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Carbon dynamics in boreal peat-lands of the Yenisey region, Western Siberia

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Abstract

Here we investigate the vegetation history and peat accumulation at the eastern boarder of the West Siberian plain, near the river Yenisey, south of permafrost. In this region peat started to accumulate 15 000 yr ago as gyttia 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 to 6500 yr younger than POC. The probability to finding peat layers older than 12 000 yr 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. Since 2000 yr these bogs changed into *Sphagnum* mires which accumulate 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 West Siberian bogs is discussed as a consequence of the local hydrology. The high accumulation rate of peat in un-frozen mires is taken as an indication that thawing of permafrost peat may change northern peatlands also into long-lasting carbon sinks.

1 Introduction

Peatlands are a main component in the global terrestrial carbon pools and thus of special importance in the global carbon cycle (Gorham, 1991; Ciais et al., 2014; Schurr 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; Schurr 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 (Schurr et al., 2015), and the West Siberian plain along the Ob and Yenisey rivers

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contains one of the world's largest peat lands ranging from the permafrost in the arctic to the un-frozen southern boreal region. Thus, this peat land area extending far into the non-permafrost region may serve as example of peat-land behavior 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 peat lands of the Yenisey Rivers watershed remain fairly unknown even though they cover about 40 to 50 % of the land surface between Ob (78° E) and Yenisey (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 had not been glaciated during the Pleistocene. The maximum extent of glaciations in the Pleistocene (900–400 thousand 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 Artic ocean coast line and the Taimyr Peninsula 90 thousand years ago (Astakhov, 1993). The West bank of Yenisey appears to have been a flat landscape with rivers draining to the West. The geomorphological situation is further complicated by the fact, that the West bank of Yenisey is known as the Tugulan depression (Arkhipov, 1993; Karpenko, 1986, 1999; 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) already pointed out that ground water fed peatlands are widespread in this region. The age of these peatlands was determined to range between 6245 ± 65 and 9025 ± 180 yr of ^{14}C-age before present (Karpenko, 1996, 2006, 2014) which translates into a calibrated age of about 7000 to 10 000 before present (cal BP). The peat carbon accumulation rate was estimated to be 38.6 and 26.9 g C m^{2} yr^{-1} based

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on bulk densities from Naumov et al. (1994), and C-contents from Pyavchenko (1985), respectively.

In the following we investigate the boreal peatlands of Western Yenisey. Based on the present land cover we are interested in the variation of 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 contributories, 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 West 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 maintained 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 West Siberia (60 to 61° N, 89 to 90° E) between two tributaries of Yenisey, the Sym and the Dubches River (Fig. 1). The total area of investigation covers about 7500 km^2 (a circle about of 90 km diameter), 40 % of which is peatland, 60 % are 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 coast-line to the Taimyr Peninsula with a lake piling up in front of this ice barrier mainly in the Ob-river basin. The Yenisey

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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 un-frozen soil may serve as 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* 10 to 20 thousand years before present (BP). Following the Boelling and Alleroed period (14.7–12.7 thousand years cal. 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 Boelling warm period when trees were present close to modern northern tree line (Krivonogov, 1989).

The present relief between Ob and Yenisey rivers consists of shallow valleys and ridges made of Pleistocene alluvial sands and clays. Altitudes vary from 60 to 120 m a.s.l., with highest elevations (146 to 155 m NN) 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 main annual temperature is -3.5 ± 1.3 °C (1936–2012), ranging from -26 °C mean temperature in January to ± 18 °C mean daily temperature 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 snow melt (Ivanov, 1981).

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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 to 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 maintaining positive water balance despite runoff of snow melt, 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 peat-land types and peat stratigraphy

Presently three major groups of peatland types occur in the study region: (a) rain-fed bogs, which rise above the ground-water level and cover about 80 % of the peatland area, (b) run-off and groundwater-fed fens covering about 13 % of peatland area, (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* ssp. and *Calliergon* ssp.

3. Woody and sedge-woody peat consisting of roots and fallen stems of trees (*Pinus* ssp., *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*;

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6. *Scheuchzeria* peat, formed by the 10 to 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, *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 1; 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 peat land 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 (Supplement S1).

