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

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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 CO2 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 (Väliiranta et al. 2017).

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).
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 reliability of the C and CO2 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, CO2 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-influenced 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 (Namatėva 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 14C AMS dating (12 samples of Sphagnum stems), spheroidal carbonaceous particles, radionuclide dating using naturally occurring 210Pb and tephrochronology. A chronology of the peat sequence was produced by using Bayesian age–depth modelling software Bacon 2.2 (Blauw & Christen 2011). Individual 14C 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 (C₂₆H₂₆N₂O₂S) as a standard (ThermoFisher Scientific) and algae Spirulina as reference material (IVA Analysetechnik 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):

\[ \text{CAR} = r \cdot C \cdot \rho, \]

where \( r \) – each 1-cm layer from the peat growth rate (m yr⁻¹), \( C \) – concentration (g C g⁻¹) and \( \rho \) – 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 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...
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 $23 \pm 2$ 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 Mikoleśka was 140–142 g C m⁻² yr⁻¹ (Fialkiewicz-Koziel 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 dominated vegetation and peat (Belyea & Warner 1996; Philben et al. 2014).

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*.
(Lappmyran) to 50 g C m\(^{-2}\) yr\(^{-1}\) in central-southern Sweden (Åkerlänna Rõmosse 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 \textit{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; Mathijsen 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 CAR for the Teici peatland complex (14 400 ha), our estimates to approximately 0.016076 Gt CO₂e or 0.034129 ppm of atmospheric CO₂ over a 1000-year period (Stivrins et al. 2017). C/N ratios (Anderson 2002; Loisel et al. 2014). Local species and peatland types, leading to fluctuations in the CAR, indicating that potentially warmer 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 CO₂ concentrations.

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REFERENCES

Anderson, D. E. 2002. Carbon accumulation and C/N ratios of peat bogs in North-West Scotland. Scottish Geographical Journal, 118, 323–341.

Belyea, L. R. & Warner, B. G. 1996. Temporal scale and the accumulation of peat in a Sphagnum bog. Canadian Journal of Botany, 74, 366–377.

Bergmanis, U. 2004. Pasākumo plāns dabiskā hidroloģiskā režīma atjaunošanai Teiciu purvā [Strategy of Natural Hydrological Regime Reconstruction in Teici Bog]. Teici Nature Reserve Administration Research Department, Ķaudona, 25 pp. [in Latvian]. Available online at https://www.daba.gov.lv/upload/File/DAPl_apstiprin/DR_Teici-06_pie-6_5.pdf [accessed 16 March 2017].

Bergmanis, U., Brehm, K. & Mathes, J. 2002. Dabiskā hidroloģiskā režīma atjaunošana augstajos un pārejas purvos [Reconstruction of natural hydrology in raised and transitional bogs]. In Aktuāli saņuļas sugu un biotopu apsaimniekošanas piemēri Latvijā [Relevant Wild Species and Biotope Management Examples from Latvia] (Oparmanis, O., ed.), pp. 49–61. SIA, Ulma [in Latvian].

Blaauw, M. & Christen, J. A. 2011. Flexible paleoclimate age-depth models using an auto-regressive gamma process. Bayesian Analysis, 6, 457–474.

Borgmark, A. & Schoning, K. 2006. A comparative study of peat proxies from two eastern central Swedish bogs and their relation to meteorological data. Journal of Quaternary Science, 21, 109–114.

Broder, T., Blodau, C., Biester, H. & Knorr, K. H. 2012. Peat decomposition records in three pristine ombrotrophic bogs in southern Patagonia. Biogeoosciences, 9, 1479–1491.

Chambers, F. M., Beilman, D. W. & Yu, Z. 2011. Methods for determining peat humification and for quantifying peat bulk density, organic matter and carbon content for palaeo-studies of climate and peatland carbon dynamics. Mires and Peat, 7, 1–10.

