Holocene peat and carbon accumulation rates in the southern taiga of western Siberia

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Abstract

Although recent studies have recognized peatlands as a sink for atmospheric CO₂, little is known about the role of Siberian peatlands in the global carbon cycle. We have estimated the Holocene peat and carbon accumulation rate in the peatlands of the southern taiga and subtaiga zones of western Siberia. We explain the accumulation rates by calculating the average peat accumulation rate and the long-term apparent rate of carbon accumulation (LORCA) and by using the model of Clymo (1984, Philosophical Transactions of the Royal Society of London Series B 303, 605–654). At three key areas in the southern taiga and subtaiga zones we studied eight sites, at which the dry bulk density, ash content, and carbon content were measured every 10 cm. Age was established by radiocarbon dating. The average peat accumulation rate at the eight sites varied from 0.35 ± 0.03 to 1.13 ± 0.02 mm yr⁻¹ and the LORCA values of bogs and fens varied from 19.0 ± 1.1 to 69.0 ± 4.4 g C m⁻² yr⁻¹. The accumulation rates had different trends especially during the early Holocene, caused by variations in vegetation succession resulting in differences in peat and carbon accumulation rates. The indirect effects of climate change through local hydrology appeared to be more important than direct influences of changes in precipitation and temperature. River valley fens were more drained during wetter periods as a result of deeper river incision, while bogs became wetter. From our dry bulk density results and our age–depth profiles we conclude that compaction is negligible and decay was not a relevant factor for undrained peatlands. These results contribute to our understanding of the influence of peatlands on the global carbon cycle and their potential impact on global change.

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Keywords: Peat; Carbon accumulation; Bogs; Fens; Taiga; Holocene; Siberia

Introduction

Recent studies of the world’s global carbon cycle and global climatic change have recognized the importance of mires (undrained peatlands) as a sink of atmospheric CO₂ (e.g., Tolonen and Turunen, 1996; Vitt et al., 2000; Wieder, 2001). In contrast to other terrestrial ecosystems, for example forests, mires are able to store carbon for many thousands of years. Besides, at present the carbon stock in peatlands is higher than that in forests. Apps et al. (1993) and Gorham (1991) indicated that boreal and subarctic peatlands accumulated 4.19 to 4.55 × 10¹⁵ g carbon. In comparison, boreal forests including dead wood and soil organic matter contain 2.90 to 3.85 × 10¹⁷ g carbon (Apps et al., 1993; Goodale et al., 2002) and the amount of carbon in the atmosphere is approximately 7.20 × 10¹⁵ g (Falkowski et al., 2000).

Today most peatlands are situated in the subarctic and boreal zones of the North American and Eurasian continents (Immirzi et al., 1992; Lappalainen, 1996). A large area of these peatlands appears to be situated in the western Siberian lowlands of Russia. Although many researchers have studied the Holocene development of peatlands in North America and Europe, only a few have reported data from the Russian peatlands in western scientific literature. Kremenetski et al. (2003) provided an overview of existing data for the western Siberian peatlands. They estimated that roughly 5.4 × 10¹⁶ g carbon is stored in these peatlands. Botch et al. (1995) gave an estimate of the carbon sequestration rate in European Russia and western and middle Siberia of 4.6 × 10¹³ g C yr⁻¹. For raised string-hollow bogs they found an accumulation rate of 2.15 × 10¹³ g C yr⁻¹, whereas Turunen et al. (2001) found about half of this value. Differences between these two studies can be explained by different peatland types, such as fens and forested bogs, or if the studied locations are not representative of western Siberia. There is also uncertainty about the present rate of carbon accumula-
tion in western Siberia, for which values are found ranging from $2.0 \times 10^{13}$ g C yr$^{-1}$ (Kobak et al., 1998; Kolchugina and Vinson, 1998).

In order to get a complete picture of the global carbon cycle, it is necessary to take the western Siberian carbon-accumulating ecosystems into account. Questions still to be solved are: at what rate have western Siberian peatlands been growing and how much carbon is stored in these peatlands? Our aim was to calculate the Holocene peat and carbon accumulation rates in southern taiga peatlands of western Siberia and to explain the variation in these rates. We achieved this by calculating the long-term apparent rate of carbon accumulation (LORCA) of various peatland types and by using the model of Clymo (1984). Variations in

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*Fig. 1. Location of the key areas. K = 86-Kvartal, P = Plotnikovo, V = Vasyugan.*
accumulation rate were studied by calculating the accumulation rates for some periods of the Holocene.