3 Methods

3.1 Vegetation survey and sampling of peat profiles

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

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A total of 28 cores were drilled with a corer of 3.5 cm diameter. Every 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 half meter for ^{14}C dating of the horizon. Macrofossil analyzed and C contents were measured in the remaining 7 to 8 cm thick sample of each 10 cm segment. A total of 590 peat samples were analyzed.

3.2 Plant macrofossil

Fossil plant remains were identified under the microscope, 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 weight of a $10\,cm^3$ sub-sample from the upper 2 cm thick slice taken for bulk density analysis from each 10 cm core segment after drying at 100 °C during 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.

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3.4 AMS 14C analysis

Peat core chronologies were obtained from AMS radiocarbon (^{14}C) analysis (Table S1). Radiocarbon measurements were carried out at the Max Planck Institute of Biogeochemistry in Jena (Germany). We separate dissolved organic carbon from particulate organic matter by dispersing peat samples in double-distillated water (1 : 4 by weight) by shaking for 2 h. The material was then wet-sieved and freeze-dried. The fraction of > 36 µm and < 63 µm was adjusted to pH 9 by adding NaOH and centrifuged at 2900 g. The frieze-dried pellet was taken as Particulate Organic Matter (POC) and the frieze-dried supernate as Dissolved Organic Matter (DOC). Both fractions were analyzed for ^{14}C analysis using an accelerated 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 comparing the ^{14}C spectra of the AMS with the ^{14}C standard of the Northern Hemisphere using Oxcal (https://c14.arch.ox.ac.uk/embed.php?File=index.html, Reimer et al., 2004). The ^{14}C standard was calibrated.

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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; Supplement 2).

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 (gyttia) of 15 925 ± 65 yr cal. BP (Core 14) and 13 285 ± 37 yr cal. BP (Core 11 see also Table S1 in the Supplement). Only three cores (profile 10, 11, 14; 10 % of all profiles) started from gyttia. The next oldest profiles (28 and 29: Fig. 2; Table S1) started from mineral soils and not from gyttia at 12 421 ± 104 yr cal. BP (Core 28) and 11 950 ± 120 yr cal. BP (Core 29), indicating that at that time the region was a variegated landscape with shallow lakes producing gyttia and upland sites on mineral sand or clay. The oldest gyttia (Cores 11 and 14) was found near 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 yr cal. BP ranging from 525 to 15 606 yr. The organic matter at the bottom of the core 29 containing a mixture of organic and inorganic material (peaty-clay) was about 4000 yr 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 yr 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 yr cal. BP. 15 % of the cores started between 2000 and 5000 yr cal. BP also as herbaceous fens, forested swamps and pine-cotton grass bogs (Cores 1, 3a, 4, 19, 23) also on mineral soil, and 8 % of the cores started less than 2000 yr ago (cal. BP) as rain-fed cotton grass-sphagnum bogs and swampy dark coniferous forests also on mineral soil. Only about 1000 yr cal. BP, *Sphagnum* peat started 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.

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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} since 15 000 yr cal. BP (Fig. 3a, closed circles, r^2 of linear regression = 0.87). Profiles in the ancient valleys of Khoiba (Cores 13) and Dubches River (Cores 28, 29) accumulated at a higher rate in the early Holocene between 8000 and 12 000 yr cal. BP (0.77 mm yr^{-1}, slope of regression r^2 = 0.95; Fig. 3a, open circles). The data points above the regression line during the past 2000 yr cal. BP are taken as an indication of a more rapid peat depth accumulation rate when the rain-fed Sphagnum bogs appeared. These data are however within the 95 % confidence line of the regression. The regression line in Fig. 3 has an *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) had generally 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 peat, which is dominated mainly by *Sphagnum* moss, the DOC-age is 180 to 1775 yr younger than POC (Cores 11, 13, 15, 17,26) (see also Supplement S2). The maximal difference in upper layers was recorded 2620 yr. The weight of DOC as fraction of total carbon (DOC/TOC) is 18.9 ± 17.3 %.

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 yr years. The maximum age-difference between DOC and POC was 5370 to 6500 yr cal. BP at the peat base, which is of the same order as the age difference between the bottom peat layer and the under-laying mineral-organic deposit (Fig. 3a).

4.2 Bulk density and ash concentration

The average bulk density (g_{dw} cm^{-3}) was 0.23 ± 0.20 g_{dw} cm^{-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 of 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, open symbols) 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).

