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Mud-bottom hollows: exceptional features in carbon-accumulating bogs?

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Abstract: Mud-bottom hollows are depressions on the bog surface where *Sphagnum* mosses have died and peat accumulation is retarded or even replaced with loss by oxidation. Results of measurements carried out at Männikjärve Bog, central Estonia, confirmed that peat accumulation has stopped and that in 1999–2001 the uppermost 2–3 cm thick surface layer of mud-bottom hollows became thinner by 1.95 ± 0.75 mm yr^{-1} (n = 188). Different methods revealed the corresponding carbon loss from the mud-bottom hollows 25 mm thick surface layer as 50–60 g C m^{-2} yr^{-1}. As a result, the surface of mud-bottom hollows becomes lower as compared to surroundings with peat accumulation *c.* 1.5 mm yr^{-1}, and they are likely to have an important role in the differentiation of bog microtopography. Owing to the combination of a cessation in peat accumulation, carbon loss by oxidation and increased emission of decomposition gases, mud-bottom hollows could have an important influence on the carbon budget of bogs.

Key words: Bog, mire surface, carbon loss, peat oxidation and accumulation, mud-bottom hollows.

Introduction

In mires, owing to the combination of specific environmental conditions, up to 20% of the dead plant biomass remains undecomposed and accumulates as peat (Tolonen and Turunen, 1996; Yu *et al.*, 2001). Therefore mires have generally been treated as carbon sinks in most studies of the global carbon cycle, although in reality they are perhaps better regarded as a store than a sink (see Chambers and Charman, this issue). Estimates of the amount of stored organic matter as peat range from 120–260 Gt (Franzén, 1994) to 450 Gt in northern peatlands (Gorham, 1991) in terms of carbon. This carbon pool is approximately one-third of the total world soil pool (Post *et al.*, 1982) and therefore northern peatlands may become an important source for atmospheric C in a time of significant climatic change. Indeed, Franzén (1994) introduced a theory that ice-age cycles are largely generated by the peat growth in temperate wetlands and its impact on the greenhouse effect.

The dynamics of carbon accumulation is determined by the ratio between production and decomposition of organic matter and is highly variable over different time and space scales. There could be periods and areas in mires where carbon accumulation is retarded or even replaced with C loss by oxidation and emission of CH_4 and CO_2. Depending on climatic conditions, some peat-forming ecosystems have been found to be potential net sources of CO_2 to the atmosphere (Waddington and Roulet, 1996; Caroll and Crill, 1997; Vourlitis and Oechel, 1997). Mires are also essential natural sources of an important greenhouse gas – methane. It is not clear whether the warming potential of the conversion of CO_2 to CH_4 is less than or more than the cooling potential of the removal of CO_2 by mires as peat (Clymo, 1996).

Change of peatlands between carbon sources and sinks would affect significantly the global carbon budget (Yu *et al.*, 2001), but little is known about the variability of carbon fluxes and sequestration through time in mires, especially in response to climatic change (Moore *et al.*, 1998). The response of mires to changing environmental conditions will partly be determined by the mire microtopography (Bridgham *et al.*, 1995; Waddington and Roulet, 1996; Weltzin *et al.*, 2001). Exceptional in terms of the carbon budget may be mud-bottom hollows in bogs where, owing to degeneration of *Sphagnum* mosses and vascular plants, peat accumulation is presumably retarded and replaced by an increased emission of decomposition gases, especially CH_4 (Crill *et al.*, 1992; Frenzel and Karofeld, 2000). Because mud-bottom hollows may cover large areas of some bogs (Figure 1) and because they are more common in northern areas of the Boreal zone (Paasio, 1934), which may experience greater climatic changes, they may play an important role in the carbon budget of boreal bogs and also in the changing concentration of carbon gases in the atmosphere.

