Biogeosciences, 12, 7057–7070, 2015
www.biogeosciences.net/12/7057/2015/
doi:10.5194/bg-12-7057-2015

Biogeosciences Open Access EGU

Carbon dynamics in boreal peatlands of the Yenisey region, western Siberia

E. D. Schulze[1], E. Lapshina[2], I. Filippov[2], I. Kuhlmann[1], and D. Mollicone[1,3]

[1]Max Planck Institute for Biogeochemistry, P.O. Box 100164, 07701 Jena, Germany
[2]Yugra State University, Khanty-Mansiysk, Khanty-Mansiysk Autonomous District, 628012 Russia
[3]Dept. of Forestry, FAO, Viale delle Terme di Caracalla, 00153 Rome, Italy

Correspondence to: E. D. Schulze (dschulze@bgc-jena.mpg.de)

Received: 26 May 2015 – Published in Biogeosciences Discuss.: 17 July 2015
Revised: 16 November 2015 – Accepted: 18 November 2015 – Published: 7 December 2015

Abstract. Here we investigate the vegetation history and peat accumulation at the eastern boarder of the West Siberian Plain, near the Yenisey River, south of permafrost. In this region, peat started to accumulate 15 000 years ago as gyttja of shallow lakes in ancient river valleys. This peat is older than previously reported, mainly due to separating particulate organic carbon (POC) from dissolved organic carbon (DOC), which was 1900–6500 years younger than POC. The probability of finding peat layers older than 12 000 years is about 2 %. Peat accumulated as fen peat at a constant rate of 0.2 mm yr^{-1} and 0.01 kg C m^{-2} yr^{-1}. The accumulation was higher in ancient river valley environments. Over the last 2000 years these bogs changed into *Sphagnum* mires which have accumulated up to about 0.1 kg C m^{-2} yr^{-1} until present.

The long-lasting fen stage, which makes the Yenisey bogs distinct from the western Siberian bogs, is discussed as a consequence of the local hydrology. The high accumulation rate of peat in unfrozen mires is taken as an indication that thawing of permafrost peat may also change northern peatlands into long-lasting carbon sinks.

1 Introduction

Peatlands are a main component in the global terrestrial carbon pools and are thus of special importance in the global carbon cycle (Gorham, 1991; Ciais et al., 2014; Schuur et al., 2015). There are major concerns about the activation of these carbon pools during climate change (Moore et al., 1998; Belyea and Malmer, 2004; Schuur et al., 2015). Even though the total area of peat is larger in the Arctic than in the boreal region, the largest peat depths have been recorded in the permafrost-free boreal zone (Kauppi et al., 1997; Beilman et al., 2009). Therefore, in the context of global change, quantitative knowledge about the dynamics of these boreal and temperate peatlands is important. The Siberian wetlands are of particular interest due to their vast extent (Schuur et al., 2015), and the West Siberian Plain along the Ob and Yenisey rivers contains one of the world's largest peatlands ranging from the permafrost in the Arctic to the unfrozen southern boreal region. Thus, this peatland area extending far into the non-permafrost region may serve as an example of peatland behaviour under conditions of a warmer climate. While the West Siberian Plain along the Ob River has been studied in the past (e.g. Liss et al., 2001; Lapshina and Pologova, 2001; Beilmann et al., 2009; Sheng et al., 2004), the eastern peatlands of the Yenisey River's watershed remain fairly unknown even though they cover about 40–50 % of the land surface between the Ob (78° E) and Yenisey rivers (90° E).

In this study we investigate peat profiles at the eastern margin of the West Siberian Plain adjoining to the Yenisey River. This region was not glaciated during the Pleistocene. The maximum extent of glaciations in the Pleistocene (900–400 000 years ago) reached 61°30′ (Arkhipov et al., 1999), bordering our study area to the north. During the last glaciation, the Yenisey watershed remained ice-free. Following Krinner et al. (2004) the northern part of the West Siberian Plain was covered by lakes being dammed by the northern ice sheet at the Siberian Arctic Ocean coastline and the Taimyr Peninsula 90 000 years ago (Astakhov, 1993). The west bank of the Yenisey appears to have been a flat land-

Published by Copernicus Publications on behalf of the European Geosciences Union.

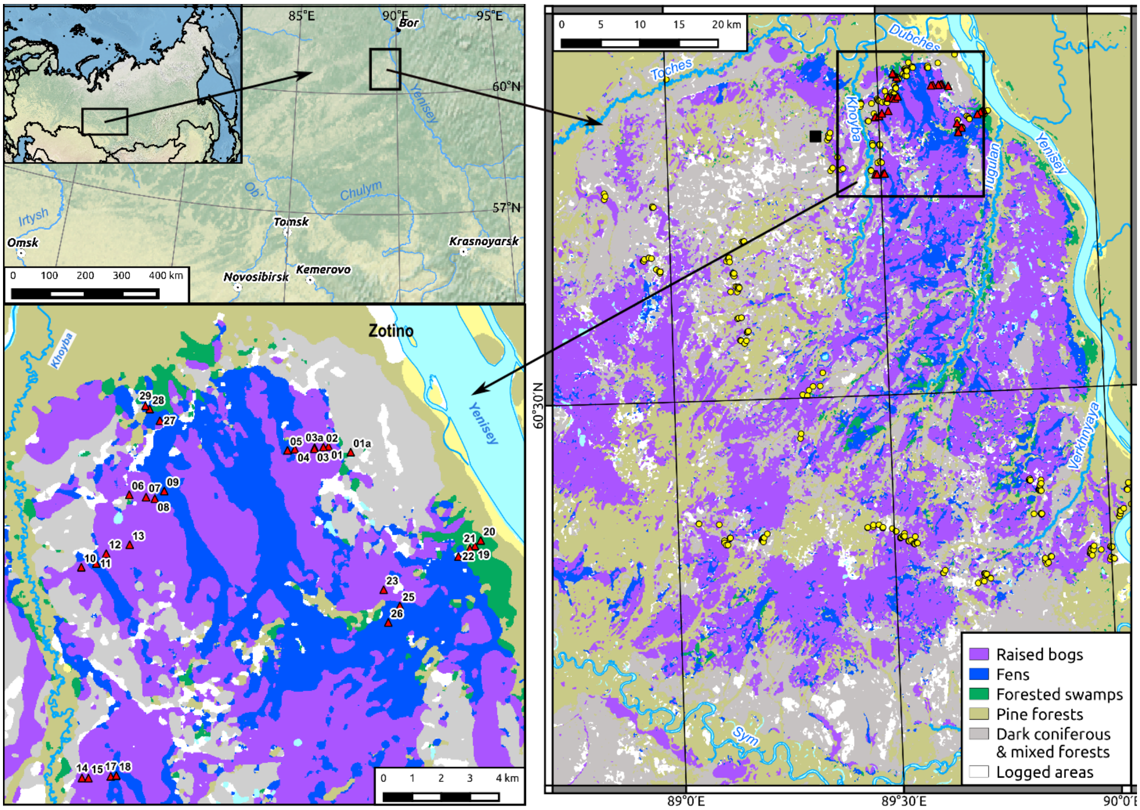

Figure 1. Map of study area with present-day peatland types and surrounding upland vegetation. Zotino Tall Tower: black square (Heimann et al., 2014); vegetation relevés: yellow circles; peat cores: red triangles with core numbers on magnified map.

scape with rivers draining to the west. The geomorphological situation is further complicated by the fact that the west bank of the Yenisey is known as the Tugulan depression (Arkhipov, 1993; Karpenko, 1986, 1996; Glebov, 1988), an area subsiding below the Central Siberian Plateau since the Lower Cretaceous (Shibistov and Schulze, 2007). The area is still subsiding. The water flow of ancient rivers reversed from west to east flow during the Holocene.

The area is dominated by rain-fed raised bogs. However, Glebov (1969) and Karpenko (1986) have already pointed out that groundwater-fed peatlands are widespread in this region. The age of these peatlands was determined to range between 6245 ± 65 and 9025 ± 180 years of ^{14}C age before present (average ± standard deviation; Karpenko, 1996, 2006), which translates into a calibrated age of about 7000–10 000 before present (cal BP). The peat carbon accumulation rate was estimated to be 38.6 and 26.9 $\mathrm{g\,C\,m^{-2}\,yr^{-1}}$ based on bulk densities from Lazarev et al. (1982) and C contents from Pyavchenko (1985), respectively.

In the following we investigate the boreal peatlands of the western Yenisey. Based on the present land cover we are interested in the variation in the stratigraphy of peat in relation to topography, and in the identification of the maximum age, depth and growth of different peatland types. Since the Yenisey receives a major quantity of water from western contributaries, we are also interested in the flow of dissolved organic carbon (DOC) and its ^{14}C age in peat profiles. To our knowledge no estimate exists for the flow of DOC into groundwater in western Siberia.

Our hypothesis is that carbon accumulation of peat started at the time of glacial retreat in shallow lakes. The accumulation of carbon (C) in these peatlands and its decomposition depends on the sequestration environment. Assuming that the fen-type mire accumulated at lower rate than raised peat bogs (Tolonen and Turunen, 1996), we hypothesize that the accumulation rate increased until present, and that these mires continued to be a carbon sink since early Holocene.