4.3 Carbon contents

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

Carbon accumulated at constant concentration (Supplement S3) and a linear rate over the past 15 000 yr 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 flood-plains had a higher initial accumulation rate (between 12 000 and 8000 yr 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 is 52 ± 23 g C m^{-2} yr^{-1} since about 1000 yr 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 to 62 g C m^{-2} yr^{-1}, Kurbatova et al., 2002) and by 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).

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

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5 Discussion

5.1 Maximum peat age

Carbon started to accumulate from gyttia more than 15 000 yr 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. These data are about 2000–4000 yr earlier than previously reported for this region (Karpenko, 1996: 9025 ± 180 yr ^{14}C-age, equaling 10 200 yr cal. BP) and from the West Siberian lowland (Smith et al., 2004: 9000 to 11 500 yr cal. BP). The peat at the base of the Salym-Yugan Mire at the same latitude of our study area in West Siberia was 12 305 yr cal. BP based as measured 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 to 9000 yr cal. PB) and in Canada (Zoltai et al., 1988; Halsey et al., 1998: 10 000 to 8000 yr cal. BP). It appears likely that the peatlands between Sym and Dubches rivers initiated in the very Early Holocene following the Alleroed (14 700–12 700 yr cal. PB). 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 the 29 cores taken in this study, the chance to reach a horizon that is older than 12 000 yr is about 2 %. The study sites experienced no large scale flooding events since glaciation. Mineral sediments were only found in the bottom layers of peat deposits.

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5.2 Peat landscape development

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.

After melt of the northern ice sheet, the Yenisey did not anymore drain 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 gyttia sequence of the fen development. With ongoing development of the post-Pleistocene drainage system, *Equisetum fluviatile* established which is a relatively short plant species (up to 1 m tall), which grew with a rising water table. *Equisetum* was followed by various *Carex* and *Menyanthes* communities which accumulated peat at almost constant rate, independent of the vegetation type. Peatlands did not only gain depth, but expanded in area since 12 000 yr.

About 1000 to 2000 yr 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 to groundwater. Forests could not establish on fen peat but *Carex* rather than *Menyanthes* dominated the vegetation. We can only speculate about the causes of the rise of fen profiles and the following change into *Sphagnum* peat which appears to be special for this region.

In the initial phase, peatland probably filled up the existing relief until rivers cut their new drainage system through this region. Following Darcy's law (Nobel, 1991) the flow

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of water through a saturated substrate is determined only by the pressure difference between the peat surface and the drainage system and not by the hydraulic conductance, it remains difficult to explain the rise of ground water above the drainage system. The subsidence of the Tugulan depression (Arkhipov, 1993) appears not to be large enough to explain 6 m of fen profiles. However, with the change in the drainage direction the topography did change, and the present up-hill Pine forests indicate periods of erosion. Thus, the landscape had initially a larger fraction of Pine vs. peatland, and the excess water from the pine-land would contribute to the water table of the lowland. Figure 7 suggests that the area of Pine-land continually decreased while the peatland expanded. This change in land-cover does not explain the constant rise of the water table, and the change towards a *Sphagnum* cover. It is possible, that the drainage system changed at that time when *Sphagnum* became dominant. The only biological agent that could affect the regional hydrology would have been the beaver, which might have been affected by the migration of the Ket people into the Jennisey basin 2000 yr ago (Vajda, 2001). Due to hunting the beaver was almost extinct by end of 19th century (Ducroz et al., 2005).

The present hydrological balance of the growing season is close to nil, and would not support ombrotrophic bogs. The contribution of winter precipitation depends on the timing of frost vs. snow fall. Most of the snow melt is lost by flooding, but it was estimated in West Siberia that about 20 % of snow water may contribute to the peat water balance. A contribution of water from up-land Pine forest emerges as 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 represents the present water balance, where up-land spring water emerging from Pine forest support fens close to the forest edge which would then help to maintain the water table in the a *Sphagnum* dominated “ridge-hollow complex”. The ridges indicate a lateral flow of water even at rather low elevation differences.

