2017). We used data from Tartu because climatic conditions there are more similar to those in the Teici region (continental) than in Riga (maritime), where also instrumental records of climatic parameters were available. We used the Granger causality test to predict whether one time-series is significantly forecasting another (Granger 1969, 1980). This is achieved by using different lags of one time-series (X) to model the change in the second series (Y). The test is comparing two models predicting Y: one with only lagged values of Y, and the other with lagged values of both Y and X. The series X is said to 'Granger-cause' Y while the second model (with both lagged Y and X) is significantly ($p<0.05$) better in describing Y than the model with only lagged Y. In addition to the Granger causality tests, we also tested whether the CAR and climate variables were significantly associated at the instantaneous time-periods by using simple linear regression (F-test). The instantaneous association is likely to be caused by a third exogenous variable that was not accounted for (Granger 1969, 1980). In Teici Bog data, the time-series data are not uniformly distributed, with samples having 1 to 5 years between them. Before Granger causality tests, we averaged the data for 5-year time periods (resulting in 30 periods) and used these periods for testing the time lags. All the statistical analyses were performed in the R environment (version 3.0.3) (R Core Team 2015).

RESULTS

High-resolution chronology indicates high peat accumulation rates without hiatuses up to 3.5 mm yr^{-1} from 1835 to 1965 AD and 10 mm yr^{-1} after 2000 AD (Fig. 2). Higher peat accumulation rates mean that peat was capturing a substantial amount of C (Figs 3, 4). During natural conditions (1835–1925) and minor

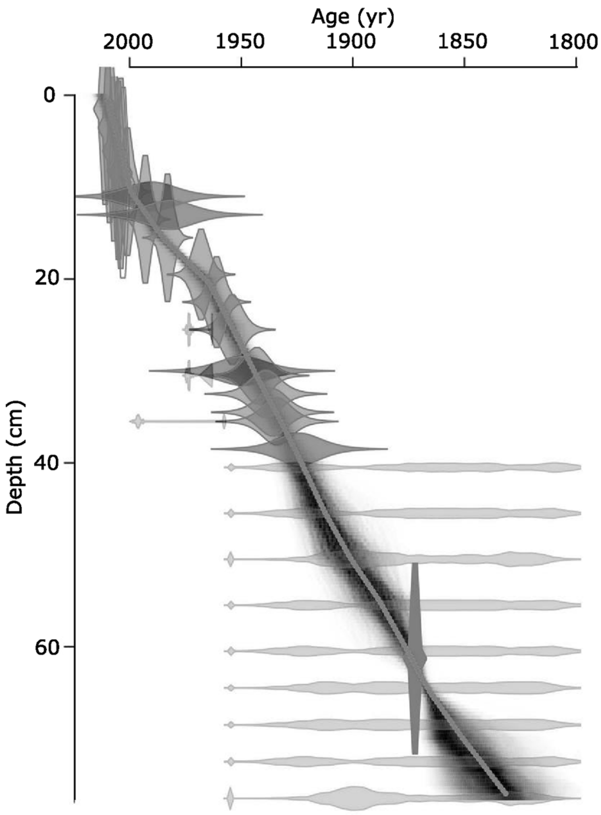

Fig. 2. Age–depth model for the Teici sediment sequence (Stivrins et al. 2016). The age–depth model is based on ^{14}C AMS, dionuclide ^{210}Pb, spheroidal carbonaceous particles and tephra from the Askja eruption of 1875. The grey solid curve shows the weighted mean ages for all depths, and greyscales show uncertainties (darker grey indicates a more certain section).

ditching (1925–1960), the average CAR was 169 ± 14 and 179 ± 15 g C m^{-2} yr^{-1}, respectively. The CAR was lower during the major ditching period of 1960–1999 with an average of 159 ± 48 g C m^{-2} yr^{-1} and substantially higher from 1999 to 2013, reaching 262 ± 59 g C m^{-2} yr^{-1}. Standard deviations from the mean values indicate relatively minor fluctuations from 1835 to 1960 and high deviations from 1960 onwards.