Charman, D. J., Beilman, D. W., Blaauw, M., Booth, R. K., Brewer, S., Chambers, F. M., Christen, J. A., Gallego-Sala, A., Harrison, S. P., Hughes, P. D. M., Jackson, S. T., Korbola, M., Maquary, D., Mitchell, F. J. G., Prentice, I. C., van der Linden, M., De Vleseschouwer, F., Yu, Z. C., Alm, J., Bauer, I. E., Corish, Y. M. C., Garneau, M., Hohl, V., Huang, Y., Karofeld, E., Le Roux, G., Loisel, J., Moschen, R., Nichols, J. E., Nieminen, T. M., MacDonald, G. M., Phadtare, N. R., Rausch, N., Sillasoo, Ü., Swindles, G. T., Tuittila, E.-S., Ukonmaanaho, L., Vääränta, M., van Bellen, S., van Geel, B., Vitt, D. H. & Zhao, Y. 2013.
Climate-related changes in peatland carbon accumulation during the last millennium. *Biogeosciences*, 10, 929–944.

Clymo, R. S. 1983. Peat. In *Mires: Swamp, Bog, Fen and Moor. Regional Studies. Ecosystems of the World 4A* (Gore, A., ed.), pp. 159–224. Elsevier Scientific, Amsterdam, New York.

Clymo, R. S. 1984. The limits to peat bog growth. *Philosophical Transactions of the Royal Society of London, Series B: Biological Sciences*, 303, 605–654.

Davidson, J. E. H., Stephenson, D. B. & Turau, A. A. 2016. Time series modeling of paleoclimate data. *Environmetrics*, 27, 55–65.

Fiałkiewicz-Koziel, B., Smieja-Król, B., Piotrowska, N., Sikorski, J. & Galka, M. 2014. Carbon accumulation rates in two poor fens with different water regimes: influence of anthropogenic impact and environmental change. *The Holocene*, 24, 1539–1549.

Galka, M., Tobolski, Ł., Lamentowicz, M., Ersek, V., Jassey, V. E. J., van der Knaap, W. O. & Lamentowicz, M. 2017. Unveiling exceptional Baltic peatland bog ecotology, autogenic succession and climate change during the last 2000 years in CE Europe using replicate cores, multiproxy data and functional traits of testate amoebae. *Quaternary Science Reviews*, 156, 90–106.

Gancone, A., Skrebele, A., Rubene, L., Ratniece, V., Cakars, I., Kiewicz-Kozieł, M. & Samson, M. 2018. Combining short-term manipulative experiments with long-term palaeoecological investigations at high resolution to assess the response of *Sphagnum* peatlands to drought, fire and warming. *Mires and Peat*, 18, 1–17.

Gerdol, R. & Vicentini, R. 2011. Response to heat stress of *Sphagnum* species from alpine bogs at different altitudes. *Environmental and Experimental Botany*, 74, 22–30.

Granger, C. W. J. 1969. Investigating causal relations by *Philosophical Transactions of the Royal Society of London, Series B: Biological Sciences*, 303, 605–654.

Granger, C. W. J. 1980. Testing for causality. A personal viewpoint. *Journal of Economic Dynamics and Control*, 2, 329–352.

Illmets, M., Ilves, E. & Rajamäe, R. 1984. About the spatial-temporal dynamics of peat growth in Estonian bogs. *Proceedings of the Academy of Sciences of the Estonian SSR, Geology*, 33, 158–173 [in Russian, with English summary].

IPCC 2014. 2013. Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (Hiraishi, T., Kug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. & Troxler, T. G., eds). IPCC, Switzerland. Available online at http://www.ipcc-nggip.iges.or.jp/public/wetlands/index.html [accessed 16 March 2017].

Kalnina, L., Stivrins, N., Kusk, E., Ozola, I., Pujate, A., Zeimule, S., Grudzinska, I. & Ratniece, V. 2015. Peat stratigraphy and changes in peat formation during the Holocene in Latvia. *Quaternary International*, 383, 186–195.

Korhola, A., Tolonen, K., Turunen, J. & Jungner, H. 1995. Estimating long-term carbon accumulation rates in boreal peatlands by radiocarbon dating. *Radiocarbon*, 37, 575–584.

Koster, K., Cohen, K. M., Stafleu, J. & Stouthamer, E. 2018. Using 13C-dated peat beds for reconstructing subsidence by compression in the Holland coastal plain of the Netherlands. *Journal of Coastal Research*, 34, 1035–1045.

