CARBON ACCUMULATION IN PRISTINE AND DRAINED MIRES

by

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The carbon accumulation of 73 peat columns from 48 pristine and drained mires was investigated using a total of 367 dates and age-depth models derived from bulk density measurements. Peat columns were collected from mires of varying depth, age, degree of natural state and nutrient conditions in aapa mire and raised bog regions and coastal mires from southern and central Finland and Russian Karelia. Particular attention was paid to the accumulation of carbon over the last 300 years, as this period encompasses the best estimates of the oxic layer (acrotelm) age across the range of sites investigated.

In general, drained mires are initially more nutrient-rich than pristine mires. Organic matter decomposes more rapidly at drained sites than at pristine sites, resulting in thinner peat layers and carbon accumulation but a higher dry bulk density and carbon content. The average carbon accumulation was calculated as 24.0 g m⁻² yr⁻¹ at pristine sites and 19.4 g m⁻² yr⁻¹ at drained sites, while for peat layers younger than 300 years the respective figures were 45.3 and 34.5 g m⁻² yr⁻¹ at pristine and drained sites. For the <300-year-old peat layers studied here, the average thickness was 19 cm less and the carbon accumulation rate 10.8 g m⁻² yr⁻¹ lower in drained areas than in pristine areas.

The amount carbon accumulation of surface peat layers depends upon the mire site type, vegetation and natural state; variations reflect differences in plant communities as well as factors that affect biomass production and decay rates. The highest accumulation rates and thus carbon binding for layers younger than 300 years were measured in the ombrotrophic mire site types (Sphagnum fuscum bog and Sphagnum fuscum pine bog), and the second highest rates in wet, treeless oligotrophic and minerotrophic mire site types. The lowest values of carbon accumulation over the last 300 years were obtained for the most transformed, sparsely forested and forested mire site types, where the water table was lowest. Depending on the nutrient conditions of mires, carbon binding can decrease or increase after drainage. At the most nutrient poor sites, carbon binding can increase after drainage.

Keywords (GeoRef Thesaurus, AGI): mires, peatlands, drainage, peat, carbon, deposition, nitrogen, Holocene, Finland, Russian Federation, Republic of Karelia

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INTRODUCTION

Whilst the carbon accumulation of peat layers has been quite intensively studied in mires (e.g. Toloenen et al. 1992, Turunen et al. 2002, Laine et al. 2004, Mäkilä 1997, Mäkilä et al. 2001, Mäkilä & Moisanen 2007, Mäkilä & Saarnisto 2008), information on carbon accumulation in drained mires is scarce (e.g. Minkkinen et al. 1998, Laine et al. 2004). This paper describes a comparative study of rates of carbon accumulation of three types of boreal mires, with and without artificial drainage. The approach involves the derivation of mean carbon accumulation rates, as well as the rates over their full Holocene lifetimes. The aim of this study was to examine the influence of drainage, mire site type and vegetation on the accumulation of carbon over the last 300 years and to define the role of mires as a carbon sink and source.

MATERIALS AND METHODS

Net rates of carbon accumulation over different time periods were determined by $^{14}$C dating of material from different depths of peat columns. These were collected in connection with a Geological Survey of Finland peat inventory from 69 peat columns from 48 mires in southern and central Finland and four columns in Russian Karelia. The quantities of carbon sequestered during recent centuries and over the entire lifetimes of the mires were determined using a total of 367 dates (186 $^{14}$C AMS and 181 conventional dates) and age-depth models derived from bulk density measurements (Mäkilä & Goslar 2008). Several datings were performed for different depth zones of some mires (3–19 dates per column).

Study sites

The locations of the study sites relative to the principal Finnish mire regions (aapa minerotrophic mire and raised oligotrophic bog) are indicated in Figure 1. The sites were also classified as pristine or drained. A pristine mire is defined here as one that appears to largely be in a natural condition and undrained, although marginal ditches may be present (Mäkilä & Goslar 2008).

Figure 1. Locations of the study sites superimposed on the mire complex type regions (numbered 1–7) of Finland according to Ruuhijärvi & Hosiaisluoma (1989). Coastal mires are marked with blue triangles. The raised bog region occurs to the south of the black line (Regions 1–3) and the aapa mire area to the north (Regions 4–7).
Sample collection

Shallow volumetric samples of 10x10 cm square and 20 cm deep were obtained using a metal frame (Mäkilä & Goslar 2008) (Figure 2). Deeper samples were obtained using a volumetric piston sampler (8 cm diameter, 20 cm long) or a 5-cm-diameter Russian peat sampler.