Peat includes a high amount of organic matter (on average 98%) from 1835 to 1925 and from 1999 to 2013 (Fig. 3; Stivrins et al. 2017). A lower organic matter content was detected from 1960 to 1999 (96–97%) with an exception in 1988 (99–100%). Bulk density was relatively constant at 0.08 g cm^{-3} with a peak of 0.20 g cm^{-3} in 1988 and lower values after 1999. Organic C content ranges from 43% to 47% with a shift in 1965 from 44% to 46% (Fig. 3). Total nitrogen (N) content ranges between 0.3% and 0.7% (Fig. 3). With some short-term variability, N values tend to increase towards

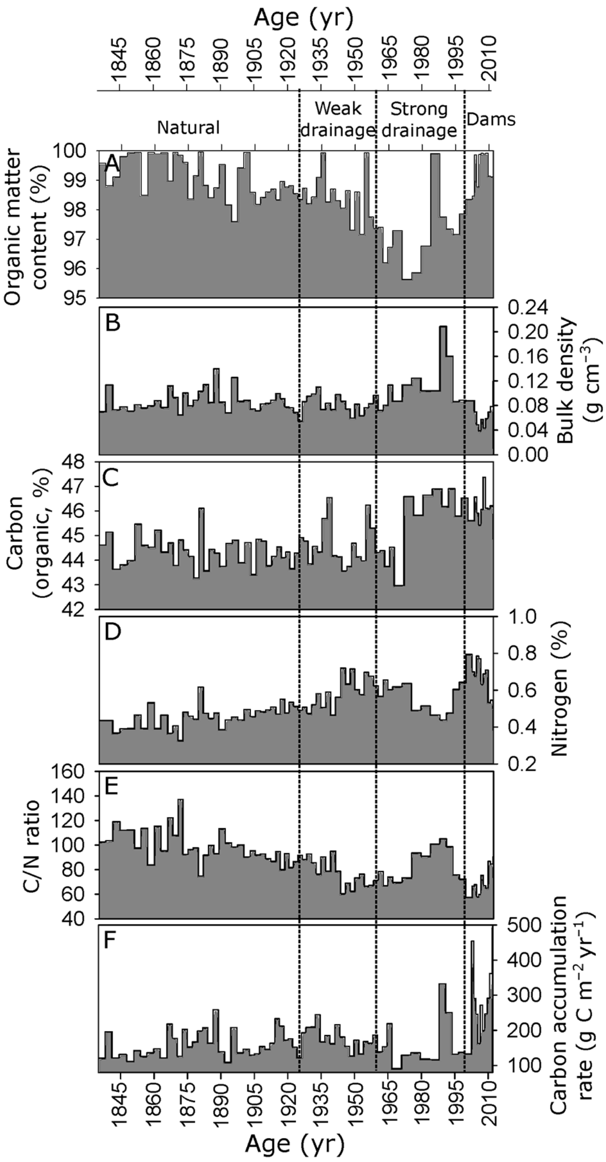

Fig. 3. Measured and estimated properties of the Teici Bog sequence (starting from the top): **A**, organic matter content (%; from Stivrins et al. 2017); **B**, peat bulk density (g cm^{-3}); **C**, organic carbon (%); **D**, nitrogen (%); **E**, C/N ratio; **F**, carbon accumulation rate (g C m^{-2} yr^{-1}). The age is provided at the top and bottom *x*-axes. The data are shown for each measured centimetre-slice. Dashed vertical lines indicate ditching periods/ conditions – natural (1835–1925), weak drainage (1925–1960), strong drainage (1960–1999), restored water level with dams (1999–2013).

the top of the core. The calculated atomic C/N ratio varied from 67 to 138 (Fig. 3). The C/N ratio shows a gradually increasing trend with depth, reaching the highest values of the whole core near the base of the analysed sequence. Overall, the C/N ratio results are comparable to previously reported values for *Sphagnum*-dominated vegetation and peat (Belyea & Warner 1996; Philben et al. 2014).

Previously published *Testate amoebae*-based water table reconstructions (water table depth – WTD, Stivrins et al. 2017) indicate lower WTD during 1866–1925 and 1999–2013, but higher in 1925–1999 (Figs 4, 5). Historical mean temperature measurements show an increasing trend over the last 180 years with a minor dip during the 1960s (Fig. 4). Historical mean precipitation values are higher during the last 60 years. The ordination of local vegetation taxa (based on plant macrofossil data) shows variability since the drainage installation (Fig. 5). The 1st Principal Correspondence Analysis (PCA) axis shows changes in vegetation composition immediately with the first (weak) drainage. There is no clear environmental gradient association for the 1st axis. The observed variation in the 2nd PCA axis is associated with the wetness gradient, where lower values indicate drier conditions, but higher values indicate wetter conditions (Fig. 5). Wetter conditions are associated with the presence of *Sphagnum balticum* and drier conditions with *Sphagnum magellanicum* (Stivrins et al. 2017).