2 Study area

2.1 Geography and climate

The study area is located in boreal forest zone of western Siberia (60–61° N, 89–90° E) between two tributaries of the Yenisey, the Sym and the Dubches rivers (Fig. 1). The total area of investigation covers about 7500 $\mathrm{km^2}$ (a circle of about 90 km diameter), 40 % of which is peatland and the other 60 % is pine forest on alluvial sand and mixed boreal forests on drained loamy soils. The study area is bordered in the south-west by a shallow divide of alluvial sands and clays between the Ob and Yenisey basins.

During the Last Glacial Maximum the southern border of the ice sheet extended from Scandinavia along the present Arctic Ocean coastline to the Taimyr Peninsula, with a lake piling up in front of this ice barrier mainly in the Ob River basin. The Yenisey drained into this lake. Also, Yenisey water drained into the Ob River basin at the latitude of our study area via the ancient valleys of Kas and Ket (Olyunin, 1993; Krinner et al., 2004). The river of Kas reversed its flow direction towards the east after the Pleistocene.

Presently there is no permafrost in the study area. Thus, the peatlands of Siberia extend to the south beyond the permafrost area, and these bogs on unfrozen soil may serve as an example of how peatlands respond to a warmer climate. According to pollen data (Levina et al., 1989; Pitkänen et al., 2002) the boreal zone of western Siberia was covered by *Betula nana* shrubs and steppe-like vegetation with *Artemisia*, *Cyperaceae*, and *Chenopodiaceae* 20 000–14 700 years BP. Following the Bølling and Allerød period (14 700–12 700 cal years BP) the climate was warming, as indicated by the appearance of spruce and birch. The central part of the West Siberian Plain (59–60° N) was covered by the northern-taiga forests during the Bølling warm period, when trees were present close to the modern northern tree line (Krivonogov, 1989).

The present relief between the Ob and Yenisey rivers consists of shallow valleys and ridges made of Pleistocene alluvial sands and clays. Altitudes vary from 60 to 120 m above sea level, with highest elevations (146–155 m above sea level) formed by alluvial sand deposits. Numerous small rivers and creeks drain the area into Sym, Tulugan and Dubches rivers. The upland vegetation is *Pinus sylvestris* forest on sandy soils (Wirth et al., 1999) and mixed birch–dark conifer forests with *Pinus sibirica*, *Picea obovata*, *Betula pubescens*, and *Pinus sylvestris* on loamy alluvial soils near rivers and creeks (Il'ina et al., 1985).

The climate is continental, with long cold winters and short but warm summers. According to the data of the Bor weather station (located at 61°06′ N, 92°01′ E), the mean annual temperature is -3.5 ± 1.3 °C (1936–2012), ranging from -26 °C mean daily temperature in January to $+18$ °C in July. Mean annual precipitation is 559 ± 90 mm (1936–2012). An unknown part of this precipitation is stored in an annual cycle in the peat lands or lost by flooding after snowmelt (Ivanov, 1981). The mean average rainfall during the growing season (> 5 °C daily temperature) is 268 ± 63 mm yr^{-1} (1936–2012). Based on eddy covariance measurements in our study region, mean evaporation during the growing season (> 5 °C daily temperature) was 280 mm (Kurbatova at al., 2002), when rainfall was 265 mm (1998–2000). The mean annual precipitation in the same period was 540 ± 86.2 mm. Snow and late autumn rainfall was about 275 mm. Even though a proportion of this precipitation may remain in the bogs and maintain a positive water balance despite run-off of snowmelt, the present water balance is close to zero and strongly depends on the date when frost seals the surface, which determines the storage of autumn rains.

2.2 Present-day peatland types and peat stratigraphy

Presently three major groups of peatland types occur in the study region: (a) rain-fed bogs, which rise above the groundwater level and cover about 80 % of the peatland area; (b) run-off and groundwater-fed fens, covering about 13 % of peatland area; and (c) forested swamps, covering about 7 % of peatland area (Fig. 1).

Based on macrofossils, the peat profiles consist of the following peat types:

1. *Equisetum fluviatile* peat, which develops in shallow water on muddy ground.
2. Brown moss peat composed of the mosses *Drepanocladus* spp. and *Calliergon* spp.
3. Woody and sedge-woody peat consisting of roots and fallen stems of trees (*Pinus* spp., *Betula pubescens*, and *Picea obovata*) and tussock sedges (*Carex cespitosa*).
4. Herbaceous peat, consisting of the floating angiosperm *Menyanthes trifoliata*, the fern *Thelypteris palustris*, and the horsetail *Equisetum fluviatile*.
5. *Carex* (sedge) peat consisting mainly of *Carex lasiocarpa*, sometimes with some admixture of *Menyanthes trifoliata*.
6. *Scheuchzeria* peat, formed by the 10–20 cm tall monocot *Scheuchzeria palustris*.
7. *Eriophorum* peat, composed of *E. vaginatum*.
8. *Sphagnum* peat consisting mainly of the peat moss *Sphagnum fuscum* forming nutrient-limited raised bogs above the mineral groundwater. Under more nutrient-rich conditions, other peat mosses, such as *S. warnstrofii*, occur on the top of fen deposits.

The peat types are the building blocks for peat profiles where the specific sequence represents a sequence starting from lake water or waterlogged mineral soil to rain-fed bogs. Thus, the peat stratigraphy describes the profiles below the mire surface (Table S1; Fig. 2).

In the following we explain how profile types and peatland types correspond. The peatland type represents the present land surface of the region. However, this landscape may cover a range of profile types of different peat composition and dynamics. Thus, for understanding C storage at landscape level it is important to understand the history of peatland formation. Examples of typical peatland types with their associated profiles and peat types are shown in Fig. 2. The profiles and the surface vegetation and the peat stratigraphy of the main peatland types are described in detail in the Supplement (Sect. S1).

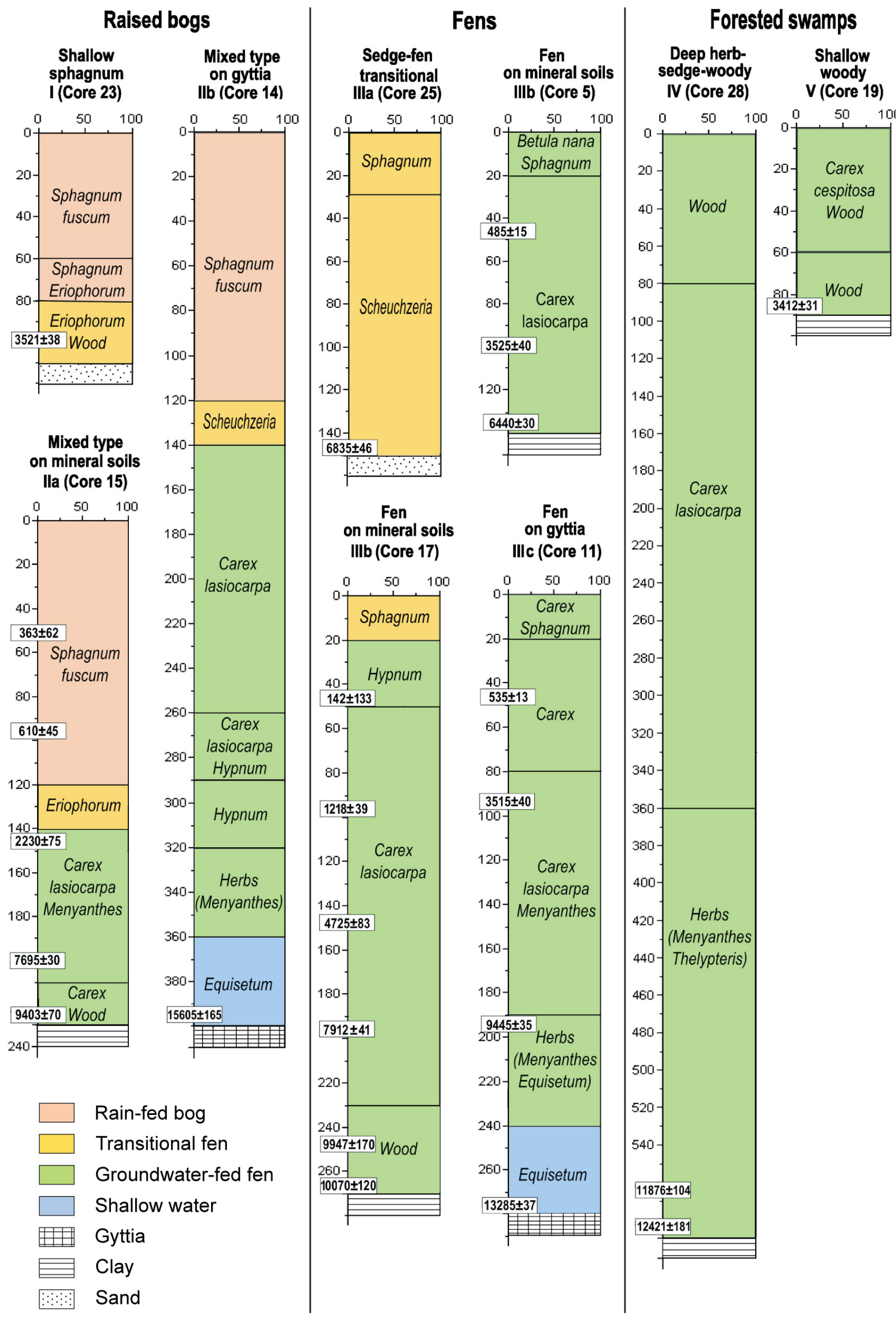

Figure 2. Main types of peat profiles of various peatlands in the study area. Numbers in boxes indicate the carbon age.