Dry bulk density measurements, carbon and nitrogen analysis

Dry bulk density and water content were determined from volumetric samples dried to constant weight at 105 °C. A Leco CHN 600 analyser was used to determine carbon and nitrogen contents as proportions of total dry matter.

AMS $^{14}$C dating

In order to obtain high-resolution records, samples for $^{14}$C dating were taken from (3–5 mm thick) slices. The material selected was mostly pure Sphagnum, because this species forms the bulk of most peat deposits. As the amount of pure Sphagnum available in each sample was small, the only suitable method for $^{14}$C dating was accelerator mass spectrometry (AMS), which was carried out at the Poznan Radiocarbon Laboratory (Poz) in Poland (Goslar et al. 2004, Goslar et al. 2005). Accurate dating is important for all approaches, and is highly important when using age-depth models to calculate rates of peat increment and carbon accumulation. AMS dating can provide more accurate dating results than conventional $^{14}$C dating because it requires much less material for the analysis and is often more precise (smaller error estimate). This is why AMS $^{14}$C dating has been used with surface peat layers. The samples taken before 2003 were dated in the $^{14}$C laboratory of the Geological Survey of Finland (Su).
RESULTS

Calculation of accumulation rate and carbon pool

The long-term apparent rate of carbon accumulation for the entire peat deposit (LARCA), and the actual rate of carbon accumulation (ARCA 300 = layers <300 years old) were calculated using peat columns of known dry bulk density, carbon content and age according to Clymo et al. (1998). The following equation was used to calculate carbon accumulation rates:

\[ A_c^e = r \times \rho \times C \times 1000 \]

Where \( A_c^e \) = carbon accumulation rate (g m\(^{-2}\) yr\(^{-1}\)), \( r \) = rate of vertical peat increment (mm yr\(^{-1}\)), \( \rho \) = dry bulk density (g cm\(^{-3}\)) and \( C \) = carbon content as a proportion of dry bulk density (%). Separate mean values were calculated for different mire site types, regions and on the basis of the natural status of mires, i.e. pristine v. drained.

Dry bulk density, carbon and nitrogen contents

The average dry bulk density in peat layers younger than 300 years was 56.9 kg m\(^{-3}\) at pristine sites and 68.6 kg m\(^{-3}\) at drained sites. The proportion of carbon and the nitrogen was slightly lower at pristine sites than at drained sites (Table 1). As the carbon content remains rather similar in different types of environments, the change in the C:N ratio is mainly due the proportional change in nitrogen (N). The C:N ratio increased as the proportion of nitrogen decreased. Importantly, higher carbon accumulation rates correlated with a low nitrogen content and high C:N ratio. A higher peat increment (thickness) correlated with a low dry bulk density, low nitrogen content and high C:N ratio (Table 1). In the present study, the lowest nitrogen and carbon contents were found in coastal Sphagnum bogs and the highest in the Carex aapa mire region, whilst the C:N ratio was slightly higher in coastal mires than in the raised bog region (Table 1).

Table 1. Mean values of the carbon accumulation rate, thickness, dry bulk density, C and N content and C:N ratio for surface layers younger than 300 years of the study sites, calculated according to mire region and natural state.