Site description

For this study a total of eight sites in three key areas were selected in western Siberia, a region bordered by the Ural Mountains in the west, the Yenisey River in the east, the Kara Sea in the north, and the Altai Mountains and Kazakh Mountains in the west, the Yenisey River in the east, the Altai Mountains, and the Kazakh Mountains in the west. The key areas are located in two bioclimatic zones (Il’ina et al., 1985; Katz, 1971; Romanova, 1976) and the eight drilling sites within these key areas represent different peatland types.

The key area “86-Kvartal” (56°20’N, 84°35’E) at the watershed between the rivers Ob and Tom is located within the birch–aspen forest zone or subtaiga zone. At this location three different peatland sites were selected: a river valley fen covered by a sedge-brown moss vegetation, a forested fen, and a “ryam” on a raised bog. The Russian term “ryam” refers to the relatively dry parts of an ombrotrophic bog where the vegetation consists of pines, dwarf shrubs, and Sphagnum species.

In the neighborhood of the village of “Plotnikovo” we studied a transect at the bog complex between the small rivers Bakchar and Iksa (56°51’N, 82°50’E). The transect connects two ryam sites and crosses a sedge–Sphagnum through-flow fen. The area belongs to the southern taiga subzone.

The key area “Vasyugan” is located in the central part of the largest undivided, undrained peat bog in the world (Great Vasyugan Bog Complex), covering an area of more than 6 × 10^8 km^2 situated on the watershed between the rivers Ob and Irtish. The vegetation of the studied site belongs to the southern taiga subzone (56°50’N, 78°25’E). The selected peatland is of the “ryam” type.

The actual climate at the key areas is strictly continental, with a mean annual temperature around 0°C (Bleuten and Lapshina, 2001). Average monthly temperature varies from −20°C in January to +19°C in July. More than 2/3 of the total annual precipitation of 500 mm comes as summer rain. Average winter snow depth is 0.25 to 0.45 m.

Methodology

The average rate of peat and carbon accumulation of a peat layer can be calculated by dividing the amount of accumulated peat and carbon by the corresponding time interval. This assumes that a peat layer remains intact once it is formed and that the accumulation rate is equal to the production rate. For the total peat layer, this gives the long-term apparent rate of carbon accumulation (LORCA). It is called an apparent rate because it is calculated from the thickness of the peat deposits, while neglecting peat decomposition. Therefore this method underestimates the calculated production rates when there is any peat decay. The model of peat accumulation proposed by Clymo (1984) takes both production and decay into account. The main assumptions of this model are:

- production and decay differ between the acrotelm and catotelm layers—i.e., aerobic and anaerobic conditions;
- the amount of decay is proportional to the amount of accumulated peat mass;
- production and decay are constant over time;
- compaction is negligible.

In our study we used the peat accumulation equation for the catotelm, which is the anaerobic zone beneath the lowest water table,

\[ \frac{dx}{dt} = p - \alpha x, \]  

(1)

where \( x = \) total accumulated dry matter (or carbon) per unit area, \( p = \) rate of addition of dry matter (or carbon) per unit area, i.e., production rate, \( \alpha = \) decay constant. Solved for \( x \) as a function of \( t \) this becomes

\[ x = \frac{p}{\alpha} (1 - e^{-\alpha t}). \]  

(2)

Eq. (2) allows the computation of an age–mass profile, which can be converted to an age–depth profile if the dry bulk density (\( \rho \)) is known. In the case where \( \rho \) is constant the depth is calculated by \( x/\rho \).

In order to calculate the LORCA and Holocene variations in peat and carbon accumulation as well as to fit the Clymo model we

- collected continuous peat samples over the whole peat depth;
- measured the dry bulk density and the organic matter content of all samples;
- determined the peat type of all samples;
- analyzed the carbon content of various peat types;