The Granger causality tests indicated that only temperature was significantly associated with the CAR, having both a significant instantaneous association and lagged (for 5 years and 15 years) associations with the CAR (Table 1). All associations were positive correlations. Without the acrotelm, the 15-year lag was marginally significant (p = 0.009) which could be an evidence of the accumulation effect resulting from temperature. Nevertheless, in both tests with and without (not shown here) the acrotelm there was a clear binding that was positive, i.e. underlining the time-lag effect of the temperature on the CAR.

DISCUSSION

Our results show that the CAR was 169 g C m^{-2} yr^{-1} (1.69 t C ha^{-1} yr^{-1}) in Teici Bog over the last 180 years (excluding the acrotelm part). These estimates are extremely high in comparison with the estimated average CAR for the Northern Hemisphere peatlands 23 ± 2 g C m^{-2} yr^{-1} (0.1–0.4 t C ha^{-1} yr^{-1}) (Korhola et al. 1995; Yu et al. 2009; Loisel et al. 2014). A comparable or even higher CAR has been estimated in Polish peatlands. The CAR in the waterlogged poor fen Bagno Mikołeska was 140–142 g C m^{-2} yr^{-1} (Fiałkiewicz-Kozieł et al. 2014) and in the Rzecin peatland 170–190 g C m^{-2} yr^{-1} (Milecka et al. 2017) (Fig. 1). However, the CAR in a period without a clear human impact on Teici Bog (1835–1925) was 169 g C m^{-2} yr^{-1}. In the rest of Europe, prior to the extensive anthropogenic impact, the CAR has varied from 25 g C m^{-2} yr^{-1} in northern Sweden