<table>
<thead>
<tr>
<th>Region</th>
<th>Natural state</th>
<th>Carbon accumulation rate g m(^{-2}) yr(^{-1})</th>
<th>Thickness m</th>
<th>Dry bulk density kg m(^{-3})</th>
<th>C %</th>
<th>N %</th>
<th>C:N Ratio %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aapa mire</td>
<td>Pristine</td>
<td>36.0</td>
<td>0.40</td>
<td>60.0</td>
<td>46.0</td>
<td>1.46</td>
<td>34.7</td>
</tr>
<tr>
<td></td>
<td>Drained</td>
<td>30.0</td>
<td>0.31</td>
<td>68.3</td>
<td>45.8</td>
<td>1.50</td>
<td>37.9</td>
</tr>
<tr>
<td>Raised bog</td>
<td>Pristine</td>
<td>46.0</td>
<td>0.55</td>
<td>56.2</td>
<td>46.1</td>
<td>0.90</td>
<td>53.4</td>
</tr>
<tr>
<td></td>
<td>Drained</td>
<td>33.7</td>
<td>0.32</td>
<td>69.3</td>
<td>47.5</td>
<td>1.34</td>
<td>40.6</td>
</tr>
<tr>
<td>Coastal mire</td>
<td>Pristine</td>
<td>60.4</td>
<td>0.74</td>
<td>52.4</td>
<td>44.5</td>
<td>0.99</td>
<td>46.5</td>
</tr>
<tr>
<td></td>
<td>Drained</td>
<td>65.9</td>
<td>0.69</td>
<td>63.0</td>
<td>45.8</td>
<td>0.87</td>
<td>53.5</td>
</tr>
<tr>
<td>All studied</td>
<td>Pristine</td>
<td>45.3</td>
<td>0.53</td>
<td>56.9</td>
<td>45.8</td>
<td>1.16</td>
<td>43.7</td>
</tr>
<tr>
<td>columns</td>
<td>Drained</td>
<td>34.5</td>
<td>0.34</td>
<td>68.6</td>
<td>46.8</td>
<td>1.36</td>
<td>40.6</td>
</tr>
</tbody>
</table>

Carbon accumulation rate

The average carbon accumulation values in entire peat layer was 24.0 g m\(^{-2}\) yr\(^{-1}\) at pristine sites and 19.4 g m\(^{-2}\) yr\(^{-1}\) at drained sites. The average carbon accumulation calculated for each of the three mire regions was 14.6 g m\(^{-2}\) yr\(^{-1}\) for the aapa mire region, 19.8 g m\(^{-2}\) yr\(^{-1}\) for the raised bog region and 43.0 g m\(^{-2}\) yr\(^{-1}\) for coastal mires (Table 2). The mean value for peat layers younger than 300 years was 33.8 g m\(^{-2}\) yr\(^{-1}\) for the aapa mire region, 38.4 g m\(^{-2}\) yr\(^{-1}\) for the raised bog region and 61.3 g m\(^{-2}\) yr\(^{-1}\) for coastal mires (Table 1). The carbon accumulation rates were lower at drained sites than at pristine sites, except for coastal mires, whereas dry bulk density and carbon content were higher at drained sites than at pristine sites, except for the aapa mire region (Table 1).
Plant components and the degree of decomposition estimated from the preservation state of moss remains indicate that the carbon accumulation rate for layers younger than 300 years is highest at ombrotrophic mire site types (Sphagnum fuscum bog and Sphagnum fuscum pine bog), and the second highest rates were recorded at wet, treeless oligotrophic and minerotrophic mire site types. The lowest values for layers younger than 300 years were obtained for the most transformed, sparsely forested and forested mire site types (Figure 3).

Table 2. Mean values of the apparent carbon accumulation rate, thickness and age for entire peat profiles, calculated for each of the three mire regions and a natural state.

<table>
<thead>
<tr>
<th>Region</th>
<th>Natural state</th>
<th>Carbon accumulation rate g m⁻² yr⁻¹</th>
<th>Thickness m</th>
<th>AMS-¹⁴C Age yrs cal. BP</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aapa mire</td>
<td>Pristine</td>
<td>14.3</td>
<td>2.71</td>
<td>8312</td>
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<tr>
<td></td>
<td>Drained</td>
<td>15.2</td>
<td>1.84</td>
<td>5586</td>
</tr>
<tr>
<td>Raised bog</td>
<td>Pristine</td>
<td>23.6</td>
<td>3.78</td>
<td>5585</td>
</tr>
<tr>
<td></td>
<td>Drained</td>
<td>17.5</td>
<td>2.58</td>
<td>6953</td>
</tr>
<tr>
<td>Coastal mire</td>
<td>Pristine</td>
<td>40.9</td>
<td>1.80</td>
<td>1653</td>
</tr>
<tr>
<td></td>
<td>Drained</td>
<td>53.2</td>
<td>1.74</td>
<td>1005</td>
</tr>
<tr>
<td>All studied</td>
<td>Pristine</td>
<td>24.0</td>
<td>2.78</td>
<td>5857</td>
</tr>
<tr>
<td>columns</td>
<td>Drained</td>
<td>19.4</td>
<td>2.31</td>
<td>6138</td>
</tr>
</tbody>
</table>

Figure 3. Average carbon accumulation rates for layers younger than 300 years, calculated for the different mire site types and drained peatlands represented amongst the study sites. English names of mire site types according to Laine & Vasander (1990).
DISCUSSION