3 Methods

3.1 Vegetation survey and sampling of peat profiles

The peatland types and their associated surface vegetation were investigated based on 300 plots. The information of the plots was upscaled using high-resolution satellite (Landsat ETM+) images (Fig. 1) as a basis for selection of the locations for coring peat profiles. Even though the peat sampling was concentrated in the north-eastern part of the study region, for logistical reasons, all peatland and profile types were collected.

A total of 28 cores were drilled with a corer of 3.5 cm diameter (TBG-1, Geoltorfrazvedka, Moscow). Each core was cut into 10 cm pieces. The upper 2 cm thick slice from each 10 cm segment was taken for bulk density measurements. The basal 1 cm thick slice of each core positioned immediately above the peat–mineral interface was taken for radiocarbon analysis to quantify the maximum age of that profile.

In addition, for 9 of the 28 cores, a 1 cm thick slice was taken every 0.5 m for ^{14}C dating of the horizon. Macrofossil analysed and C contents were measured in the remaining 7–8 cm thick sample of each 10 cm segment. A total of 590 peat samples were analysed.

3.2 Plant macrofossil

Fossil plant remains were identified under the microscope (Zeiss Axiostar, 10–40× magnification, Jena, Germany), following sieving of samples (0.25 mm) under flowing water. The contribution of a specific macrofossil as volume fraction of the washed sample was estimated. For each sample the peat types were identified based on the dominance of plant species according to Matukhin et al. (2000).

3.3 Bulk density and carbon content

Bulk density (BD: $g\,cm^{-3}$) was determined as the weight of a $10\,cm^3$ subsample from the upper 2 cm thick slice taken for bulk density analysis from each 10 cm core segment after drying at 100 °C over 24 h.

The carbon content of peat was determined from carbon concentrations per total dry weight ($g\,C\,g_{dw}^{-1}$) as determined from samples used for ^{14}C analysis. Carbon concentration was constant (46.94 % ± 3.71 %) up to 90 % of the profile depth. Close to the mineral soil at the bottom of the profile, C concentrations decrease, mainly due to increased ash content. For the final 10 % we interpolated the measured C concentration at the deepest layer and the average of the top layer. C content ($kg\,C\,m^{-2}$) was obtained from C concentration, bulk density, and the depth of the investigated layer.

3.4 Separation of DOC and POC

In order to obtain the age of the peat deposits we separated dissolved organic carbon (DOC) and particulate organic carbon (POC) to remove confounding effects on age of DOC flow in the profile. We separated DOC from POC by dispersing peat samples in double-distilled water (1 : 4 by weight) and shaking for 2 h. The solution was wet-sieved (63 and 36 µm metallic sieve) and the filtered matter (< 36 µm) was adjusted to pH 9 by adding NaOH and centrifuged at 2900 *g* for 30 min (Megafuge 3.0, Heraeus, Hanau, Germany). The obtained supernatant was filtered through a 1.6 µm glass fibre filter which has been baked at 500 °C before use to avoid C contamination. The filtered matter < 1.6 µm and the pellet > 1.6 and < 36 µm were freeze-dried (Piatkowski, Munich, Germany). The freeze-dried pellet (> 1.6, < 36 µm) was defined as particulate organic matter (POC) and the freeze-dried supernatant (< 1.6 µm) as dissolved organic matter (DOC). The fraction > 63 µm was discarded because it contained inorganic dust particles.

3.5 Ash content

Ash content was determined by igniting bulk peat at 500 °C (Nabertherm, model L9/11, Lilienthal, Germany). Even though Siberia is known for its forest fires (Goldammer and Furayev, 1996), there was no indication of a peat fire, mainly due to the shallow surface water of the fen stage. Aeolian deposits of soot and dust from forest fires in the upland pine forests is possible, but these deposits were of similar age to the biomass that was conserved as peat. We cannot exclude the formation of calcite from oxalate (Regev et al., 2011), but we could not detect any calcite in our samples.

AMS ^{14}C analysis

Peat core chronologies were obtained from AMS radiocarbon (^{14}C) analysis (Table S1). DOC and POC were analysed for ^{14}C using an accelerator mass spectrometer (Steinhof et al., 2004). Samples were dry-combusted, and a small aliquot of the resulting CO_2 was used to determine $\delta^{13}C$, while the majority of the CO_2 was catalytically reduced to graphite at 625 °C using Fe powder in the presence of H_2. The resulting graphite-coated iron was pressed into targets and measured for ^{14}C. The radiocarbon activity is expressed as $\Delta^{14}C$, the difference in parts per thousand (‰) between the $^{14}C/^{12}C$ ratio in the sample compared to that of the standard oxalic acid (Trumbore, 2009). The standard was corrected for decay between 1950 and the year of measurement (2009 in this study). The $\delta^{13}C$ values of the samples were used to correct for mass-dependent isotope fractionation effects on ^{14}C. The absolute age was determined as age before present (BP) by calibration of the ^{14}C spectra of the AMS sample with the calibrated ^{14}C standard of the Northern Hemisphere using OxCal (Reimer et al., 2004).

All data were processed using the statistical package of R (R Development Core Team 2010).

4 Results

4.1 Peat accumulation and profile age

The average depth of the studied mires was 215 ± 130 cm, ranging from 40 (Core 20) to 587 cm (Core 28) (Sect. S2).

The oldest deposition of organic matter was on the bottom of the 0.1 (Core 11) to 0.2 m (Core 14) thick lake sediment (gyttja) of 15 925 ± 65 cal years BP (Core 14) and 13 285 ± 37 cal years BP (Core 11; see also Table S1). Only three cores (profile 10, 11, 14; 10 % of all profiles) started from gyttja. The next oldest profiles (28 and 29: Fig. 2; Table S1) started from mineral soils at 12 421 ± 104 cal years BP (Core 28) and 11 950 ± 120 cal years BP (Core 29), indicating that at that time the region was a variegated landscape with shallow lakes producing gyttja and upland sites on mineral sand or clay. The oldest gyttja (Cores 11 and 14) was

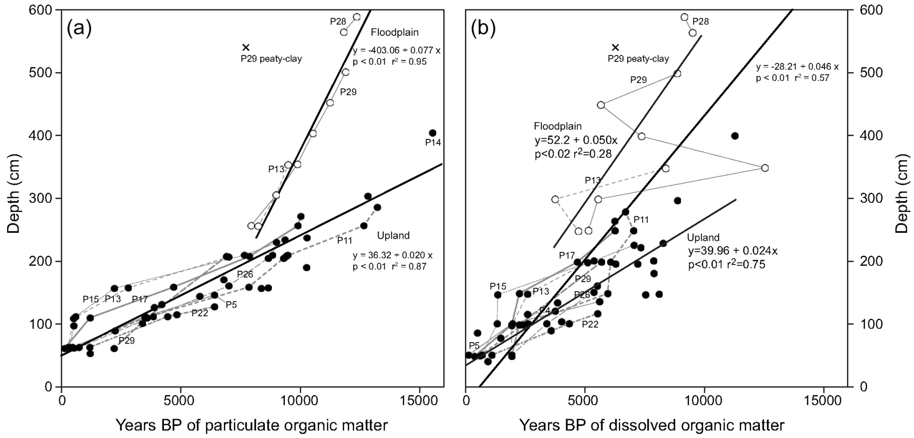

Figure 3. Relations between ^{14}C POC age **(a)** and ^{14}C DOC age **(b)** and peat profile depth. Unfilled circles: lake sediments and peat originating from ancient river valleys; filled circles: lake sediments and peat developed outside of old river valleys. $n = 10$ for flood plains and 57 for upland peats. Numbers preceded by P indicate profile number. A common regression of all data points is also shown in **(b)**.

found near the Khoiba River. The oldest profiles on mineral soil were found in old meanders of the Dubches River valley.

The average basal age of the peat deposits was 6410 ± 4023 cal years BP ranging from 525 to 15 606 years. The organic matter at the bottom of Core 29, containing a mixture of organic and inorganic material (peaty clay), was about 4000 years younger than the overlaying peat at the base of Core 29 (Fig. 3a, one sample only). First wood samples of forested swamps were found 10 070 years ago (Core 17, cal BP).

For 50 % of the cores the peat accumulation started as a fen with herbaceous and sedge vegetation on mineral soil (clay) between 5000 and 10 000 cal years BP. Fifteen percent of the cores also started between 2000 and 5000 cal years BP as herbaceous fens, forested swamps and pine–cotton grass bogs (Cores 1, 3a, 4, 19, 23) on mineral soil, and 8 % of the cores started less than 2000 years ago (cal BP) as rain-fed cotton grass–*Sphagnum* bogs and swampy dark coniferous forests also on mineral soil. Only about 2000 cal years BP did *Sphagnum* peat start to cover the older fen deposits (Cores 13, 15). *Sphagnum* also covered new areas on sandy soils (Cores 3, 3A). These rain-fed layers presently reach 1.2 m thickness.