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5.3 Peat and Carbon accumulation

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

The change from fen-type vegetation towards rain-fed bogs is the only change which results in an increased peat accumulation over the past 500 to 1000 yr, following 10 000 yr of constant 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 resulted in an increased peat production. Eddy covariance measurements and the Pine method (Arneth et al., 2002; Schulze et al., 2002) indicate modern accumulation rates for the Yenisey region similar to those in West 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, but 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 of fen plants. Since mosses have a lower rate of photosynthesis than herbaceous angiosperms, we do not think that primary productivity increased.

In comparison, in Finland the Holocene average C accumulation rate estimation varied from 19.8 to 26.1 gC m^{-2} yr^{-1} in raised bog region and from 14.6 to 17.3 gC 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 gC m^{-2} yr^{-1} (Ovenden, 1990), with average value 29 gC m^{-2} yr^{-1} (Gorgam, 1991). The long-term C accumulation rate in 32 sites from Alaska to Newfoundland was 25 gC m^{-2} yr^{-1} (Gorham et al., 2003 as cited by Mäkilä and Saarnisto, 2008), what is close to the Middle boreal zone of West Siberia and significantly higher than in our study region. High peat

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accumulation rate occurred only in old river valleys (Core 28, 29) and ancient valleys depressions (Core 13) in Late Glacial and Early Holocene (12 000–8000 yr 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 downwards by gravitation (Siegel and Glaser, 1987; Waddington and Roulet, 1997). This observation of young DOC confirms studies from Western Europe and Canada (Arevena et al., 1993; Charman et al., 1994, 1999; Clymo and Bryant, 2008). Also other studies 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 differences recorded between DOC and POC was 5370–6500 yr 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 rain water presses or pumps part of the existing water column into the groundwater, and thus young DOC moves downward always replacing old by 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 that water may move also in lateral direction (see Fig. 3 DOC outlayer).

Contrasting 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 repeatedly (Charman et al., 1994; Pitkanen et al., 2002; Turunen et al., 2001) and in blanket bogs of Britain (e.g. Charman, 1992). 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 showed no effect of climate changes over the past 10 000 yr. Peat accumulation of the fen-type bogs is determined by the regional hydrology and the water table. The plant species cover and peat type adjusts to changes in climate and hydrology. There is a substantial increase in peat accumulation over the past 1000 yr when *Sphagnum* covered the fen-type landscape. There is no indication of a 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. Thus, extrapolating from the un-frozen Yeinsey profiles, which contain 3 to 5 times as much C as the closely adjacent peat on permafrost (Schurr et al., 2015), we would envisage an increased peat accumulation with permafrost thawing in regions of a positive water balance.

6 Conclusions

The present study suggests that peat in the Yenisey region south of the permafrost line is considerably older than previously reported. Peat started to accumulate with the retreat of the northern ice sheet. The specific situation of the Dubces/Sym region results in an extremely long fen period which may be associated with the formation of a new post-Pleistocene drainage system. The presently observed mires maintain their water balance in part from snow melt and in part by water from up-hill Pine forest.

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DOC flux could potentially be quite large, and it may move laterally by pressure gradients rather then through base sediments.

The total amounts of peat that accumulated since the Pleistocene 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.

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Author contributions. E. D. Schulze wrote the manuscript, E. Lapshina supervised the sample preparation, I. Filippov headed the field work, I. Kuhlmann invented the DOC-POC seperation, D. Mollicone initiated the study and produced the satellite maps as basis of the survey.

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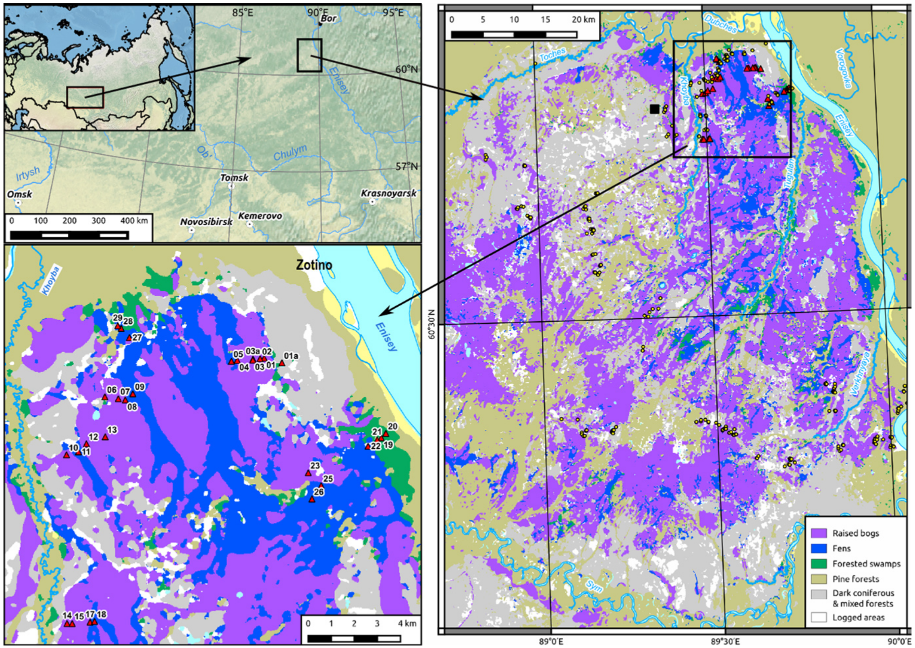