<table>
<thead>
<tr>
<th>Peat type</th>
<th>Carbon content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ombrotrophic peat</strong></td>
<td></td>
</tr>
<tr>
<td>Herb – moss</td>
<td>51.3 ± 3.6</td>
</tr>
<tr>
<td>Moss</td>
<td>49.0 ± 1.1</td>
</tr>
<tr>
<td>Sphagnum fuscum</td>
<td>47.7 ± 2.5</td>
</tr>
<tr>
<td><strong>Transitional peat</strong></td>
<td></td>
</tr>
<tr>
<td>Wood</td>
<td>55.7 ± 2.5</td>
</tr>
<tr>
<td>Wood – herb</td>
<td>52.2 ± 2.2</td>
</tr>
<tr>
<td>Herb</td>
<td>55.1 ± 1.6</td>
</tr>
<tr>
<td>Wood – moss</td>
<td>54.9 ± 0.6</td>
</tr>
<tr>
<td>Moss</td>
<td>48.6 ± 3.4</td>
</tr>
<tr>
<td><strong>Minerotrophic peat</strong></td>
<td></td>
</tr>
<tr>
<td>Wood</td>
<td>52.8 ± 4.2</td>
</tr>
<tr>
<td>Wood – herb</td>
<td>54.3 ± 2.8</td>
</tr>
<tr>
<td>Herb</td>
<td>54.5 ± 2.5</td>
</tr>
<tr>
<td>Herb – moss</td>
<td>51.6 ± 2.8</td>
</tr>
<tr>
<td>Moss</td>
<td>50.4 ± 2.8</td>
</tr>
</tbody>
</table>
determined the carbon content of all samples using the carbon content of the peat types; dated peat samples at various depths. At every site we drilled with a Russian peat sampler. The Russian peat sampler collects a peat core of diameter 0.04 m and length 0.5 m. From the 0.5-m cores we

### Table 2
Radiocarbon dates and calibrated ages of peat samples from the studied sites

<table>
<thead>
<tr>
<th>Key area and site</th>
<th>Sample depth (m)</th>
<th>Laboratory number</th>
<th>Age (±1σ) (14C yr B.P.)</th>
<th>Calibrated age (2σ range and median value) (cal yr B.P.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zh0</td>
<td>0.90–1.00</td>
<td>IGRAS-1875</td>
<td>1590 ± 50</td>
<td>1610 (1480) 1350</td>
</tr>
<tr>
<td>Zh0</td>
<td>1.40–1.50</td>
<td>IGRAS-2040</td>
<td>2610 ± 80</td>
<td>2950 (2650) 2350</td>
</tr>
<tr>
<td>Zh0</td>
<td>1.90–2.00</td>
<td>IGRAS-1873</td>
<td>3060 ± 80</td>
<td>3450 (3220) 2990</td>
</tr>
<tr>
<td>Zh0</td>
<td>2.40–2.50</td>
<td>IGRAS-1876</td>
<td>3440 ± 50</td>
<td>3840 (3700) 3560</td>
</tr>
<tr>
<td>Zh0</td>
<td>3.40–3.50</td>
<td>IGRAS-1881</td>
<td>4330 ± 50</td>
<td>5050 (4940) 4820</td>
</tr>
<tr>
<td>Zh0</td>
<td>3.90–4.00</td>
<td>IGRAS-1879</td>
<td>5410 ± 60</td>
<td>6310 (6150) 5990</td>
</tr>
<tr>
<td>Zh0</td>
<td>4.90–5.00</td>
<td>IGRAS-1878</td>
<td>6430 ± 90</td>
<td>7560 (7360) 7160</td>
</tr>
<tr>
<td>Zh0</td>
<td>5.90–6.00</td>
<td>IGRAS-1883</td>
<td>7160 ± 90</td>
<td>8170 (7980) 7790</td>
</tr>
<tr>
<td>Zh0</td>
<td>7.20–7.30</td>
<td>IGRAS-1928</td>
<td>7850 ± 120</td>
<td>9000 (8700) 8400</td>
</tr>
<tr>
<td>Kir1</td>
<td>3.90–4.00</td>
<td>IGRAS-1938</td>
<td>5180 ± 100</td>
<td>6200 (5930) 5650</td>
</tr>
<tr>
<td>E1</td>
<td>2.10–2.20</td>
<td>IGRAS-1911</td>
<td>4540 ± 90</td>
<td>5500 (5180) 4850</td>
</tr>
</tbody>
</table>