Kuhry, P. & Vitt, D. H. 1996. Fossil carbon/nitrogen ratios as a measure of peat decomposition. *Ecology*, 77, 271–275.

Lamentowicz, M., Słowińska, S., Słowiński, M., Jassey, V. E. J., Chojnicki, B. H., Reczuga, M. K., Zielinska, M., Marcisz, K., Lamentowicz, L., Barabach, J., Samson, M., Kobaczez, P. & Butler, A. 2016. Combining short-term manipulative experiments with long-term palaeoecological investigations at high resolution to assess the response of *Sphagnum* peatlands to drought, fire and warming. *Mires and Peat*, 18, 1–17.

Limpens, J., Berendse, F., Blodau, C., Canadell, J. G., Freeman, C., Holden, J., Roulet, N., Rydin, H. & Schaapman-Strub, G. 2008. Peatlands and the carbon cycle: from local processes to global implications – a synthesis. *Biogeosciences*, 5, 1475–1491.

Loisel, J. & Yu, Z. 2013. Recent acceleration of carbon accumulation in a boreal peatland, south central Alaska. *Journal of Geophysical Research, Biogeosciences*, 118, 41–53.

Loisel, J., Gallego-Sala, A. V. & Yu, Z. 2012. Global-scale pattern of peatland *Sphagnum* growth driven by photo-synthetically active radiation and growing season length. *Biogeosciences*, 9, 2737–2746.

Loisel, J., Zischeng, Y., Beilman, D. W., Camill, P., Alm, J., Amesbury, M. J., Anderson, D., Andersson, S., Bochicchio, C., Barber, K., Belyea, L. R., Bunbury, J., Chambers, F. M., Charman, D. J., De Vleeschouwer, F., Płatkiewicz-Kozieł, B., Finkelstein, S. A., Galka, M., Garneau, M., Hammarlund, L., Hinchcliffe, W., Holmiquist, J., Hughes, P., Jones, M. C., Klein, E. S., Kokfelt, U., Kohola, A., Kuhry, P., Lamarr, A., Lamentowicz, M., Large, D., Lavoie, M., MacDonald, G., Magnan, G., Máklí, A., Mallon, G., Mathijssen, P., Maquoy, D., McCarroll, J., Moore, T. R., Nichols, J., O’Reilly, B., Oksanen, P., Packalen, M., Petee, D., Richard, P. J. H., Robinson, S., Ronkainen, T., Rundgren, M., Sannel, A. B. K., Tarnocai, C., Thom, T., Tuittila, E.-S., Turcuses, M., Väîrantha, M., van der Linden, M., van Geel, B., van Bellen, S., Vitt, D., Zhao, Y. & Zhou, W. 2014. A database and synthesis of northern peatland soil properties and Holocene carbon and nitrogen accumulation. *The Holocene*, 24, 1028–1042.

Mathijssen, P., Tuovinen, J.-P., Kohila, A., Aurela, M., Juutinen, S., Laurila, T., Niemelä, E., Tuittila, E.-S. & Väîrantha, M. 2014. Development, carbon accumulation, and radiative forcing of a subarctic fen over the Holocene. *The Holocene*, 24, 1156–1166.

Mathijssen, P. J. H., Väîrantha, M., Korrenszl, A., Aleksycki, P., Vesala, T., Rinne, J. & Tuittila, E.-S. 2016. Reconstruction of Holocene carbon dynamics in a large boreal peatland complex, southern Finland. *Quaternary Science Reviews*, 142, 1–15.

Meyers, P. A. & Teranes, J. L. 2001. Sediment organic matter. *Sediment organic matter. In *Tracking Environmental Change Using Lake Sediments, Vol. 2: Physical and Geochemical Methods* (Last, W. M. & Smol, J. P., eds), pp. 241–269. Kluwer Academic Publishers, Dordrecht, The Netherlands.
Milecka, K., Kowalewski, G., Fialkiewicz-Koziel, B., Galka, M., Lamentowicz, M., Chojnicki, B. H., Goslar, T. & Barabach, J. 2017. Hydrological changes in the Rzecin peatland (Puszcza Notecka, Poland) induced by anthropogenic factors: implications for mire development and carbon sequestration. The Holocene, 27, 651–664.