Figure 1. Map of study area with present-day peatland types and surrounding upland vegetation. Zotino Tall tower: black square (Heimann et al., 2014); vegetation relevés: yellow circles, peat cores: red triangles with core numbers on magnified map.

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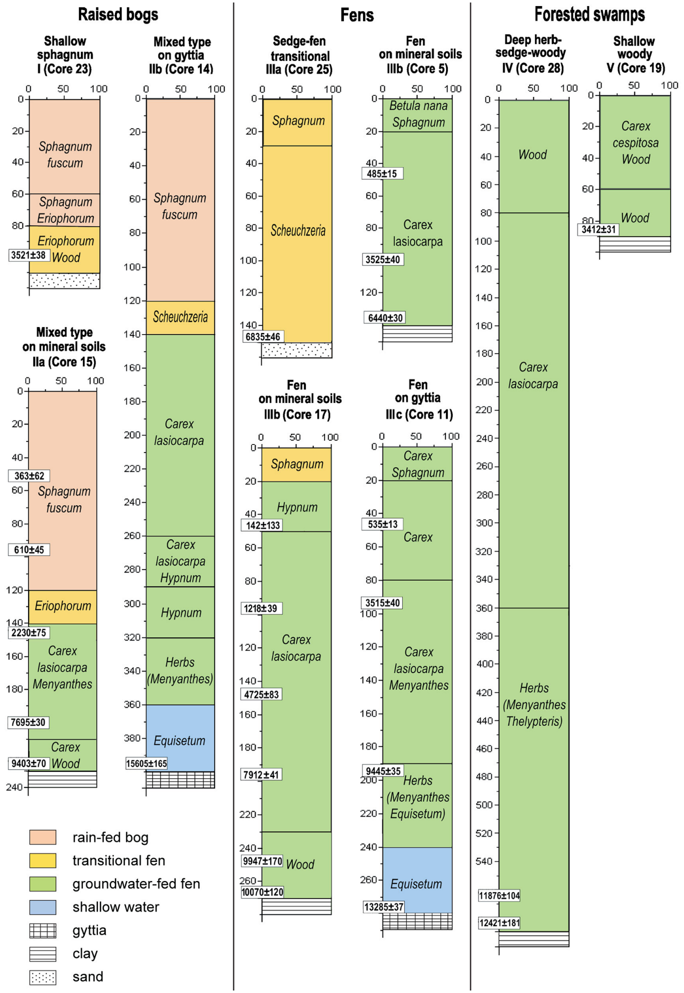

Figure 2. Main types of peat profiles of various peatlands in the study area.

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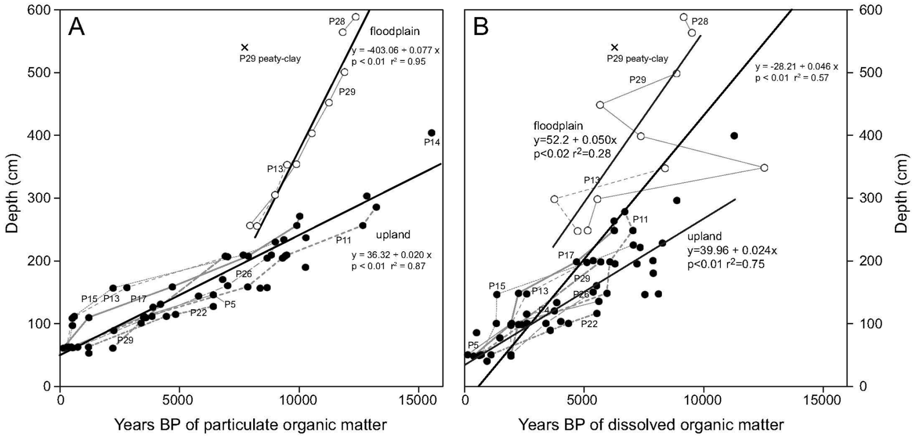