### Table 3
Basal peat ages and average accumulation rates of the studied sites

<table>
<thead>
<tr>
<th>Key area and site</th>
<th>Present peatland type</th>
<th>Present peatland type</th>
<th>Basal peat age (cal yr B.P.)</th>
<th>Basal peat age (cal yr B.P.)</th>
<th>Peat depth (m)</th>
<th>Peat depth (m)</th>
<th>Accumulated carbon (kg m⁻²)</th>
<th>Accumulated carbon (kg m⁻²)</th>
<th>Average peat accumulation rate (mm yr⁻¹)</th>
<th>Average peat accumulation rate (mm yr⁻¹)</th>
<th>LORCA (g C m⁻² yr⁻¹)</th>
<th>LORCA (g C m⁻² yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zh0</td>
<td>River valley fen</td>
<td>River valley fen</td>
<td>8700 ± 300</td>
<td>7.30 ± 0.05</td>
<td>600.3 ± 32.6</td>
<td>600.3 ± 32.6</td>
<td>0.84 ± 0.03</td>
<td>0.84 ± 0.03</td>
<td>69.0 ± 4.4</td>
<td>69.0 ± 4.4</td>
<td>60.0 ± 4.4</td>
<td>60.0 ± 4.4</td>
</tr>
<tr>
<td>Kir1</td>
<td>Ryam on top of raised bog</td>
<td>Ryam on top of raised bog</td>
<td>5930 ± 280</td>
<td>4.00 ± 0.05</td>
<td>193.2 ± 10.6</td>
<td>193.2 ± 10.6</td>
<td>0.67 ± 0.03</td>
<td>0.67 ± 0.03</td>
<td>32.6 ± 2.4</td>
<td>32.6 ± 2.4</td>
<td>31.6 ± 2.4</td>
<td>31.6 ± 2.4</td>
</tr>
<tr>
<td>E1</td>
<td>Forested fen</td>
<td>Forested fen</td>
<td>5180 ± 330</td>
<td>2.20 ± 0.05</td>
<td>174.0 ± 11.4</td>
<td>174.0 ± 11.4</td>
<td>0.42 ± 0.03</td>
<td>0.42 ± 0.03</td>
<td>33.6 ± 3.1</td>
<td>33.6 ± 3.1</td>
<td>32.6 ± 3.1</td>
<td>32.6 ± 3.1</td>
</tr>
</tbody>
</table>

### Plotnikovo

<table>
<thead>
<tr>
<th>Key area and site</th>
<th>Present peatland type</th>
<th>Basal peat age (cal yr B.P.)</th>
<th>Basal peat age (cal yr B.P.)</th>
<th>Peat depth (m)</th>
<th>Peat depth (m)</th>
<th>Accumulated carbon (kg m⁻²)</th>
<th>Accumulated carbon (kg m⁻²)</th>
<th>Average peat accumulation rate (mm yr⁻¹)</th>
<th>Average peat accumulation rate (mm yr⁻¹)</th>
<th>LORCA (g C m⁻² yr⁻¹)</th>
<th>LORCA (g C m⁻² yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>Ryam in bog complex</td>
<td>Ryam in bog complex</td>
<td>6460 ± 180</td>
<td>2.40 ± 0.05</td>
<td>175.2 ± 8.5</td>
<td>175.2 ± 8.5</td>
<td>0.37 ± 0.01</td>
<td>27.1 ± 1.5</td>
<td>27.1 ± 1.5</td>
<td>26.1 ± 1.5</td>
<td>26.1 ± 1.5</td>
</tr>
<tr>
<td>P2</td>
<td>Through-flow fen in bog complex</td>
<td>Through-flow fen in bog complex</td>
<td>5330 ± 280</td>
<td>2.00 ± 0.05</td>
<td>111.6 ± 6.0</td>
<td>111.6 ± 6.0</td>
<td>0.38 ± 0.02</td>
<td>20.9 ± 1.6</td>
<td>20.9 ± 1.6</td>
<td>20.0 ± 1.6</td>
<td>20.0 ± 1.6</td>
</tr>
<tr>
<td>P4</td>
<td>Through-flow fen in bog complex</td>
<td>Through-flow fen in bog complex</td>
<td>4550 ± 300</td>
<td>1.60 ± 0.05</td>
<td>89.1 ± 5.6</td>
<td>89.1 ± 5.6</td>
<td>0.35 ± 0.03</td>
<td>19.6 ± 1.8</td>
<td>19.6 ± 1.8</td>
<td>19.0 ± 1.8</td>
<td>19.0 ± 1.8</td>
</tr>
<tr>
<td>P8</td>
<td>Ryam in bog complex</td>
<td>Ryam in bog complex</td>
<td>4810 ± 160</td>
<td>2.00 ± 0.05</td>
<td>91.2 ± 4.3</td>
<td>91.2 ± 4.3</td>
<td>0.42 ± 0.02</td>
<td>19.0 ± 1.1</td>
<td>19.0 ± 1.1</td>
<td>18.0 ± 1.1</td>
<td>18.0 ± 1.1</td>
</tr>
</tbody>
</table>