Mineral–organic lake sediments and particulate organic carbon (POC) of various peat types accumulated linearly over time at a rate of 0.2 mm yr^{-1} from 15 000 years cal BP (Fig. 3a, closed circles, r^2 of linear regression = 0.87). Profiles in the ancient valleys of the Khoiba (Cores 13) and Dubches rivers (Cores 28, 29) accumulated peat at a higher rate than upland profiles in the early Holocene between 8000 and 12 000 cal years BP (0.77 mm yr^{-1}, slope of regression $r^2 = 0.95$; Fig. 3a, open circles). The data points above the regression line of the past 2000 years are taken as an indication of a more rapid peat depth accumulation rate when the rain-fed *Sphagnum* bogs appeared. These data are, however,

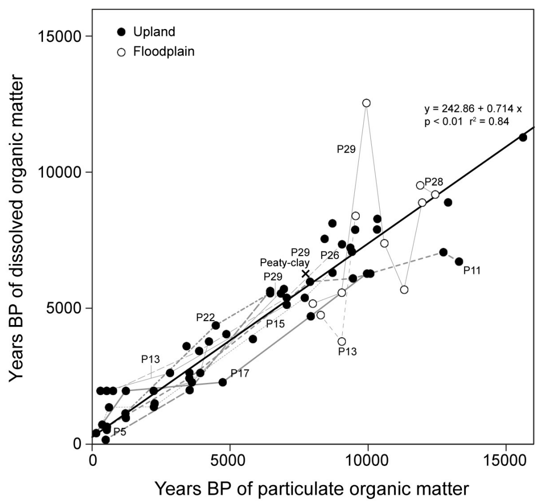

Figure 4. Linear relationship between DOC and POC ^{14} ages with RMA regression. $n = 10$ for flood plains and 57 for upland peats. Numbers preceded by P indicate profile number.

within the 95 % confidence line of the regression. The regression line in Fig. 3 has a y axis intercept resulting from the fact that we do not have sufficient data to describe the most recent peat accumulation by *Sphagnum*. The initial slope is higher than indicated by the linear regression.

Dissolved organic matter (DOC) generally had a younger ^{14}C age than the particulate organic material (Fig. 3b). The scatter of the data is much larger than for POC, and this scatter increases with age. In the upper 1 to 2 m of peat, which is dominated mainly by *Sphagnum* moss, the DOC age is 180–1775 years younger than POC (Cores 11, 13, 15, 17, 26) (see also Sect. S2). The maximal difference in upper layers was recorded as 2620 years. The weight of DOC as a fraction of total carbon (DOC / TOC) is 18.9 ± 17.3 %.

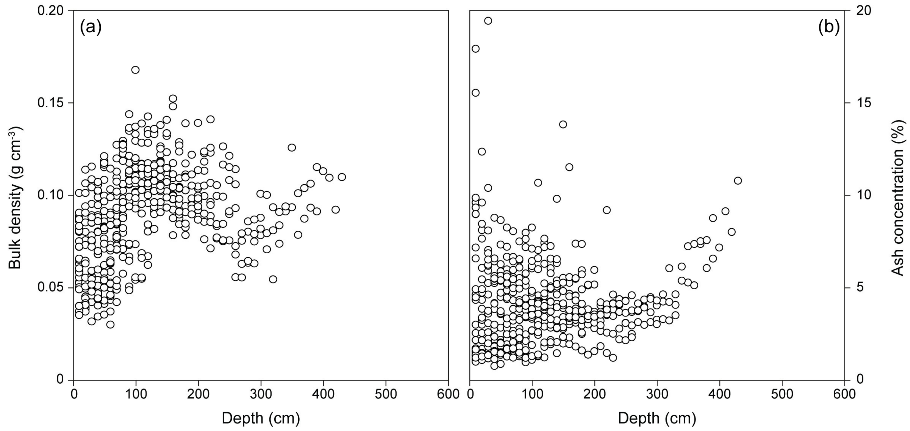

Figure 5. (a) Bulk density and **(b)** ash content as related to profile depth.

DOC and POC were linearly related (Fig. 4) with a slope of about 0.71 ($r^2 = 0.84$). On average, for the oldest POC material, the age difference between POC and DOC was 1905 ± 1556 years. The maximum age difference between DOC and POC was 5370–6500 years cal BP at the peat base, which is of the same order as the age difference between the bottom peat layer and the underlying mineral–organic deposit (Fig. 3a).

4.2 Bulk density and ash concentration

The average bulk density ($g_{dw}\,cm^{-3}$) was $0.23 \pm 0.20\,g_{dw}\,nm^{-3}$. Bulk density (Fig. 5a) increased with depth. However, deeper cores had a lower bulk density at greater depth. Bulk density increased again close to the bottom of the profiles with mineral soil. The variation in bulk density was in part caused by woody deposits.

Ash concentration ($mg\,g_{dw}^{-1}$) showed a large variation between profiles in the uppermost horizons (Fig. 5b) due to higher ash concentrations in shallow fen profiles. Ash concentration increased again close to the bottom of the peat profile. The high ash contents in the lowest 10 % of the profile are not shown (see Supplement). The profiles show no indication of flooding or fire, and the variation in ash concentration is probably due to aeolian input of dust from upland forests, e.g. after forest fires.

4.3 Carbon contents

The average C content ($kg\,m^2$) was $7.3 \pm 6.7\,kg_{dw}\,m^{-2}$ for 10 cm thick layers (Fig. 6).

Carbon accumulated at constant concentration (Sect. S3) and a linear rate over the past 15 000 years independent of the peatland and peat profile type at a rate of $10\,g\,C_{dw}\,m^{-2}\,yr^{-1}$. Similar to Fig. 3, profiles which originated from the ancient floodplains had a higher initial accumulation rate (between 12 000 and 8000 years BP) of about $50\,g_{dw}\,m^{-2}\,yr^{-1}$. The linear regression shows a y axis intercept, indicating that not only depth accumulation but also the most recent C accumulation is higher. Extrapolating to zero, the accumulation rate has been $52 \pm 23\,g\,C\,m^{-2}\,yr^{-1}$ since about 1000 years ago, when the former fen-type bogs became rain-fed *Sphagnum* bogs, and $102\,g\,C\,m^{-2}\,yr^{-1}$ in a 147-year-old top layer (Core 17, 47 cm depth). The accumulation in the top layers is within the ranges measured by eddy covariance (43–$62\,g\,C\,m^{-2}\,yr^{-1}$; Kurbatova et al., 2002) and the pine method ($84\,g\,C\,m^{-2}\,yr^{-1}$ by linear regression of depth accumulation as dated by tree rings of pine; Schulze et al., 2002).

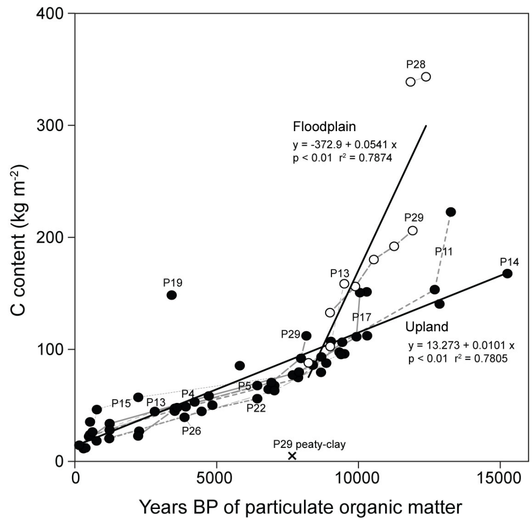

Figure 6. Cumulative carbon content in different profiles as related to the ^{14}C age at the bottom or at intermediate sections of the profile. Unfilled circles: lake sediments and peat originating from ancient river valleys; filled circles: lake sediments and peat developed outside of old river valleys.

The total amount of C at 3 m depth is $120 \pm 15\,kg\,C_{dw}\,m^{-2}$. This is considerably more than the amounts on permafrost in adjacent regions (Schuur et al., 2015).

5 Discussion

5.1 Maximum peat age

Carbon started to accumulate from gyttja more than 15 000 years ago (cal BP) and from *Equisetum fluviatile* growing in shallow water about 13 000 cal BP. Terrestrial peat accumulation began as early as 12 000 cal BP. The age of the peat matrix are about 2000–4000 years earlier than previously reported for this region (Karpenko, 1996: 9025 ± 180 years ^{14}C age, equalling 10 200 cal years BP), between Ob and Yenisey rivers (Blyakharchyk and Sulerzhitsky, 1999: 9480 ± 90 years ^{14}C age, equivalent to 11 000 cal years BP) and from the central part of the western Siberian lowland (Smith et al., 2004: 9000–11 500 cal years BP), which were based on bulk peat ages. The peat at the base of the Salym–Yugan Mire at the same latitude of our study area in western Siberia was dated to 12 305 cal years BP based on measurements from plant particles (Turunen, 1999; Pitkänen et al., 2002). The maximum age of our study is also higher than for bulk peat in Finland (Mäkilä and Saarnisto, 2008: 10 400–9000 cal years BP) and in Canada (Zoltai et al., 1988; Halsey et al., 1998: 10 000–8000 cal years BP). It appears likely that the peatlands between the Sym and Dubches rivers initiated in the very early Holocene following the Allerød (14 700–12 700 cal years BP). The difference in maximal peat age compared to earlier publications is most likely due to the separation of POC and DOC ages in this study. DOC is several thousand years younger than POC, and this age difference contaminates the ^{14}C value of POC in bulk and plant samples because of the high contribution in weight of DOC / TOC.