Figure 3. Relations between ^{14}C-POC age **(a)** and ^{14}C-DOC age **(b)** and peat profile depth. Un-filled circles: lake sediments and peat originating from ancient river valleys; filled circles: lake sediments and peat developed outside of old river valleys. The single data point of high DOC age is probably caused by lateral water flow in the old river channel. The point was not included in the regression.

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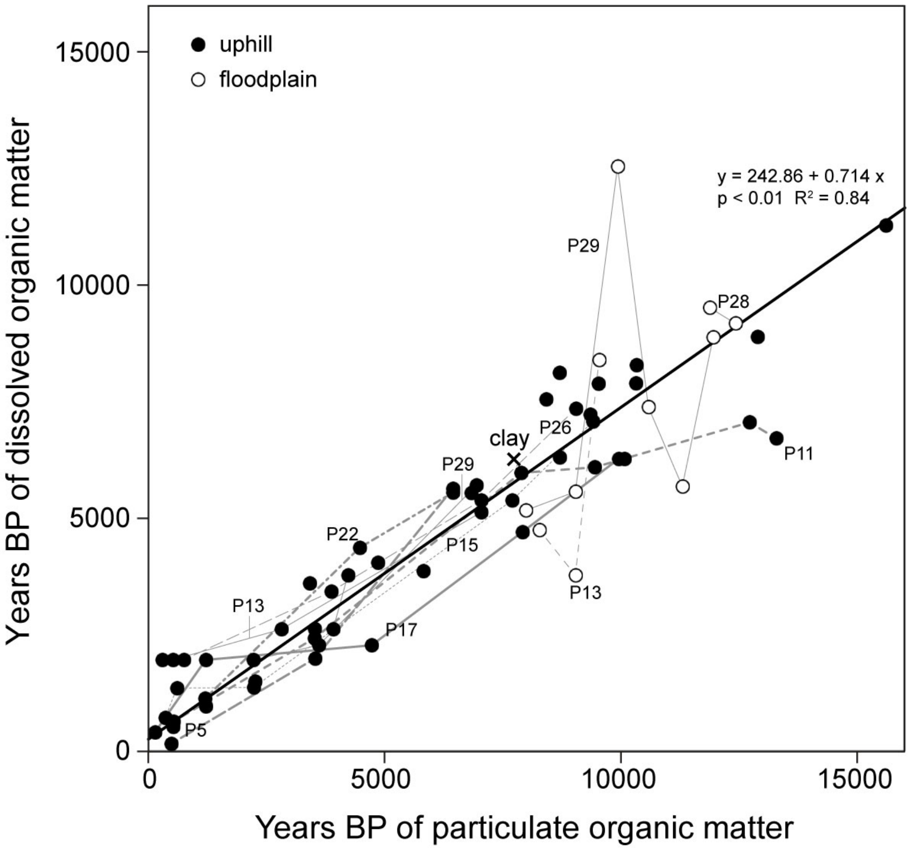

Figure 4. Linear relationship between DOC and POC-^{14}C ages with RMA regression.