Namaēva, A. 2012. Mikroainavā telpiskā struktūra un to ietekmējošie faktori (Austruvaldijas zemienes augstajos purvos (Spatial Structure of Raised Bog Microlandscapes and Their Influencing Factors in Eastern Latvia)). Doctoral dissertation, University of Latvia, Riga, 154 pp. [in Latvian]. Available online at https://dspace.lu.lv/dspace/handle/7/5167 [accessed 17 March 2017].

Peters, G. P., Andrew, R. M., Canadell, J. G., Fuss, S., Jackson, R. B., Korsbakken, J. I., Le Quéré, C. & Nakicenovic, N. 2017. Key indicators to track current progress and future ambition of the Paris Agreement. Nature Climate Change, 7, 118–123.

Philben, M., Kaiser, K. & Benner, R. 2014. Does oxygen exposure time control the extent of organic matter decomposition in peatlands? Journal of Geophysical Research, Biogeosciences, 119, 897–909.

R Core Team. 2015. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna. Available online at http://www.R-project.org/ [accessed 17 March 2017].

Reichstein, M., Bahn, M., Ciais, P., Frank, D., Mahecha, M. D., Seneviratne, S. I., Zscheischler, J., Beer, C., Buchmann, N., Frank, D. C., Papale, D., Ramming, A., Smith, P., Thonicke, K., van der Velde, M., Vieca, S., Walz, A. & Wattenbach, M. 2013. Extreme climates and the carbon cycle. Nature, 500, 287–295.

Reimer, P. J., Bard, E., Bayliss, A., Beck, J. W., Blackwell, P. G., Bronk Ramsey, C., Buck, C. E., Cheng, H., Edwards, R. L., Friedrich, M., Grootes, P. M., Kromer, B., McCormac, G. F., Manning, S. W., Reimer, R. W., Southon, J. R., Turney, C. S. M. & van der Plicht, J. 2013. IntCal13 and Marine13 radiocarbon age calibration curves, 0–50,000 years cal BP. Radiocarbon, 55, 1869–1887.

Rogelj, J., den Elzen, M., Hönne, N., Franssen, T., Fedke, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K. & Meinshausen, M. 2016. Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature, 534, 631–639.

Speranza, A., Hanke, J., van Geel, B. & Fanta, J. 2000. Late-Holocene human impact and peat development in the Černá Hora bog, Krkonoše Mountains, Czech Republic. The Holocene, 10, 575–585.

Stern, D. I. & Kaufmann, R. K. 2014. Anthropogenic and natural causes of climate change. Climatic Change, 122, 257–269.

Stivirins, N., Wulf, S., Wastegård, S., Lind, E. M., Aliksaar, T., Galka, M., Andersen, T. J., Heinsalu, A., Seppä, H. & Veski, S. 2016. Detection of the Askja AD 1875 cryptotephra in Latvia, Eastern Europe. Journal of Quaternary Science, 31, 437–441.

Stivirins, N., Ozola, I., Galka, M., Kuske, E., Aliksaar, T., Andersen, T. J., Lamentowicz, M., Wulf, S. & Reitalu, T. 2017. Drivers of peat accumulation rate in a raised bog: impact of drainage, climate, and local vegetation composition. Mires and Peat, 19, 1–19.

Swindles, G. T., Morris, P. J., Mullan, D., Watson, E. J., Turner, T. E., Roland, T. P., Amesbury, M. J., Kokfelt, U., Schoning, K., Pratte, S., Gallego-Sala, A., Charman, D. J., Sanderson, N., Garneau, M., Carrivick, J. L., Wouds, C., Holden, J., Parry, L. & Galloway, J. M. 2015. The long-term fate of permafrost peatlands under rapid climate warming. Scientific Reports, 5, No. 17951.

Tahvonen, O. 1994. Net national emission, CO2 taxation and the role of forestry. Finnish Forest Research Institute, Research Papers, 490, 1–16.