Variation in carbon accumulation rate in relation to mire site type and peat type

Due to natural mire succession and variations in local conditions, spatial variation in the carbon accumulation rate can largely be explained in terms of the composition of the vegetation and decomposition rates. Connections have commonly been observed between mire vegetation, its nutrient content and moisture status (Laine & Vanha-Majamaa 1992, Laine et al. 1995, Laiho 2006). The highest carbon accumulation rates and thus carbon binding were found in coastal mires, where species of *Sphagnum* sect. *Acutifolia* with a low carbon and nitrogen content are prevalent. This younger bog type produces more moss than an old bog, and the amount of decayed and compacted peat is lower.

For *Carex* species, production is mainly determined by the availability of nutrients such as nitrogen and phosphorus, whereas decay rates vary according to the nutrient contents of their different parts (Thormann et al. 2001). In the present study, the lowest nitrogen and carbon contents were found in coastal *Sphagnum* bogs and the highest in the *Carex* aapa mire region, whilst the C:N ratio was slightly higher in coastal mires than in the raised bog region. The lower carbon accumulation values of <300-year-old surface layers were recorded where *Carex* species dominate and *Sphagnum* moss is mainly decomposed, and the lowest values were found in sparsely forested and forested mire site types where the water table was lowest.

Effect of drainage on carbon accumulation

In the present study, carbon accumulation rates were generally lower at drained sites than at pristine sites, whereas dry bulk density and carbon content were higher at drained sites than at pristine sites. Drained sites are often initially more nutrient-rich than pristine areas. Organic matter decomposes more rapidly, resulting in thinner peat layers and lower carbon accumulation as well as a higher dry bulk density and carbon content than at pristine sites (Table 1). At nutrient-rich sites the decomposition of peat can increase so much that carbon is lost from peat to the atmosphere, whereas in the most nutrient poor sites, carbon binding can increase after drainage. Methane emissions in drained areas are always lower than in pristine areas (Laine et al. 2004).

For the less than 300-year-old peat layers studied here, the average thickness was 19 cm less and the carbon accumulation rate 10.8 g m\(^{-2}\) yr\(^{-1}\) lower in drained areas than in pristine areas (Table 1). The low bulk density and high total porosity of peat means that drainage causes subsidence of the mire surface, which may be in the order of 15–40 cm during the first decades after drainage (Mäkilä 1994). The slower rate of vertical growth is mainly explained by secondary compaction, reflected by the greater dry bulk density values for drained areas, which in turn are confirmed by the data of Mäkilä (1994) for almost 50 000 volumetric samples collected from pristine and drained mires in various parts of Finland. Initially, most of the subsidence occurs through physical collapse of the peat matrix as water is removed, but later the phenomenon is increasingly attributable to oxidation and decomposition of the peat (Paivänen & Paavilainen 1996).

As a direct result of drainage, buoyancy is lost and the moss carpet collapses, causing the surface of the mire to sink. Later, subsidence continues as the rate of oxic decomposition in the surface layers increases. However, upward growth of mosses and the accumulation of organic matter at the surface of the peatland may continue simultaneously with decomposition and compaction of sub-surface peat (Paivänen & Paavilainen 1996).

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CONCLUSIONS

It is difficult to compare peat properties and carbon accumulation rates between pristine and drained mires. Drained sites are often initially more nutrient-rich than pristine areas. Organic matter has decomposed more rapidly, resulting in thinner peat layers and lower carbon accumulation as well as a higher dry bulk density and carbon content than at pristine sites. Besides the natural state, the accumulation of carbon by surface peat layers also depends on the mire site type and vegetation. Variations reflect differences in plant communities as well as factors that affect biomass production and decay rates. The highest accumulation rates and thus highest carbon binding for layers younger than 300 years were measured in ombrotrophic mire site types, and the second highest rates in wet, treeless oligotrophic and minerotrophic mire site types. The lower values over the last 300 years were obtained for sparsely forested and forested mire site types and the lowest values were from the most transformed peatlands where the water table was lowest. Depending on the nutrient conditions of mires, carbon binding can decrease or increase after drainage. At the most nutrient poor sites, carbon binding can increase after drainage. The results indicate how important it is to understand the carbon accumulation rates of surface layers and the long-term dynamics of mire carbon accumulation in order to set the current flux estimates in perspective.

REFERENCES