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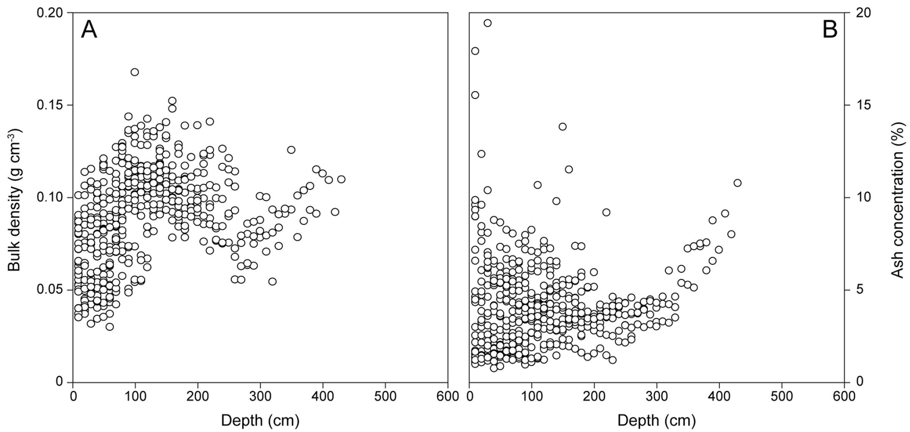

Figure 5. (a) Bulk density and **(b)** ash content as related to profile depth

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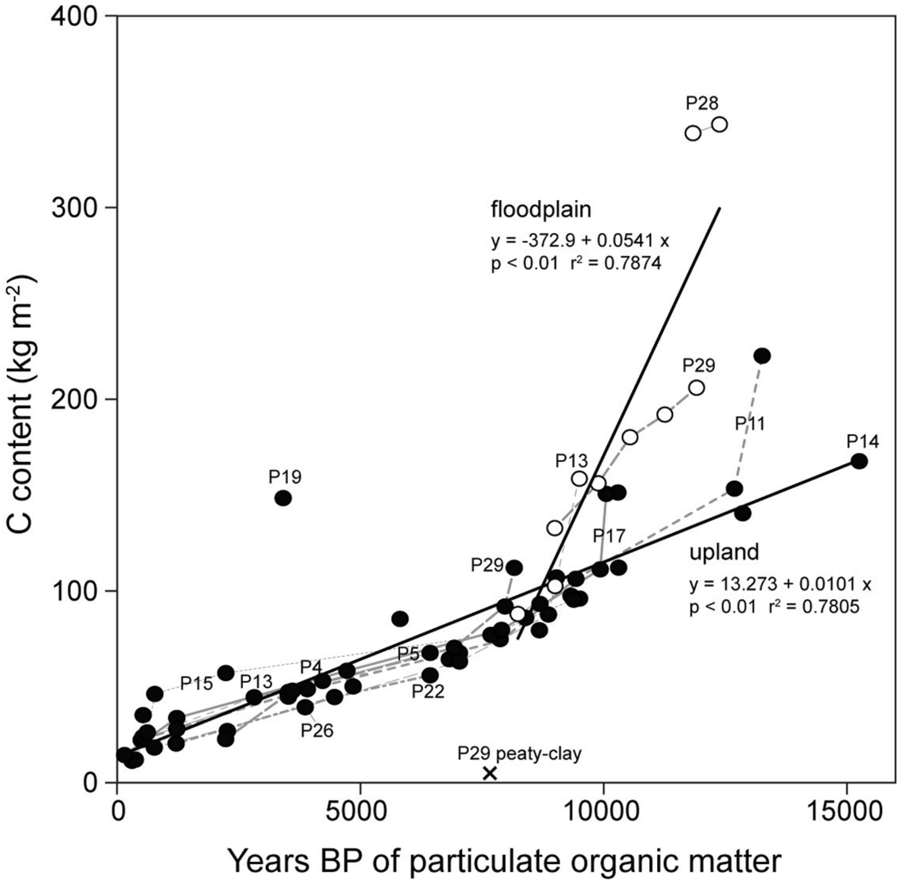

Figure 6. Cumulative carbon content in different profiles as related to the 14C-age at the bottom or at intermediate sections of the profile. Un-filled circles: lake sediments and peat originating from ancient river valleys; filled circles: lake sediments and peat developed outside of old river valleys.