The main aim of the present study was to reveal the peat-accumulation or oxidation rate in the mud-bottom hollows, and to estimate the potential organic matter and carbon loss from the surface layer of mud-bottom hollows. Briefly defined, mud-bottom hollows with a diameter up to tens of metres are depressions on the bog surface where *Sphagnum* mosses have died and the surface is formed of bare peat or a dense algal mat with single vascular plants. During dry summers the surface layer becomes dry and cracks into polygons of 20–30 cm with upturned edges. The underneath of this dried surface remains green. Karofeld (1999) noted: ‘Different terms like mud-bottom hollow, mud-bottom, bare or naked peat area, flark, regressive complex, etc. have been used. The term mud-bottom hollow is employed

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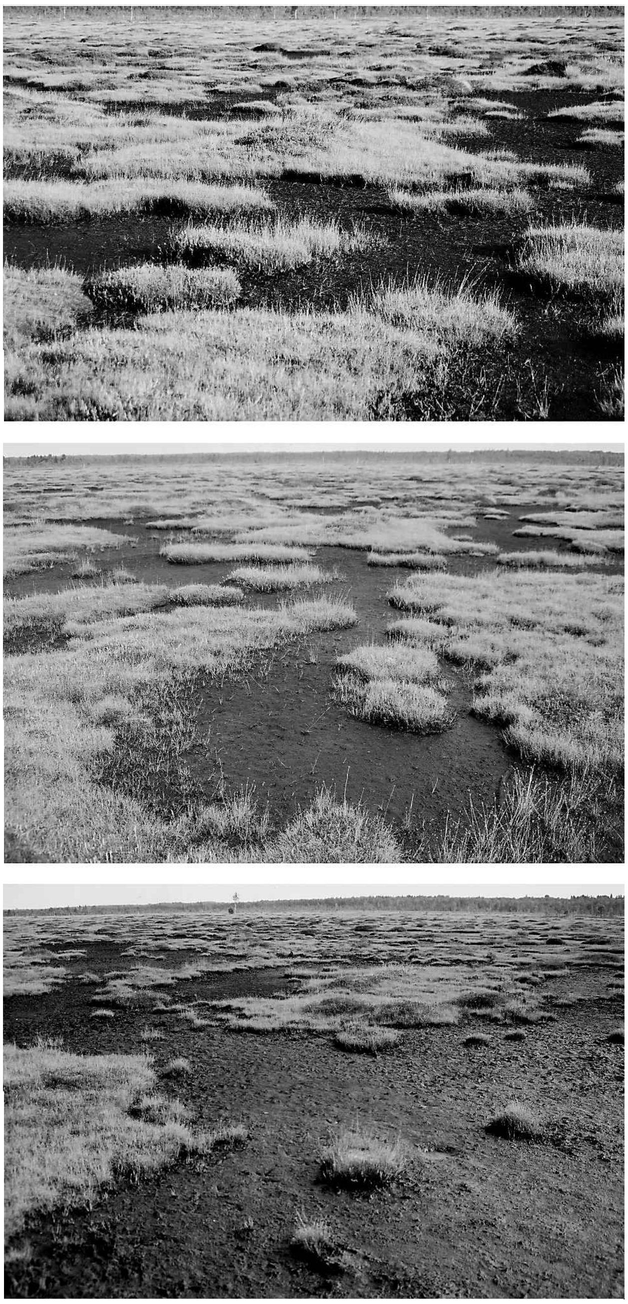

Figure 1 Mud-bottom hollows may cover large areas of some parts of the bog massif (Nigula Bog, SW Estonia).

most widely …'. It is therefore used here. However, the term is potentially misleading as there is no mud, and they differ from real bog-hollows.

Material and methods

Field measurements were carried out on Männikjärve Bog in central Estonia (N 58°52′55″, E 26°14′87″). Männikjärve Bog (area 320 ha, maximum peat depth 7.5 m) is a bog of limnogenic origin with a well-developed hollow-ridge-pool complex in the centre and forested margins. The mud-bottom hollows there were first described by Thomson (1924), and later in more detail by Masing (1958; 1982) and Karofeld (1999; 2001; Karofeld and Toom, 1999). Karofeld and Toom (1999) found that the total number of algal species in mud-bottoms was 22, but on individual plots it varied from 4 to 13. They reported that, of 41 mud-bottoms studied, 19 had formed on hollow peat dominated by *S. cuspidatum*, 12 on *S. magellanicum* lawn peat and 10 on hummock peat dominated by *S. fuscum* and *S. rubellum*.