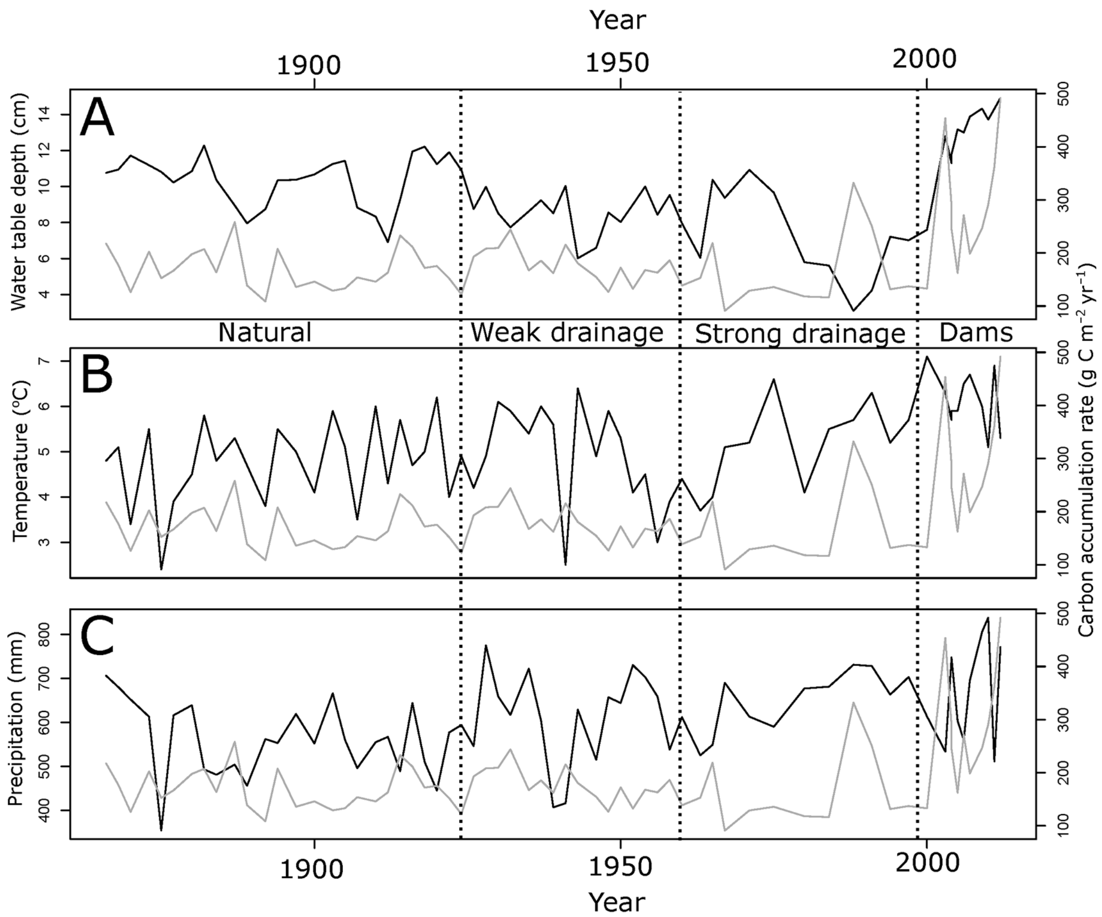

Fig. 4. Solid black lines show reconstructed mean water table depth from the bog surface (**A**; Stivrins et al. 2017), historical mean air temperature (**B**; Estonian Institute of Hydrology and Meteorology) and precipitation in the city of Tartu, Estonia (**C**; Estonian Institute of Hydrology and Meteorology). The solid grey line shows a reconstructed carbon accumulation rate of Teici Bog.

(Lappmyran) to 50 g C m^{-2} yr^{-1} in central-southern Sweden (Åkerlänna Römosse and Saxnäs Mosse) and northern Germany (Barschpfuhl) (van der Linden et al. 2014). In northern and southern Finland (Siikaneva and Siikajoki, Fig. 1), the CAR had relatively minor variations from 10 to 25 g C m^{-2} yr^{-1} throughout the last 11 000 years (Mathijssen et al. 2016).

It is noteworthy that our results indicate an increasing CAR during both natural and minor ditching periods (Figs 4, 5). During the first minor drainage installation at Teici Bog (the 1920s–1930s), ditches were excavated manually, and the drainage did not have a visually significant impact on the hydrological regime (Bergmanis 2004; Stivrins et al. 2017). Due to the mute effect of minor ditching, the peat had a positive growth balance as high as 4 mm yr^{-1} during both natural and minor ditching conditions (Stivrins et al. 2017). Under these circumstances, the CAR in Teici Bog was 179 ± 14 g C m^{-2} yr^{-1}. Whereas from the 1960s–1999, drainage system installation involved massive works using specialized auto-motorized equipment, which impacted bog's hydrology and caused a decrease in the peat accumulation rate leading to a subsequent change in the C/N ratio and a decrease in the CAR to 159 ± 48 g C m^{-2} yr^{-1} (Figs 4, 5).

Differences in the CAR can be attributed to diverse influencing aspects. High peat accumulation rates could suggest that there may have been optimal growing conditions for *Sphagnum* moss, such as the WTD not deeper than 15 cm from peatland surface (Gałka et al. 2017). This agrees with the previous study in Teici Bog, revealing that the water level did not fall more than 15–16 cm below the surface over the last 150 years (Stivrins et al. 2017). Contrary to the expected result, the WTD was higher during the ditching periods and lower during the natural and recent times (Fig. 5). Although the WTD was higher during the minor and major ditching periods, it was most likely an artefact of