### Vasyugan

<table>
<thead>
<tr>
<th>Key area and site</th>
<th>Present peatland type</th>
<th>Present peatland type</th>
<th>Basal peat age (cal yr B.P.)</th>
<th>Basal peat age (cal yr B.P.)</th>
<th>Peat depth (m)</th>
<th>Peat depth (m)</th>
<th>Accumulated carbon (kg m⁻²)</th>
<th>Accumulated carbon (kg m⁻²)</th>
<th>Average peat accumulation rate (mm yr⁻¹)</th>
<th>Average peat accumulation rate (mm yr⁻¹)</th>
<th>LORCA (g C m⁻² yr⁻¹)</th>
<th>LORCA (g C m⁻² yr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V21</td>
<td>Ryam in bog complex</td>
<td>Ryam in bog complex</td>
<td>9710 ± 180</td>
<td>11.00 ± 0.05</td>
<td>388.0 ± 21.1</td>
<td>388.0 ± 21.1</td>
<td>1.13 ± 0.02</td>
<td>1.13 ± 0.02</td>
<td>40.0 ± 2.3</td>
<td>40.0 ± 2.3</td>
<td>39.0 ± 2.3</td>
<td>39.0 ± 2.3</td>
</tr>
</tbody>
</table>

Calibration with OxCal 3.5 (Bronk Ramsey, 1995) using the INTCAL98 calibration curve (Stuiver et al., 1998).

- determined the carbon content of all samples using the carbon content of the peat types;
- dated peat samples at various depths.
collected samples of known volume every 10 cm over the whole peat depth. By drying at 105°C and incinerating at 550°C we measured the dry bulk density, ash content, and organic matter content of the samples. In order to determine the peat type of the samples, we analyzed the macrofossil plant remains.

We analyzed the carbon contents of 49 peat samples from various sites and depths representing the most common peat types of western Siberia. The applied method uses a surplus of K₂Cr₂O₇ in H₂SO₄ to oxidize organic matter. The excess of K₂Cr₂O₇, which is related to the amount of organic matter, is measured by titration. With these carbon contents of different peat types we determined the carbon content and amount of accumulated carbon of all peat samples.

The age of the peat layers was estimated by radiocarbon dating of 10-cm bulk samples in the Institute of Geography.

Fig. 2. Plant remains, age, carbon content, and organic matter content of sites V21 and Zh0 (after Bleuten and Lapshina, 2001).
We converted the radiocarbon dates (14C yr B.P.) to calibrated ages (cal yr B.P.) with the program OxCal 3.5 (Bronk Ramsey, 1995) using the INTCAL98 calibration curve.

We calculated the average Holocene peat accumulation rate at the sites by dividing the peat thickness by the basal age. Analogously, we calculated LORCA by dividing the total amount of accumulated carbon per unit area by the basal age.

From the eight sites we chose the groundwater-fed minerotrophic river valley fen Zh0 (68-Kvartal key area) and the ombrotrophic ryam V21 (Vasyugan key area) to study Holocene variations in the accumulation rates, for which radiocarbon samples at several depths were taken. Accumulation rates were calculated for the peat layers between the radiocarbon dated core sections. The role of decay is evaluated by fitting the data of these two sites in the model of Clymo (1984). The mean dry bulk densities for the cores, needed in the Clymo model to convert accumulated dry matter to depth, were obtained by averaging the dry bulk densities of the separate samples. We used the least-squares method for the fits. After fitting we converted the obtained production rates ($p$ in Eq. (2)) to carbon production rates using the appropriate ash content and carbon content.

### Results

Table 1 shows that the ombrotrophic *Sphagnum fuscum* peat has the lowest carbon content. In general herb and wood peat are characterized by higher carbon content than *Sphagnum* peat.

The calibrated ages of the dated peat samples are listed in Table 2. The median value of the 2$\sigma$ range is used as age for further calculations. To account for the uncertainty in the age, 2$\sigma$ is used as error.