Preliminary data on the rate of peat accumulation on the surface of mud-bottom hollows were achieved by the *Drosera* method, based on the measurement of distance between leaf rosettes formed annually on the rising *Sphagnum* surface (Tyuremnov, 1976). After careful removal and cleaning of *D. anglica* plants from peat 2–3 (4) leaf rosettes can be seen. The distance between rosettes corresponds approximately to the bog surface rise during the preceding year.

More exact measurements of the peat accumulation or loss rate on the mud-bottom hollows were carried out in eight sites (5–10 replicates in each site) using 10 cm long rigid strings and bamboo pins with a copper wire stopper near the lower end. Strings and pins were coated with silicon so that peat particles or algae would not adhere, and were then installed into small cuttings (2–3 cm long and *c.* 3 cm deep) in the flat parts of mud-bottom hollows without plants, signs of gas eruption or other disturbance. After inserting the strings and pins to 2–3 cm depth they were turned horizontally 90° to fix stoppers in the peat (Figure 2). The strings and pins were refixed, if necessary, every spring after snowmelt and thawing of mud-bottom hollows, and the zero reading for a particular year was taken. The length of the strings and pins above the mud-bottom hollow surface was measured over three years (1999–2001) every spring and autumn at periods with comparable depth (approximately 1 cm) of bog water table. To make results from different years and exposure periods more comparable, they were also recalculated for a 100-day period.

A laboratory experiment was performed to study the possible effect of changing bog water depth on the thickness of algal mat and uppermost peat layer on the changes in the above described strings and pins length. Four peat monoliths (10 × 14 × 6 cm) from the surface of a mud-bottom hollow were placed into perforated plastic boxes and then mounted into a bigger container filled with bog water. The water level in the container was adjusted to a depth approximately 1 cm below the surface of the monoliths and adjusted daily by adding rainwater. Six bamboo pins (described above) were installed in each monolith. The length above the surface of each pin was measured next day after the beginning of the experiment and then repeated after one week. Thereafter one of the monoliths was fixed with its surface 1.5 cm and the other 0.5 cm above water level, whereas two more monoliths were kept as controls with initial water-table depth (1 cm)

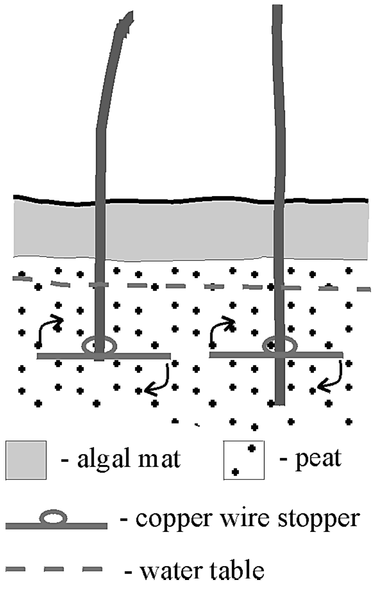

Figure 2 Principal scheme of the measuring strings and pins installation for peat-accumulation/oxidation measurements (not to scale).

and the length of the pins was measured once more after another week.

To reveal the seasonal changes in peat characteristics (bulk density g cm^{-3}, C and N content %, C/N ratio) three peat monoliths (8.5 × 19 × 4 cm) were cut off from the surface of a mud-bottom hollow in May 2001. Monoliths were mounted into perforated plastic boxes of the same size; two of these were placed back into their original location, whereas a third monolith was stored in a freezer. Two monoliths from a mud-bottom hollow were sampled in August and November, correspondingly. Thereafter, all three frozen samples were cut to the known volume, analyses were made separately from the uppermost 10 mm thick dense algal mat and from the underlying 15 mm thick *Sphagnum* (hollow) peat layer. Carbon and nitrogen content (% from dry samples dried to constant weight at 80°C) as well as C/N ratio (three subsamples from each sample and three measurement from each of them) was determined in the Laboratory of Thermal Engineering Department, of Tallinn Technical University, on an Elementar Analyser Vario EL CHNOS.