Tanneberger, F., Tegetmeyer, C., Busse, S., Barthelmes, A., Shumka, S., Moles Mariné, A., Jendredijan, K., Steiner, G. M., Essl, F., Etzold, J., Mendes, C., Kozulin, A., Frankard, P., Milanović, D., Geneva, A., Apostolova, I., Alegro, A., Delipetrou, P., Navrátilová, J., Risager, M., Levits, A., Fosaa, A. M., Tuominen, S., Muller, F., Bakuradze, T., Sommer, M., Christianis, K., Szurdoki, E., Oskarsson, H., Brink, S. H., Connolly, J., Bragazza, L., Marinelli, G., Aleksěns, O., Prieide, A., Sungaila, D., Melovski, L., Belous, T., Saveljč, D., de Vries, F., Moen, A., Dembek, W., Matejš, J., Hananu, J., Sirin, A., Markina, A., Napreenko, M., Lazrević, P., Šefterová Stanová, V., Skoberne, P., Heras Pérez, P., Pontevedra-Pombal, X., Lonndstad, J., Küchler, M., Wüst-Galley, C., Kirsa, S., Mykytiuk, O., Lindsay, R. & Joosten, H. 2017. The peatland map of Europe. Mires and Peat, 19, 1–17.

Väinäranta, M., Salojärvi, N., Vupsalio, A., Juutinen, S., Korhola, A., Luoto, M. & Tuittila, E.-S. 2017. Holocene fen–bog transitions, current status in Finland and future perspectives. The Holocene, 5, 752–764.

Van der Linden, M. & van Geel, B. 2006. Late Holocene climate change and human impact recorded in a south Swedish ombrotrophic peat bog. Palaeoecography, Palaeoclimatology, Palaeoecology, 240, 649–667.

Van der Linden, M., Heijmans, M. M. P. D. & van Geel, B. 2014. Carbon accumulation in peat deposits from northern Sweden to northern Germany during the last millennium. The Holocene, 24, 1117–1125.

Vardy, S. R., Warner, B. G., Turnen, J. & Aravena, R. 2000. Carbon accumulation in permafrost peatlands in the Northwest Territories and Nunavut, Canada. The Holocene, 10, 273–280.

Victor, D. G. & Leape, J. P. 2015. After the talks. Nature, 527, 439–441.

Wardenaar, E. P. C. 1987. A new hand tool for cutting peat. Canadian Journal of Botany, 65, 1772–1773.

Willis, K. S., Beilman, D., Booth, R. K., Amesbury, M., Homquist, J. & MacDonald, G. 2015. Peatland paleohydrology in southern West Siberian Lowlands: comparison of multiple testate amoeba transfer functions, sites, and Sphaignum δ13C values. The Holocene, 25, 1425–1436.

Yu, Z. 2012. Northern peatland carbon stocks and dynamics: a review. Biogeosciences, 9, 4071–4085.

Yu, Z., Beilman, D. W. & Jones, M. C. 2009. Sensitivity of northern peatland carbon dynamics to Holocene climate change. In Carbon Cycling in Northern Peatlands (Baird, A. J., Belyea, L. R., Comas, X., Reeve, A. S. & Slater, L. D., eds), Geophysical Monograph Series, 184, 55–69.

Yu, Z., Vitt, D. H., Campbell, I. D. & Apps, M. J. 2003. Understanding Holocene peat accumulation pattern of continental fens in western Canada. Canadian Journal of Botany, 81, 267–282.
Süsiniku akumulatsioonikiirus Lätis Teiči rabas viimase 180 aasta jooksul
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On hinnatud süsiniku akumulatsioonikiirust viimase 180 aasta jooksul Lätis Teiči rabas, mõõtes süsiniku koncentratsiooni 1 cm paksustes täpselt dateeritud turbakihtides. Et välja selgitada süsiniku akumulatsiooni ajalisi seoseid kliima ja keskonnatingimustega, kasutatakse Grangeri põhjustlikkuse 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 põhjustlikkuse 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 süshappegaasi emissioonide arvutustes ning lokaalses ja regionaalses kliimapoliitikas.