Our oldest profiles were located in the ancient water flow valleys drained to the west during the glacial period. The peats of ancient valleys represent rare spots in the present landscape. Based on 590 tiles of 10 cm thickness of 29 cores taken in this study, the chance to reach a horizon that is older than 12 000 years is about 2 % (Fig. 7). The study sites have experienced no large-scale flooding events since glaciation. Mineral sediments were only found in the bottom layers of peat deposits.

5.2 Landscape development of peatlands

The Holocene development of the Yenisey wetlands is similar to that of the boreal zone of western Siberia (Romanova, 1976; Liss et al., 2001; Lapshina and Pologova, 2011) and other regions of the Northern Hemisphere (Boch and Masing, 1983; Chapin et al., 1992). However, our study area is distinct from other regions by the long-lasting fen stage of peat development. Fens are wetlands where the hydrology depends on the groundwater table. Thus, to understand the accumulation of fen peat over thousands of years, one must understand the hydrology of the region.

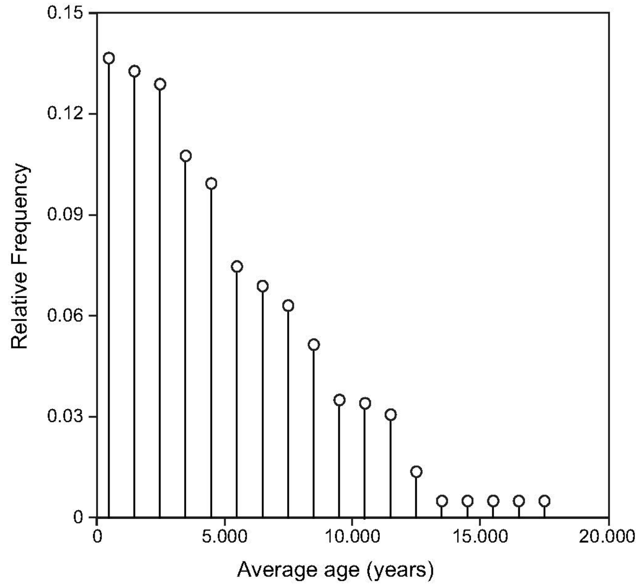

Figure 7. Histogram of the relative frequency distribution of POC age in 610 tiles of 10 cm thickness of 29 peat cores as related to age class intervals of 1000 years.

After melt of the northern ice sheet, the Yenisey no longer drained to the west. The ancient rivers, which drained to the west in the Pleistocene, reversed their flow and started draining to the east to reach the Yenisey as the lowest point in the landscape, which then drained to the north. This change in river flow could have resulted in a period of poor drainage and shallow lakes in the early gyttja sequence of the fen development. With ongoing development of the post-Pleistocene drainage system, *Equisetum fluviatile*, a relatively short plant species (up to 1 m tall), established, growing with a rising water table. *Equisetum* was followed by various *Carex* and *Menyanthes* communities which accumulated peat in shallow water at almost constant rate, independent of the vegetation type. Peatlands have not only gained depth but also expanded in the area in the last 12 000 years.

About 1000–2000 years ago the nutrient conditions and the hydrology changed. The relative frequency of peat ages changed when most fens were covered by a sheet of *Sphagnum*, which stores rainwater and may rise above the groundwater table. In the transition period, the fen did not lose contact with groundwater. Forests could not establish on fen peat, but *Carex* rather than *Menyanthes* dominated the vegetation. The causes of the rise of fen profiles and the following change into *Sphagnum* peat remain unclear.

In the early Holocene, peatlands were confined to depressions of the existing relief of meandering rivers, which cut a new drainage system through this region when flow direction changed from drainage to the west towards drainage to the east. Following this initial phase, a regional sheet of fen vegetation developed with an almost constant shallow water table over several millennia. The hydrology of this develop-

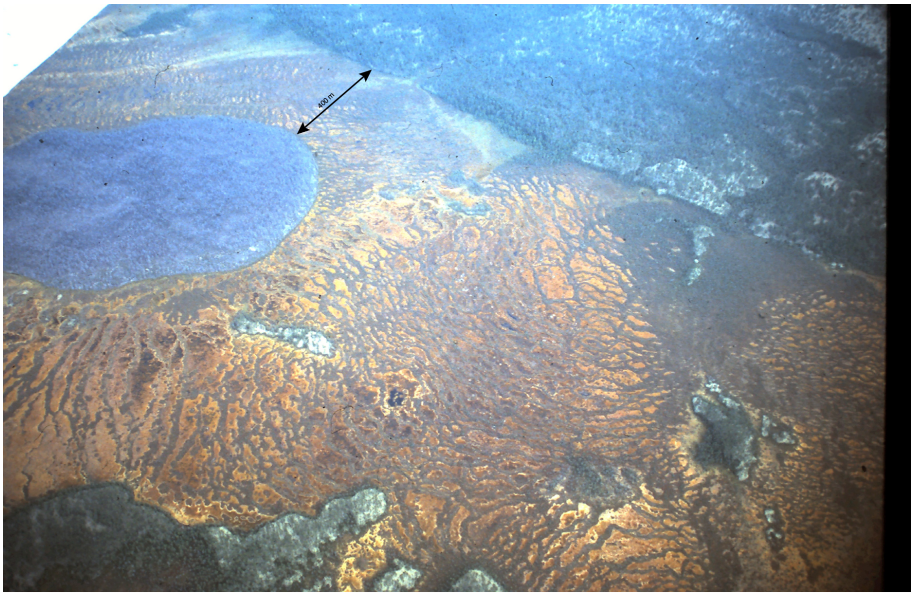

Figure 8. Aerial photograph of part of the study region, with pine forest on alluvial sand in the upper right corner, light-green fens close to the forest edge where fresh water enters into the peatland from the upland forest, and a banded ridge–hollow–mire in the centre. The round-shaped dark coloured area on the left upper edge is Bor Island, which served for an experimental forest fire (Firescan Science Team, 1996). The distance between Bor Island and the main forest land is 400 m.

ment remains a matter of debate because we cannot explain the rise in groundwater above the drainage system, which, in fact, became increasingly deeper over time as indicated by the terraces and river channel of the Yenisey. Under long-term steady-state conditions, the flow of water through a fen is determined by the pressure difference between the peat surface and the drainage system and not by the hydraulic conductance (Nobel, 1991). Thus the question remains of why these fens did not drain. The subsidence of the Tugulan depression (Arkhipov, 1993) could have supported the fen development and a rising water table. However, other parameters also changed. At the landscape level, the partitioning between forest and peatland cover changed. Figure 7 suggests that the area of forest on mineral soil continually decreased while peatlands expanded. Thus, excess water from the forests which supported the hydrology of fens has probably decreased just as much as the nutrient influx. This could result in a change from fens towards a *Sphagnum* cover. However, the change appears to have happened fairly abruptly (see Fig. 2) from wet *Carex lasiocarpa* swards, which dominated the landscape over several millennia, towards *Sphagnum*. Thus, additional factors could have triggered this change in mire type. The existing drainage system could have been temporarily blocked by falling trees of the near-river vegetation, but this would not explain a constant shallow water table over long periods of time. The drainage system may also have changed at the time when the Ket people, who lived mainly on fish, arrived in the Yennisey Basin around 2000 years ago (Vajda, 2001). This human migration could have affected the beaver populations in the main water channels, increasing or changing the drainage channels of run-off (Naiman et al., 1994; Butter and Malanson, 2005). Apparently, the combination of geological processes, changes in landscape hydrology, and human impacts explains the rise of the water table in fens and the change towards *Sphagnum* peat.

The present regional hydrological balance of the growing season is close to zero, and would not support ombrotrophic bogs. The contribution of winter precipitation depends on the timing of frost versus snowfall. Most of the snowmelt is lost by flooding, but it was estimated in western Siberia that about 20 % of snow water may contribute to the peat water balance. A contribution of water from upland pine forest emerges as a possible additional source of water during the growing season. Spring water from pine forest is very nutrient-poor, because pine grows on alluvial sand. Figure 8 presents an impression of the landscape hydrology at the edge between peat and upland forest. Upland spring water emerging from pine forest supports fens close to the forest edge (light-green area in Fig. 8), which would then help to maintain the water table in the *Sphagnum*-dominated "ridge–hollow complex" (brown striped area in Fig. 8). The ridges indicate a lateral flow of water away from the forest edge despite a flat topography. This indicates a water flow from the forest through the peat system.

5.3 Peat and carbon accumulation

The linear accumulation of carbon of about 10 $g\,C\,m^{-2}\,yr^{-1}$ or of about 20 $mm_{peat}\,yr^{-1}$ is lower than the average values for the middle boreal zone of western Siberia ($24.8 \pm 5.5\,g\,C\,m^{-2}\,yr^{-1}$) (Lapshina, 2011), where lowest rates ($15\,g\,C\,m^{-2}\,yr^{-1}$) were observed in the central parts, the bog plateau (Glebov et al., 1997; Turunen, 1999; Lapshina and Pologova, 2011).