The average peat accumulation rates and LORCA values at the eight sites are listed in Table 3. As shown in this
table, we found the highest peat and carbon accumulation rates in the 86-Kvartal and the Vasyugan key areas, at the sites Zh0 and V21. Although we found site V21 to have the highest peat accumulation rate during the Holocene, we found site Zh0 to have stored more carbon. This is directly correlated to the higher carbon content of the minerotrophic peat material (Table 1) and the higher organic matter contents of site Zh0 (Fig. 2). The differences in peat and carbon accumulation rate are also shown in Figs. 3 and 4.

We found that V21 had a higher peat accumulation rate, but a lower carbon accumulation rate during most of the Holocene. These differences were most marked during the early Holocene. In this period the peat accumulation rate of V21 increased from 0.6 to 3.3 mm yr\(^{-1}\), whereas the peat accumulation rate of Zh0 decreased from 1.6 to 0.8 mm yr\(^{-1}\) (Fig. 3). In the same period the carbon accumulation rate of V21 increased from 24 to 100 g C m\(^{-2}\) yr\(^{-1}\) in contrast to a decrease of the carbon accumulation rate of Zh0 from 174 to 51 g C m\(^{-2}\) yr\(^{-1}\). In the mid and late Holocene periods, the peat and carbon accumulations of both sites became more stable and less different.

In Fig. 2 we show the macrofossil plant remains of the sites Zh0 and V21 together with the organic matter content and carbon content. As is shown in Fig. 2, V21 consists of homogenous \textit{Sphagnum fuscum} peat layers. In this core the dry bulk density and carbon content were nearly constant with depth. Zh0 showed more variability in peat type and in carbon content.

We modeled the age–depth profiles of V21 and Zh0 with Clymo’s model (1984) (Fig. 5). The fit with the best \(r^2\) value is a straight line (Table 4). Because we assumed that decay is occurring, we fitted the data with small decay constants of 1 \(\times\) \(10^{-5}\) and 2 \(\times\) \(10^{-4}\) yr\(^{-1}\). The averaged dry bulk density was 7.5 \pm 0.2 \(\times\) \(10^4\) g m\(^{-3}\) for the V21 core and 2.11 \pm 0.09 \(\times\) \(10^5\) g m\(^{-3}\) for the Zh0 core. The averaged ash contents were respectively 1.8 \pm 0.1\% and 19.9 \pm 1.4\% of the dry peat matter. The carbon production rates belonging to the different fits are listed in Table 4.

### Table 4

<table>
<thead>
<tr>
<th>Site</th>
<th>Parameter</th>
<th>Linear fit</th>
<th>Model fit 1</th>
<th>Model fit 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>V21</td>
<td>(r^2 (p &lt; 0.05))</td>
<td>0.99</td>
<td>0.99</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>Carbon production, (p) (g C m(^{-2}) yr(^{-1}))</td>
<td>41</td>
<td>42</td>
<td>75</td>
</tr>
<tr>
<td></td>
<td>Decay constant, (\alpha) (yr(^{-1}))</td>
<td>—</td>
<td>0.00001</td>
<td>0.0002</td>
</tr>
<tr>
<td></td>
<td>Dry bulk density, (\rho) ((\times)10(^4) g m(^{-3}))</td>
<td>7.5 \pm 0.2</td>
<td>7.5 \pm 0.2</td>
<td>7.5 \pm 0.2</td>
</tr>
<tr>
<td></td>
<td>Ash content (% of dry peat matter)</td>
<td>1.8 \pm 0.1</td>
<td>1.8 \pm 0.1</td>
<td>1.8 \pm 0.1</td>
</tr>
<tr>
<td></td>
<td>Carbon content (% of dry organic matter)</td>
<td>47.9 \pm 2.5</td>
<td>47.9 \pm 2.5</td>
<td>47.9 \pm 2.5</td>
</tr>
<tr>
<td>Zh0</td>
<td>(r^2 (p &lt; 0.05))</td>
<td>0.96</td>
<td>0.95</td>
<td>0.81</td>
</tr>
<tr>
<td></td>
<td>Carbon production, (p) (g C m(^{-2}) yr(^{-1}))</td>
<td>79</td>
<td>82</td>
<td>139</td>
</tr>
<tr>
<td></td>
<td>Decay constant, (\alpha) (yr(^{-1}))</td>
<td>—</td>
<td>0.00001</td>
<td>0.0002</td>
</tr>
<tr>
<td></td>
<td>Dry bulk density, (\rho) ((\times)10(^4) g m(^{-3}))</td>
<td>2.11 \pm 0.09</td>
<td>2.11 \pm 0.09</td>
<td>2.11 \pm 0.09</td>
</tr>
<tr>
<td></td>
<td>Ash content (% of dry peat matter)</td>
<td>19.9 \pm 1.4</td>
<td>19.9 \pm 1.4</td>
<td>19.9 \pm 1.4</td>
</tr>
<tr>
<td></td>
<td>Carbon content (% of dry organic matter)</td>
<td>51.6 \pm 2.8</td>
<td>51.6 \pm 2.8</td>
<td>51.6 \pm 2.8</td>
</tr>
</tbody>
</table>