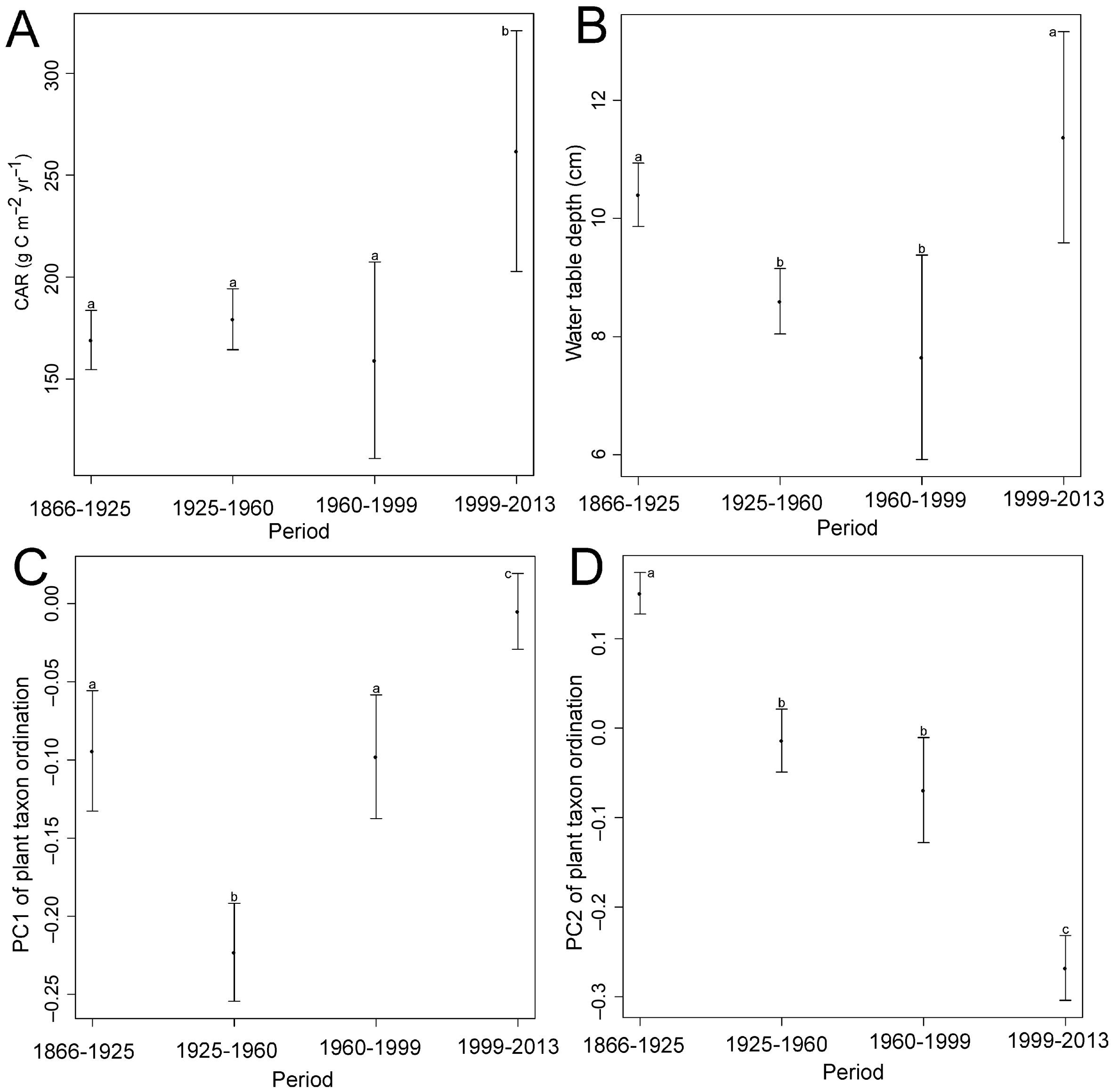

Fig. 5. Carbon accumulation rate (**A**), water table depth (**B**), plant taxon ordination PC1 (**C**) and PC2 (**D**) means and confidence intervals of the means during natural conditions (1835–1925), weak drainage (1925–1960), strong drainage (1960–1999) and restored water level with dams (1999–2013). B–D estimated using data from Stivrins et al. (2017).

Table 1. Granger-causalities between the carbon accumulation rate and climate variables in Teici Bog

Variable	Instantaneous	Granger-caused
Water table depth	Nonsignificant	Nonsignificant
Temperature	$F = 4.37$, $p = 0.046$	5-year lag, $F = 5.40$, $p = 0.028$ 10-year lag, nonsignificant 15-year lag, $F = 5.0$, $p = 0.009$
Precipitation	Nonsignificant	Nonsignificant

the bog subsidence that is recognized in territories of active peatland use in Europe (e.g. Koster et al. 2018). The installation of the ditching network led to a decrease in the peat accumulation rate that in turn led to peat compression. This was further supported by increased mineral matter content and bulk density and decreased peat accumulation rates (Stivrins et al. 2017). Hence, the increase in the WTD in Teici Bog was due to peat subsidence and not due to increased water levels.