The change from fen-type vegetation towards rain-fed bogs is the only change which has resulted in an increased peat accumulation over the past 500–1000 years, following 10 000 years of constantly low fen-peat rise with variable fen vegetation. Thus the post-glacial fen accumulation was mainly determined by the groundwater table. Only following the change into rain-fed bogs an increase in peat production. Eddy covariance measurements and the pine method (Arneth et al., 2002; Schulze et al., 2002) indicate that modern accumulation rates for the Yenisey region were similar to those in western Siberia.

There are several possible reasons for the faster peat accumulation of *Sphagnum* (Clymo, 1978, 1984). The faster increase in height is partly due to the lower bulk density of the young layers; not only height but also carbon was gained at a faster rate by *Sphagnum* compared to fen peat. This would imply that the decomposition of *Sphagnum* is slower than that of fen plants. Since mosses have a lower rate of photosynthesis than herbaceous angiosperms, we do not think that primary productivity increased. Furthermore, Yu (2012) emphasized that peat accumulation increased in the last decades.

In comparison, in Finland the Holocene average C accumulation rate estimation varied from 19.8 to $26.1\,g\,C\,m^{-2}\,yr^{-1}$ in a raised bog region and from 14.6 to $17.3\,g\,C\,m^{-2}\,yr^{-1}$ in the Aapa mire region (Turunen, 1999; Mäkilä and Goslar, 2008). The C accumulation in Canadian peatlands ranged from 10 to $35\,g\,C\,m^{-2}\,yr^{-1}$ (Ovenden, 1990), with an average value of $29\,g\,C\,m^{-2}\,yr^{-1}$ (Gorham, 1991). The long-term C accumulation rate in 32 sites from Alaska to Newfoundland was $25\,g\,C\,m^{-2}\,yr^{-1}$ (Gorham et al., 1991 as cited by Mäkilä and Saarnisto, 2008). In a review on northern peatland dynamics, Yu (2012) averaged a rate of $11\,g\,C\,m^{-2}\,yr^{-1}$, which is close to the middle boreal zone of western Siberia and significantly higher than in our study region. A high peat accumulation rate occurred only in old river valleys (Core 28, 29) and ancient valley depressions (Core 13) in the Late Glacial and early Holocene (12 000–8000 years BP), which may indicate a water limitation of this region.

5.4 DOC balance and loss

We find a linear relation between DOC and POC with increasing difference from a 1 : 1 line. This can only be explained if young dissolved organic carbon was transported not only laterally but also downwards by gravitation (Siegel and Glaser, 1987; Waddington and Roulet, 1997). This observation of young DOC confirms studies from western Europe and Canada (Aravena et al., 1993; Charman et al., 1994, 1999; Clymo and Bryant, 2008). Other studies also indicate that there is a downwards movement of DOC from upper to deeper layers of peat deposits and then into downstream water (e.g. Chasar et al., 2000). Here we show that the difference between DOC and POC increases with depth. The maximal age difference recorded between DOC and POC was 5370–6500 years at the peat base; this difference is much larger than in earlier studies. Apparently, water does not percolate through the profile as in unsaturated soils, but a surplus of rainwater presses or pumps part of the existing water column into the groundwater, and thus young DOC moves downward, always replacing older with younger DOC. This cumulative effect results in a maximum difference between DOC and POC at the mineral surface. The indicated downward flux of DOC based on age does not prevent water from also moving in a lateral direction (see Fig. 4).

In contrast to low peat horizons, DOC in the uppermost layer sometimes may have an older age than particulate organic matter (see Fig. 3). It is suggested that, under dry conditions, DOC may move upward. In dry years, the water table in *Sphagnum*–dwarf shrub communities may fall by 55 cm (Romanov, 1968; Ivanov, 1981; Ivanov and Novikov, 1976). Under these conditions, it is possible that old DOC reaches the surface layer.

The mineral–organic material (clay) below the lowest peat layer may be younger than the peat (organic material). This phenomenon of an apparent age inversion has been described numerous times (Charman et al., 1992; Pitkänen et al., 2002; Turunen et al., 2001). It has been interpreted by root penetration and/or introduction of younger humic acids from increased water flow at the peat–mineral interface. We could not detect any roots in that horizon. Thus, it is suggested that young DOC is being immobilized at the border of mineral soil by clay or by free Fe cations because these would preferentially bind to DOC.

5.5 Effects of climate change

The Yenisey peatlands have showed no effect of climate changes over the past 10 000 years. Peat accumulation of the fen-type bogs is determined by the regional hydrology and the water table. The plant species cover and peat type adjust to changes in climate and hydrology. There has been a substantial increase in peat accumulation over the past 1000 years after *Sphagnum* covered the fen-type landscape. There is no indication of decreased productivity until present (Arneth et al., 2002; Schulze et al., 2002), and we may speculate that this will continue into the future as long as rainfall exceeds evaporation. An increase in water availability was predicted for central Siberia (Tchebakova et al., 2011; IPCC, 2014). Thus, extrapolating from the unfrozen Yenisey profiles, which contain 3–5 times as much C as the closely adjacent peat on permafrost (Hugelius et al., 2014; Schuur et al., 2015), we would envisage an increase in peat accumulation with permafrost thawing in regions of positive water balance.

6 Conclusions

We hypothesized that the accumulation of peat in non-permafrost bogs of central Siberia has increased until present, and that these mires have continued to be a carbon sink since the early Holocene.

The present study suggests that peat in the Yenisey region south of the permafrost zone is considerably older than previously reported. Peat started to accumulate with the retreat of the northern ice sheet. The specific situation of the Dubches–Sym region results in a long fen period lasting more than 10 000 years which may be associated with the formation of a new post-Pleistocene drainage system but may have also been influenced by early human settlers. The presently observed mires maintain their water balance in part with snowmelt and in part with water from the uphill pine forest.

DOC flux could potentially be quite large, and it may move laterally by pressure gradients rather than through base sediments, but we have no quantitative estimate of the magnitude of this DOC flux.

Confirming our initial hypothesis, we show that the total amounts of peat that have accumulated since the Pleistocene were constant over a very long time and have even increased in recent decades. The peat accumulations are larger than on permafrost. This may indicate that, with thawing of permafrost, peatlands may in fact start to expand, rather than decompose, depending on the water balance.

The Supplement related to this article is available online at doi:10.5194/bg-12-7057-2015-supplement.

Author contributions. E. D. Schulze wrote the manuscript. E. Lapshina headed the field work and participated in manuscript preparation. I. Filippov supervised peat sampling in the field and edited the satellite map. I. Kuhlmann devised the DOC–POC separation. D. Mollicone initiated the study and produced the initial satellite maps as a basis for the survey.

Acknowledgements. We thank Annett Boerner (Adelaide, www.dn.com.au/annett-boerner.html) for the images, Nina Pologova (Tomsk) for chemical analyses, Emelian Mouldiyarov (Tomsk) for plant identification in peat, Konstantin Kremenetski (Los Angeles), and Siim Veski (Tallinn) for helpful discussions. We would also like to thank Alexandr Tsukanov (Krasnoyarsk) and Nina Filippova (Khanty-Mansiysk) for participating in field surveys. This work was funded by the MP Institute for Biogeochemistry in Jena (Germany).

The article processing charges for this open-access publication were covered by the Max Planck Society.

Edited by: Y. Kuzyakov

References

Aravena, R., Warner, B. G., Charman, D. J., Belyea, L. R., Marthur, S. P., and Dinel, H.: Carbon isotope composition of deep carbon gases in an ombrogenous peatland, Northwetern Ontario, Canada, Radiocarbon, 35, 271–276, 1993.

Arkhipov, S. A.: Kompleksnaya paleogeografichaskaya rekonstruktsiya dlya epokhi 20–18 tys. l. n. (Environments 20 000 to 18 000 yr BP), in: Razvitie landshaftov I klimata Severnoy Evrazii. Pozdniy pleystotsen–golotsen, elementy prognoza. Vyp.1. Regionalnaya paleogeografiya (Evolution of landscapes and climates of the Northern Eurasia. Late Pleistocene–Holocene elements of prognosis. I. Regional paleogeography), edited by: Velichko, A. A., Nauk, Moscow, 37–41, 1993.

Arkhipov, S. A., Volkova, V. S., Zolnikov, I. D. Zykina, V. S., and Sibir, Z.: West Siberia, in: Izmenemie klimata i landshaftov za poslednie 65 vln. let (Climate and Environment Changes During the Last 65 Million Years), edited by: Velichko, A. A. and Nechaev, V. P., GEOS, Moscow, 84–109, 1999.

Arneth, A., Kurbatova, Ju., Kolle, O., Shibistova, O. B., Lloyd, J., Vygodskaya, N. N., and Schulze, E.-D.: Comparative ecosystem-atmosphere exchange of energy and mass in a European Russian and a central Siberian bog. II. Intersesonal and interannual variability of CO_2 fluxes, Tellus B, 54, 514–530, 2002.

Astakhov, V. I.: Problema poslednego oledeneniya Zapadnoi Sibiri (Problem of the last glaciation of West Siberia), in Razvitie landshaftov I klimata Severnoy Evrazii. Pozdniy pleystotsen–golotsen, elementy prognoza. Vyp.1. Regionalnaya paleogeografiya (Evolution of landscapes and climates of the Northern Eurasia. Late Pleistocene–Holocene elements of prognosis. I. Regional paleogeography), edited by: Velichko, A. A., Nauk, Moscow, 41–44, 1993.