**Discussion**

Differences in accumulation rates—Holocene averages as well as variations throughout the Holocene—between the peatland types had two major causes. First, differences in accumulation rates were caused by differences in peat deposits, which are in turn caused by differences in the succession of peatland types and vegetation that formed the peat deposits. We found that the ombrotrophic \textit{Sphagnum fuscum} deposits of the bog site V21 had a lower dry...
bulk density and a lower carbon content than the miner-
erotrophic herb–moss deposits of site Zh0. This has lead to
a lower LORCA at site V21. The difference in peat
deposits is also reflected in the ash content (see average
values in Table 4). The ash content at the valley fen site
Zh0 is significantly higher, probably caused by inorganic
input from the river.

Second, the differences in accumulation rates between
the studied sites were caused by the specific local situation
in combination with climate change. Climate has often
been put forward as a driving force of variations in
Holocene peat accumulation (e.g., Korhola et al., 1996;
The variations in accumulation rates of our sites V21 and
Zh0 suggest that Holocene variations of these accumula-
tion rates are caused by local factors rather than by
climatic changes only. If climate is the major force behind
variations, these variations should turn out to be similar for
all peatland types within one climatic zone. However, the
variations of the sites V21 and Zh0, which indeed are
located within one climatic zone, have different trends
(Figs. 3 and 4). This is especially visible in early Holocene
time. Whereas the accumulation rate of site V21 steadily
increased, the accumulation rate of site Zh0 decreased. An
explanation for this difference is that during the wetter first
part of the early Holocene period the increased river
discharge could have lead to deeper incision of the valley
floor. The resulting drainage of the valley caused the
relative lower peat accumulation of the valley fens in that
period. This process of increased drainage, however, did
not affect bogs located at water divides. Thus, local factors
like topography—e.g., distance to river—and hydrology
apparently dominated over climate change effects. Mäkilä
et al. (2001) also point at the variations in local conditions
as an important factor influencing vegetation succession
and carbon accumulation.

In comparison with the other very few reported studies of
western Siberian peatlands, we found equal to significantly
higher peat and carbon accumulation rates for bogs and
slightly lower rates for fens. Our estimates of the peat
accumulation rates are as much as three times higher than
the values of 0.32 and 0.39 mm yr
–1 reported by Turunen et al.
(2001) for three western Siberian bogs. Their bogs are
situated in the middle taiga zone (latitude 60° N) on the flat
central parts of ombrotrophic watershed peatlands. Because
of the small climate differences (summer radiation, tempera-
ture, precipitation) we expected that accumulation rates
should be of the same order of magnitude as our ryam sites
Kir1, P1, P8, and V21 (Table 3). Our LORCA values are up
to two times higher than the LORCA values of 15.3 to 19.4
g C m
–2 yr
–1 reported by Turunen et al. (2001). The
differences may be the result of local hydrologic factors,
but are probably related to peatland fires: Turunen et al.
(2001) reported several ash layers in their cores. Even in wet
bogs, a fire event will retard the peat accumulation process
for very long time. In our cores no ash layers were detected.

Botch et al. (1995) studied peatlands all over European
Russia and western and middle Siberia and found LORCA
values for bogs of between 31.4 and 38.1 g C m
–2 yr
–1. These values are more comparable to our results. For
marshes, fens, and swamps Botch et al. (1995) found
LORCA values of 71.8 to 79.8 g C m
–2 yr
–1, which are
even higher than what we calculated for the sites E1 and
Zh0. However, the results by Botch et al. (1995) are
averages for a much larger area and therefore less suitable
for detailed comparison.