Loisel et al. (2012) demonstrated that *Sphagnum* growth varies in different bioclimatic regions, i.e. continental and maritime, with significantly higher moss growth in continental settings where Teici Bog is located. It has been found that the total C accumulation in northern peatlands is linearly related to contemporary growing season length and photosynthetically active radiation, hence the net primary productivity is more important than decomposition in determining C accumulation (Charman et al. 2013). Furthermore, the concentrations of C can be controlled by different bog plant species and peatland type leading to fluctuations in the C/N ratios (Anderson 2002; Loisel et al. 2014).

While the higher C/N ratio in the base of the analysed sequence confirms peat accumulation and wet surface conditions (Fig. 3; Borgmark & Schoning 2006; Broder et al. 2012), the overall trend in the C/N ratio is opposite to the majority of reported changes in peat profiles, where generally the C/N ratio declines with depth (Kuhry & Vitt 1996; Speranza et al. 2000; Vardy et al. 2000; van der Linden & van Geel 2006). Notable changes in the C/N ratio start to occur already during the weak drainage event and continue during the strong drainage event and even after the installation of the dams. The C/N ratio experiences several fluctuations (Fig. 3). Periods of low C/N ratios combined with high N concentrations, which are recorded in the upper part of the Teici Bog peat sequence, suggest an intensified decay of the peat (Belyea & Warner 1996; Borgmark & Schoning 2006; van der Linden & van Geel 2006). Following the interpretation of Anderson (2002), a possible explanation could be past hydrological changes that were suppressing the release of N, thus 'artificially' lowering the C/N ratio. Therefore, some periods in the peat sequence give mixed results compared to the CAR.

The recent increase in the CAR in 1999–2013 (280 g C m^{-2} yr^{-1}) is twice as high as the CAR prior to 1999 (Fig. 4). Previous studies from boreal peatlands show that commonly the CAR is higher in the upper part of the peat section because the decomposition and compaction processes are still incomplete (Clymo 1984; Yu et al. 2003; Mathijssen et al. 2014). Even more, the C/N ratio values in the topmost part of the peat sequence are consistently increasing, therefore confirming that the intensified accumulation of peat has started to overpower its decay once again.

Recently, yet another explanation for a high CAR has been proposed by several studies. Charman et al. (2013), Loisel & Yu (2013) and Loisel et al. (2014) underline the strength of climate warming that leads to a rise in C sequestration due to the increased net primary productivity of *Sphagnum*. Even when the peat decomposition history is taken into consideration, the CAR in recent decades was still higher than the average of the last 4000 years (Loisel & Yu 2013). Such a scenario is possible in northern peatlands as long as there is sufficient water supply and moss net primary productivity outweighs decomposition (Gerdol & Vicentini 2011). In the Baltics, air temperatures have shown an increasing trend over the last 150 years (Stivrins et al. 2017) and therefore it was crucial to test whether there is an association between the historical climate change and the CAR in Latvia. The statistical analyses showed significant temporal associations between the temperature and the CAR, indicating that the temperature is a likely driver of the CAR in Teici Bog. Both the instantaneous and Granger-caused associations were significantly positive (Table 1). The instantaneous association is said to be influenced by the third variable, not accounted for in the analyses (Granger 1969, 1980). In our analyses, the instantaneous association is much weaker than the lagged Granger-caused association (p-values of 0.46 vs 0.09) and the instantaneous association can, therefore, be a weaker reflection of the time-lag effect. Climate measurements were not available for the whole of the studied period from the local area, and we were using the temperature and precipitation data from Tartu (ca 190 km away). Unfortunately, the earliest instrumental records closer to Teici are available for only the last 50 years from the city of Rēzekne (ca 60 km away), which displays similar climatic trends to those in Tartu (Stivrins et al. 2017). The significant instantaneous association can also indicate that the Tartu climate measurements might not be the best descriptors of Teici temperatures and that the local temperature could be a 'third' variable, being associated with both temperature estimates from Tartu and with the CAR from Teici. The 'real' temporal association could, therefore, be even stronger than indicated here.