Beilman, D. W., MacDonald, G. M., Smith, L. C., and Reimer, P. J.: Carbon accumulation in peatlands of Est Siberia over the last 2000 yr, Global Biogeochem. Cy., 23, GB1012, 1–12, 2009.

Belyea, L. R. and Malmer, N.: Carbon sequestration in peatland: patterns and mechanisms of response to climate change, Glob. Change Biol., 10, 1043–1052, 2004.

Blyakharchyk, T. A. and Sulerzhitsky, L. D.: Holocene vegetational and climatic changes in the forest zone of Western Siberia according to pollen records from the extrazonal palsa bog Bugristoe, The Holocene, 9, 621–628, 1999.

Boch, M. S. and Masing, V. V.: Mire ecosystems in the USSR, in: Mires: Swamp, Bog, Fen and Moor, B. Regional Studies, edited by: Gore, A. J. P., Elsevier, Amsterdam, 95–152, 1983.

Butter, D. R. and Malanson, G. P.: The geomorphic influences of beaver dams and failures of beaver dams, Geomorphology, 71, 48–60, 2005.

Chapin, F. S., Jefferies, R. L., Reynolds, J. F., Shaver, G. R., and Svoboda, J.: Arctic Ecosystems in a Changing Climate, Academic Press, San Diego, 1–469, 1992.

Charman, D. J.: Blanket mire formation at the Cross Lochs, Sutherland, northern Scotland, Boreas, 21, 53–72, 1992.

Charman, D. J., Aravena, R., and Warner, B. G.: Carbon dynamics in a forested peatland in north-eastern Ontario, Canada, J. Ecol., 82, 55–62, 1994.

Charman, D. J., Aravena, R., Bryant, C. L., and Harkness, D. D.: Carbon isotopes in peat, DOC, CO_2, and CH_4 in a Holocene peatland on Dartmoor, southwestern England, Geology, 27, 539–542, 1999.

Chasar, I. I., Chanton, J. P., Glaser, P. H., Siegel, D. I., and Rivers, J. S.: Radiocarbon and stable carbon isotopic evidence for transport and transformation of dissolved organic carbon, dissolved inorganic carbon, and CH_4 in a northern Minnesota peatland, Global Biogeochem. Cy., 14, 1095–1108, 2000.

Ciais, P., Tagliabue, A., Cuntz, M., Bopp, L., Scholze, M., Hoffmann, G., Lourantou, A., Harrison, S. P., Prentice, I. C., Kelley, D. I., Koven, C., and Piao, S. L.: Large inert carbon pool in the terrestrial biosphere during the Last Glacial Maximum, Nat. Geosci., 5, 74–79, 2014.

Clymo, R. S.: A model of peat bog growth, Ecol. Stu., 27, 187–223, 1978.

Clymo, R. S.: The limits of peat bog growth, Philos. T. R. Soc. Lon. B, 303, 605–654, 1984.

Clymo, R. S. and Bryant, C. L.: Diffusion and mass flow of dissolved carbon dioxide, methane, and dissolved organic carbon in a 7 m deep raised peat bog, Geochim. Cosmochim. Ac., 72, 2048–2066, 2008.

Firescan Science Team: Fire in ecosystems of boral Eurasia: the Bor forest island fire experiment, in: Biomass Burning and Global Change, vol. 2, edited by: Levin, J. S., MIT Press, Cambridge, 848–873, 1996.

Glebov, F. Z.: Bolota I zabolochennye lesa lesnoi zony Yeniseiskogo levoberezhya (Mires and Paludified Forests of Forest Zone of Left Bank Yenisey Region), Nauka, Novosibirsk, 1–132, 1969.

Glebov, F. Z.: Vzaimootnoshenie lesa i bolota v taezhnoi zone (Interrelation of Forest and Bogs in Taiga Zone), Nauka, Novosibirsk, 1–181, 1988.

Glebov, F. Z., Karpenko, L. V., Klimanov, V. A., and Mindeeva, T. N.: Paleoekologicheskaya kharakteristika golotsena mezhdurech'ya Obi i Vasyugana po dannym torfyanogo razreza "Vodorazdel" (Paleoecological characteristic of the Holocene according data of peat core "Vodorazdel"), Ecology, 6, 412–18, 1997.

Goldammer, J. G. and Furayaev, V. V.: Fire in ecosystems of boreal Eurasia, Forestry Science, Vol. 48, Kluver Academic Publisher, Dortrecht, 355 pp., 1996.

Gorham, E.: Northern peatlands, role in the carbon cycle and probable responses to climatic warming, Ecol. Appl., 1, 182–195, 1991.

Halsey, L. A., Vitt, D. H., and Bauer, I. E.: Peatland initiation during the Holocene in continental western Canada, Climatic Change, 40, 315–342, 1998.

Heimann, M., Schulze, E. D., Winderlich, J., Andreae, M. O., Chi, X., Gerbig, C., Kolle, O., Kübler, K., Lavric, J., Mikhailov, E., Panov, A., Park, S., Rödenbeck, C., and Sorochod, A.: The Zotino Tall Tower Observatory (ZOTTO): quantifying large scale biogeochemical changes in central Siberia, Nova Act. Lc., 117, 51–64, 2014.

Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J. W., Schuur, E. A. G., Ping, C.-L., Schirrmeister, L., Grosse, G., Michaelson, G. J., Koven, C. D., O'Donnell, J. A., Elberling, B., Mishra, U., Camill, P., Yu, Z., Palmtag, J., and Kuhry, P.: Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps, Biogeosciences, 11, 6573–6593, doi:10.5194/bg-11-6573-2014, 2014.

Il'ina, I. S., Lapshina, E. I., and Lavrenko, H. H.: Rastitelnyi pokrov Zapadno-Sibirskoy ravniny (Vegetation cover of West-Siberian plain), Nauka, Novosibirsk, 1–248, 1985.

IPCC: Climate Change 2013, The physical science basis, Cambridge University Press, Cambridge, p. 987, 2014.

Ivanov, K. E.: Water Movement in Mire Lands, translated by Thgomson, A. and Ingram, H. A., Academic Press, London 1981.

Ivanov, K. E. and Novikov, S. M.: Bolota Zapadnoi Sibiri, ikh stroenie I gidrologicheskiy rezhim (Mires of West Siberia, their Structure and Hydrological Regime), Gidrometeoizdat, Leningrad, 1976.

Karpenko, L. V.: Zotinskie bolota (Zotino mires), in: Gidromorfnye leso-bolotnye ekosistemy (Hydromorphic Bog-Forest Ecosystems), Sukachev Forest Institute SB RAN, Krasnoyarsk, 17–39, 1986.

Karpenko, L. V.: Dinamika rastitelnogo pokrova, torfonakopleniya i ugleroda a Tugulanskoy kotlovine (The vegetation, peat accumulation and carbon dynamics in Tugulan basin), Geografia I prirodnye resursy (Geography and Natural Resources), 3, 74–81, 1996.

Kauppi, P. E., Posch, M., Hänninen, P., Henttonen, H. M., Ihalainen, A., Lappalainen, E., Starr, M., and Tamminen, P.: Carbon reservoirs in peatlands and forests in the boreal regions of Finland, Silva Fenn., 31, 13–25, 1997.

Krinner, G., Mangerud, J., Jakobsson, M., Crucifix, M., Ritz, C., and Svendsen, J. I.: Enhanced ice sheet growth in Eurasia owing to adjacent ice dammed lakes, Nature, 427, 429–33, 2004.

Krivonogov, S. K.: Stratigrafiya i paleogeografiya Nizhnego Priirtyshya v epokhu poslednego oledeneniya (Stratigraphy and Paleogeography of Lower Irtysh Region in Late Glacial Time), Nauka, Novosibirsk, 1–231, 1989.

Kurbatova, J., Arneth, A., Vygodskaya, N. N., Kolle, O., Varlargin, A. V., Milyukova, I. M., Tcherbakova, N. M., Schulze, E.-D., and Lloyd, J.: Comparative ecosystem-atmosphere exchange of energy and mass in a European Russian and a central Siberian bog. I. Interseasonal and interannual variability of energy and latent heat fluxes during the snow free period, Tellus B, 54, 497–513, 2002.

Lapshina, E. D.: Dinamika nakopleniya torfa na bolotakh taezhnoi zony Zapadnoy Sibiri (Peat grows dynamics on the bogs of taiga zone of West Siberia), in: West Siberian Peatlands and Carbon Cycle: Past and Present, edited by: Vomperskiy, S. E., Novosibirsk, 38–39, 2011.

Lapshina, E. D. and Pologova, N. N.: Carbon accumulation, in: Carbon Storage and Atmospheric Exchange by West Siberian Peatlands, edited by Bleuten, W. and Lapshina, E., Utrecht University Press, Utrecht, 50–72, 2001.

Lapshina, E. D. and Pologova, N. N.: Spatial dynamics of peat grows and carbon accumulation in sphagnum bogs (boreal West Siberia), in: West Siberian peatlands and carbon cycle: past and present, edited by: Vomperskiy, S. E., Novosibirsk, 96–98, 2011.