Some Finnish studies allow us to compare our results
with results from regions outside Russia. The Finnish bogs
studied by Mäkilä (1997), Tolonen and Turunen (1996),
and Turunen et al. (2002) accumulated carbon at a rate
ranging from 13.7 to 35.2 g C m
–2 yr
–1. Both Tolonen
and Turunen (1996) and Turunen et al. (2002) found that
the accumulation rate in bogs is significantly higher than
that in fens. Tolonen and Turunen (1996) found LORCA
values for Finnish fens ranging from 9.6 to 24.9 g C m
–2
yr
–1. This is in contrast to our result that the fen site Zh0
has the highest accumulation rate. We expect that these
contrasts may be explained by differences in local drainage
conditions.

Our results show that the model of Clymo is not
suitable for the studied peatlands and gives poorer results
than the calculations of LORCA. We have used two ways
of fitting the age-depth data in Fig. 5: a linear fit and a fit
for the theoretical model of Clymo (1984). The \( r^2 \) values
in Table 4 are an estimate of the deviation between the
measured and modeled age–depth values. The best fit
(lowest \( r^2 \) value) of the age–depth data is for both sites
a linear one, for which the decay constant \( \alpha \) approaches
zero. Consequently, the peat accumulation rate is better
estimated simply by its average instead by fitting the data
in the model. Analogously, LORCA is a better estimate of
the carbon production rate. However, if we assume that
decay is present, the Clymo model can be applied to the
age–depth data with certain decay constants to obtain
production rates. In our case, only small decay constants
of about \( 1 \times 10^{-5} \) yr
–1 give satisfactory fits. Note that the
performed fittings are optimized results and they are
statistically compared. Other researchers also used optimi-
ization techniques to fit the Clymo model and found
various decay constants (e.g., Korhola et al., 1996; Vitt
et al., 2000). We do not have any direct measurement of
the decay constant or the production rate and therefore we
do not have any reason to choose a certain decay constant.
However, Panikov et al. (2001) studied the CH
4 emission
rate near our key area Plotnikovo. They reported a net emission
rate in the summer of 0.45 mg CH
4-C m
–2 h
–1 for a peat
bog covered by dwarf pines and shrubs close to our site
P1. If we assume that the summer season lasts 90 days
(Panikov and Dedys, 2000) and that the contribution of
the winter season to the annual emission is 7% (an average
value according to Panikov and Dedys, 2000), the aver-
age emission rate appears to be 0.12 mg CH
4-C m
–2 h
–1
(i.e., \(1.0 \times 10^{-3}\) kg C m\(^{-2}\) yr\(^{-1}\)). From this emission rate and the accumulated amount of carbon at site P1 (Table 3) we found a decay constant of \(6 \times 10^{-6}\) yr\(^{-1}\). This supports the idea that the decay constant approaches zero and only Clymo fits with very small decay constants give good results.

Both the estimates of LORCA and the fits in the Clymo model fail to account for variations in Holocene accumulation rates. The LORCA value is an average accumulation rate as a net result of varying production and decomposition rates, whereas the Clymo model assumes a constant production and decomposition process. However, the results in Figs. 3 and 4 show that these rates varied during the Holocene. Here it should be pointed out that the accumulation rates in Figs. 3 and 4 are average rates over the period between two dates and that they are in fact, like LORCA, apparent rates. Although we did not find any indication for hiatuses in the peat deposits we cannot exclude that they occur. We need more dated samples to test this possibility.

The homogeneity of the peat deposits of site V21 allows us to evaluate the role of compaction and decay. We assume that compaction leads to an increase of the dry bulk density over depth: the deeper peat should experience more pressure from the peat on top of it and should therefore be more compacted. Decay can also result in an increase of the dry bulk density. This is due to the fact that the less dense material is probably more easily decayed. What is left after this selective decay is denser material. Because decay is a continuous process—at least to a certain depth or over a certain time—the bulk density of older and deeper peat must be higher than that of younger and less deep peat. In our study we did not find an increase in dry bulk density (Fig. 2). The homogeneous peat deposits of site V21 rule out the influence of peat type on dry bulk density. Therefore we conclude that compaction is negligible. Decay, however, is shown to be occurring by studies that measure methane emissions from peatlands (e.g., Panikov and Dedrysh, 2000). These studies showed a release of methane as a result of decay, but, as mentioned above, the rate of decay is very small. Moreover, from our results it is more likely to conclude that decay is not a relevant factor in considering carbon sequestration by undrained peatlands.

With the presented results we know more about carbon sequestration in western Siberian peatlands. This knowledge about a huge, but hitherto nearly unstudied peat region in the world contributes to our understanding of the influence of peat ecosystems on the global carbon cycle and their potential impact on global change.

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