Regarding the composition of local vegetation, Loisel et al. (2012) showed that *Sphagnum* growth varies in continental and maritime bioclimatic regions, whereas moss growth is significantly higher in continental settings where also Teici Bog is located. Our results of the plant taxon ordination underline vegetation departure from the natural conditions at times of hydrological manipulations via ditching and dam installation (Fig. 5). The concentrations of C can be controlled by different bog plant species and peatland types, leading to fluctuations in the C/N ratios (Anderson 2002; Loisel et al. 2014). Local vegetation can explain up to 7.3% of total variation in peat accumulation rates (Stivrins et al. 2017), and the change of species could also influence the CAR. Besides, it has been found that the total C accumulation in northern peatlands is linearly related to contemporary growing season length and photosynthetically active radiation, hence the net primary productivity is more important than decomposition in determining long-term C accumulation (Charman et al. 2013).

Assuming simultaneous vertical growth of the whole bog surface (Ilomets et al. 1984) and lateral peat surface expansion fixed at zero for the entire studied period, we employed a simple extrapolation using reconstructed CAR indices (169 g C m^{-2} yr^{-1}) to estimate the approximate CAR for the Teici peatland complex (14 400 ha). Our rough estimates revealed that for one year, the entire Teici peatland area accumulated 24 336 t C (89 313.12 t CO_2e), and over the last 180 years Teici has accumulated 4 380 480 t C (4380.48 kt or 0.00438 Gt), which is equal to approximately 0.016076 Gt CO_2e or 0.034129 ppm of the CO_2 rise in the atmosphere. These, of course, are only rough estimates, but the numbers obtained give at least some idea of what amounts of C could be sequestered and stored in Latvian peatlands. In this context it is noteworthy that variations in the size of the peatland sink have a significant cumulative effect on global atmospheric CO_2 concentrations with 7–12 ppm atmospheric CO_2 over a 1000-year period (Charman et al. 2013). Further high-resolution work is needed to aid detecting the CAR in other peatlands that would contribute to the national inventories and better understanding of the C cycle in understudied areas.

CONCLUSIONS

This is the first study in Latvia and probably one of the first investigations in the eastern Baltic revealing the CAR from a bog in such high resolution. Our results showed distinct deviations of the CAR associated with times of anthropogenic disturbances on the hydrological regime. Importantly, we showed that there was a significant temporal association between the temperature and the CAR, indicating that potentially warmer climate in the future could lead to an even higher CAR and more C could be stored in bogs. Considering these findings, initiatives of restoring peatlands and growing *Sphagnum* moss with adequately installed irrigation/ditching/dam systems are welcome and necessary for capturing more C under increased CO_2 concentrations.

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Süsiniku akumulatsioonikiirus Lätis Teiči rabas viimase 180 aasta jooksul

Normunds Stivrins, Merlin Liiv, Ilze Ozola ja Triin Reitalu

On hinnatud süsiniku akumulatsioonikiirust viimase 180 aasta jooksul Lätis Teiči rabas, mõõtes süsiniku kontsentratsiooni 1 cm paksustes täpselt dateeritud turbakihtides. Et välja selgitada süsiniku akumulatsiooni ajalisi seoseid kliima ja keskkonnatingimustega, kasutatakse Grangeri põhjuslikkuse testi. Tulemused näitavad, et keskmine süsiniku akumulatsioonikiirus viimase 180 aasta jooksul on 192 g C m^2 aastas. Jättes välja viimaste aastate turbakihid, kus turba lagunemine pole veel lõppenud (akrotelmi), on keskmine akumulatsioonikiirus 169 g C m^2 aastas. Grangeri põhjuslikkuse test näitab positiivset seost temperatuuri ja süsiniku akumulatsiooni vahel. Seega sõltub süsiniku akumulatsioon rabas suure tõenäosusega temperatuurist. Käesoleva uurimuse süsiniku akumulatsiooni muutused on sarnased teistes Euroopa rabades tehtud uuringutega. Temperatuuri tõustes suureneb tõenäoliselt ka süsiniku akumulatsioon Kirde-Euroopa rabades: teadmine, mida tuleks arvestada süsiniku akumulatsiooni ja süsihappegaasi emissioonide arvutustes ning lokaalses ja regionaalses kliimapoliitikas.