Lazarev, A. V. and Korcchunov, S. S.: Spravochnik po turfu (peat reference book), Nedra, Mocow, Russia, 1–168, 1982.

Levina, T. P., Orlova, L. A., Panychev, V. A., and Skabichevskaya, N. A.: Paleogeografiya i radiouglerodnaya khronologiya na rubezhe pleistotsena I golotsena Predaltaiskoi ravniny (Paleogeography and radiocarbon chronology at the turn of The Pleistocene and the Holocene of the Pre-Altai plain), in:

Cainozoe of Siberia and North-East of USSR, Nauka, Novosibirsk, 668, 129–138, 1989.

Liss, O. L., Abramova, L. I., Avetov, N. A., Berezina, N. A., Inisheva, L. I., Kurnishkova, T. V., Sluka, Z. A., Tolpysheva, T. Y., and Fedchinkova, N. K.: Bolotnye sistemy Zapadonoi Sibiri I ikh prirodookhrannoe znachenie (Mire ecosystems of West Siberia and their environmental importance, Grif I Ko, Tula, 1–584, 2001.

Mäkilä, M. and Goslar, T.: The carbon dynamics of surface peat layers in southern and central boreal mires of Finland and Russian Karelia, Suo, 59, 49–69, 2008.

Mäkilä, M. and Saarnisto, M.: Carbon accumulation in boreal peatlands during the Holocene – impact of climate variations, in: Peatlands and Climate Change, edited by: Starck, M., International Peat Society, Jyväskylä, Finland, 24–43, 2008.

Matukhin, R. G., Matukhina, V. G., Vasiliev, I. P., Mikhantieva L. S., Popova, G. I., Markov, D. V., Ospennikova, L. A., and Skobeeva, E. I.: Klassifikatsiya torfov i torfyanykh zalezhey Zapadnoy Sibiri (Classification of Peat Types and Peat Deposits of West Siberia), edited by: Ulanov, N. N., SO RAN (SB RAS), NITS OIGGM, Novosibirsk, 1–96, 2000.

Moore, T. R., Roulet, N. T., and Waddington, J. M.: Uncertainty in predicting the effect of climatic change on the carbon cycling of Canadian peatlands, Climatic Change, 40, 229–45, 1998.

Naimann, R. J., Pinay, G., Johnston, C. A., and Pastor, J.: Beaver influences on the long-term biogeochemical characteristics of boreal forest drainage networks, Ecology, 75, 905–921, 1994.

Nobel, P. S.: Physicochemical and Environmental Plant Physiology, Academic Press, San Diego, 498–499, 1991.

Olyunin, V. N.: K istorii gidroseti Zapadnoy Sibiri v epokhu poslednego oledeneniya (On the drainage network evolution during the Last Glacial time), in: Evolution of Landscapes and Climates of the Northern Eurasia. Late Pleistocene–Holocene Elements of Prognosis. I. Regional Paleogeography, edited by: Velichko, A. A., Nauka, Moscow, 44–46, 1993.

Ovenden, L.: Peat accumulation in northern wetlands, Quaternary Res., 33, 377–386, 1990.

Pitkänen, A., Turunen, J., Tahvanainen, T., and Tolonen, K.: Holocene vegetation history from the Salym-Yugan Mire Area, West Siberia, The Holocene, 12, 353–62, 2002.

Pyavchenko, N. I.: Torfyanye bolota ikh prirodnoe I khozyaistvennoe znachenie (Peat Mires, their Environmental and Economic Importance), Nauka, Moscow, 1–152, 1985.

R Development Core Team: A language and environment for statistical computing, R Foundation for Statistical Computing, Vienna, Austria, 2010.

Regev, L., Eckmeier, E., Mintz, E., Weiner, S., and Boaretto, E.: Radiocarbon concentrations of wood ash calcite: Potential for dating, Radiocarbon, 53, 117–127, 2011.

Reimer, P. J., Baillie, M. G. L., Bard, E., Bayliss, A., Beck, J. W., Bertrand, C. J. H., Blackwell, P. G., Buck, C. E., Burr, G. S., Cutler, K. B., Damon, P. E., Edwards, R. L., Fairbanks, R. G., Friedrich, M., Guilderson, T. P., Hogg, A. G., Hughen, K. A., Kromer, B., McCormac, G., Manning, S., Ramsey, C. B., Reimer, R. W., Remmele, S., Southon, J. R., Stuiver, M., Talamo, S., Tylor, F. W., van der Plicht, J., and Weyhenmeyer, C. E. : Intcal04 terrestrial radiocarbon age calibration, 0–26 Cal kyr BP, Radiocarbon, 46, 1029–1058, 2004.

Romanov, V. V.: Hydrophysics of Bogs, Israel Program for Scientific Translations, Jerusalem, 1968.

Romanova, E. A.: Obshchaya kharakteristika bolotnykh landshaftov (General characteristic of mire landscapes), in: Bolota Zapadnoi Sibiri, ikh stroenie I gidrologicheskiy rezhim (Mires of West Siberia, their Structure and Hydrological Regime), edited by: Ivanov, K. E. and Novikov, S. M., Gidrometeoizdat, Leningrad, 19–39, 1976.

Schulze, E- D., Prokushkin, A., Arneth, A., Knorre, N., and Vaganov, E. A.: Net ecosystem productivity and peat accumulation in a Siberian Aapa mire, Tellus B, 54, 531–36, 2002.

Schuur, E. A. G., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., Hugelius, G., Koven, G. D., Kuhry, P., Lawrence, D. M., Natal, S. M., Olefeldt, D., Romanowsky, V. E., Schäfer, K., Turetsky, M. R., Treat, C. C., and Vonk, J. E.: Climate change and the permafrost carbon feedback, Nature, 520, 171–179, 2015.

Sheng, Y., Smith, L. C., MacDonald, G. M., Kremenetski, K.V, Frey, K. E., Velichko, A. A., Lee, M., Beilman, D. W., and Dubinin, P.: A high resolution GIS-based inventory of the West Siberian peat carbon pool, Global Biogeochem. Cy., 18, 1–14, 2004.

Shibistov, B. V. and Schulze, E.-D.: Geology and Landscapes of Central Siberia, Museum of Geology of Central Siberia, Krasnoyask, 1–183, 2007.

Siegel, D. I. and Glaser, P. H.: Groundwater flow in a bog-fen complex, Lost River Peatland, Northern Minnesota, J. Ecol., 75, 743–54, 1987.

Smith, L. C., MacDonald, G. M., Velichko, A. A., Beilman, D. W., Borisova, O.K, Frey, K.E, Kremenetski, K. V., and Sheng, Y.: Siberian peatlands a net carbon sink and global methane source since the early Holocene, Science, 303, 353–56, 2004.

Steinhof, A., Adamiec, G., and Gleixner, G.: The new C-14 analysis laboratory in Jena, Radiocarbon, 46, 51–58, 2004.

Tchebakova, N. M., Parfenova, E. I., and Soja, A. J.: Climate change and climate-induced hot spots in forest shifts in central Siberia from observed data, Reg. Environ Change, 11, 817–827, doi:10.1007/s10113-011-0210-4, 2011.

Tolonen, K. and Turunen, J.: Accumulation rates of carbon in mires in Finland and implications for climatic change, Holocene, 6, 171–178, 1996.

Trumbore, S.: Radiocarbon and soil carbon dynamics, Annu. Rev. Earth Pl. Sc., 37, 47–66, 2009.

Turunen, J.: Carbon accumulation of natural mires ecosystems in Finland – application to boreal and subarctic mires, University of Joensuu Publication in Sciences, 55, 1–30, 1999.

Turunen, J., Tomppo, E., Tolonen, K., and Reinikainen, A.: Estimating carbon accumulation rates of undrained mires in Finland – application to boreal and subarctic regions, Global Biogeochem. Cy., 12, 69–80, 1999.

Turunen, J., Pitkänen, A., Tahvanainen, X., and Tolonen, K.: Carbon accumulation in West Siberian mires, Russia, Global Biogeochem. Cy., 15, 285–97, 2001.

Vajda, E. J.: Yeniseian Peoples and Languages: a History of Yeniseian Studies with an Annotated Bibliography and a Source Guide, Curzon Press, Surrey, 363 pp., 2001.

Waddington, J. M. and Roulet, N. T.: Groundwater flow and dissolved carbon movement in a boreal peatland, J. Hydrol., 191, 122–138, 1997.

Wirth, C., Schulze, E.-D., Schulze, W., von Stunzner Karbe, D., Ziegler, W. Miljukova, I. M., Sogatchev, A., Varlygin, A. V., Panvyorov, M., Grigoriev, S., Kusnetzova, W., Siry, M., Hardes, G., Zimmermann, R., and Vygodskaya, N. N.: Above-ground biomass and structure of pristine Siberian Scots pine forests as controlled by competition and fire, Oecologia, 121, 66–80, 1999.

Yu, Z. C.: Northern peatland carbon stocks and dynamics: a review, Biogeosciences, 9, 4071–4085, doi:10.5194/bg-9-4071-2012, 2012.

Zoltai, S. C., Taylor, S., Jeglum, J. K., Mills, G. F., and Johnson, J. D.: Wetlands of boreal Canada, Wetlands of Canada, Ecological Land Classification Series, 24, 97–154, 1988.