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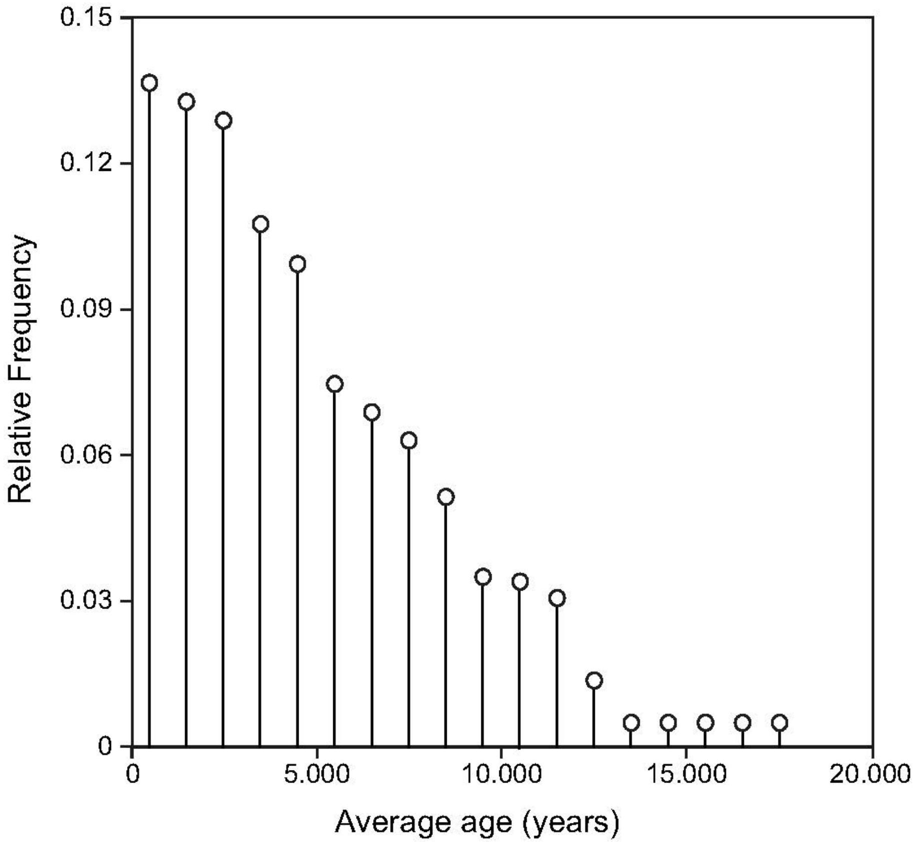

Figure 7. Histogram of the relative frequency of POC age in 610 tiles of 10 cm thickness of 29 peat cores as related to age classes of 1000 yr.

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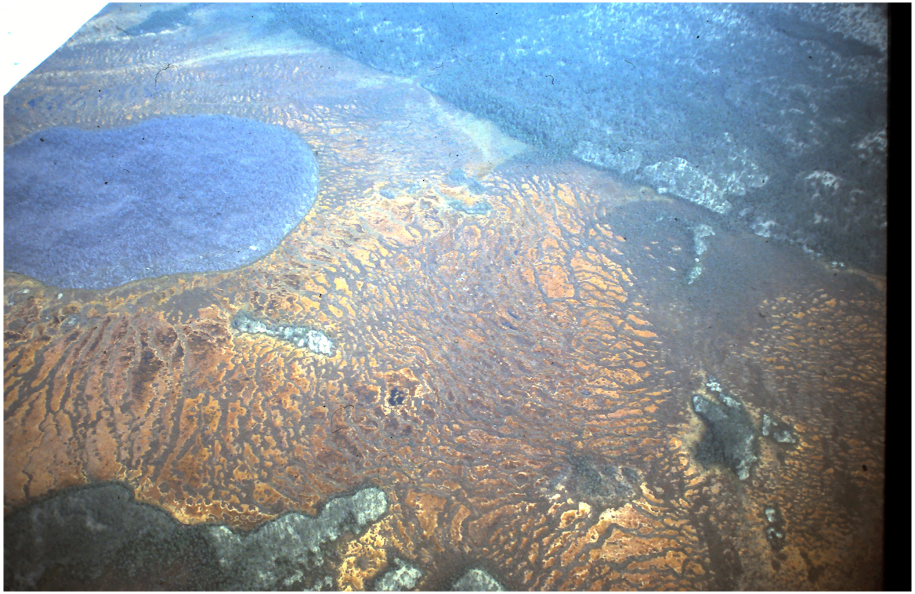

Figure 8. Aerial photograph of part of the study region with Pine forest on alluvial sand at the upper right corner, the light-green fens close to the forest edge and a banded ridge-hollow-mire in the center. The round-shaped dark colored area on the left upper edge is Bor Island which served for an experimental forest fire (Firescan Science Team, 1996).

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