Results

Peat accumulation and loss

The results achieved by the *Drosera* method showed the rise of *Sphagnum* carpet surface around the mud-bottom hollow by 13.3 ± 1.34 mm yr^{-1} (n = 12) in the edge of the *S. cuspidatum* hollow and by 17.2 ± 1.73 mm yr^{-1} (n = 12) in the *S. magellanicum* lawn. In the case of *D. anglica* plants sampled from mud-bottom hollows (n = 20), the distance between the leaf rosettes from different years was not measurable as these were packed tightly one on another.

In the laboratory experiment to reveal the possible effect of the changing water-table depth on the strings and pins length, the changes were below the detection limit 0.5 mm in all three cases (with stable, lowered or raised water table). At the applied water table depths (–0.5–1.5 cm) the surface layer of the monoliths remains moist and the peat matrix is enough rigid to sustain the autocompaction and to prevent the thinning of the monoliths' surface layer. It was concluded that studied water-table fluctuations do not have any real effect on the length of strings and pins. Therefore, changes in their length could be interpreted as peat accumulation or loss.

The changes in the length of strings and pins are shown in Figure 3. Positive values indicate the increased and negative values the decreased length. Negative values in sites 5 and 6 are caused by the occasional sprout of *Sphagnum* plants at the pins. Data for the year 2000 in site 7 are missing because of the inclination of pins. These results were discarded from further calculations. In general the length of strings increased less as compared to that of pins (1.65 ± 0.86, n = 81 and 2.18 ± 0.48 mm, n = 108, correspondingly). On average, measurements revealed the lengthening of strings and pins and corresponding thinning of the uppermost layer on mud-bottom hollows by 1.95 ± 0.75 mm (n = 188). Results from different years are given in Table 1.

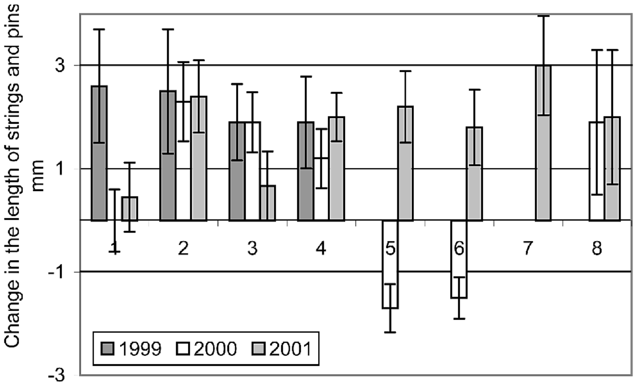

Figure 3 Changes in the length (mm, mean ± S.E) of measuring strings (sites 1–4) and pins (sites 4–8) in 1999–2001.

Table 1 Changes in the length of strings and pins in 1999–2001

	1999	2000	2001
Result of the measurement (mean ± S.E) and period length	2.23 ± 0.38 mm (n = 38) 84 days	1.46 ± 0.91 mm (n = 77) 127 days	1.82 ± 0.86 mm (n = 73) 89 days
Result of the measurement calculated for 100 days period	2.65 ± 0.32 mm	1.15 ± 1.12 mm	2.04 ± 0.76 mm

Calculations of dry matter and carbon loss

If the increase in the length of strings and pins is caused by the peat loss, then it is possible to calculate corresponding dry matter and carbon loss from the surface layer of mud-bottom hollows. Since the decomposition dynamics during the studied period is unknown, the mean bulk density and carbon content values of algal mat and underlying peat layer from May to November were used for calculations (Table 2). The calculations [(volume of certain layer cm^3 × mean bulk density g cm^{-3} × mean C content %): 25 mm × 1.95 mm] show that corresponding to the thinning of 25 mm thick layer by 1.95 ± 0.75 mm yr^{-1} the loss of dry matter is 132.6 ± 12.9 g m^{-2} and that of carbon 58.1 ± 5.7 g C m^{-2}.

Seasonal changes in the carbon volumetric content

An attempt was made to calculate the dry matter and carbon loss from the surface of mud-bottom hollows based on the seasonal changes in bulk density and carbon content of algal mat and underlying peat layer (Table 2). In the algal mat, C content was stable during the period from May to August followed by a small increase until November. However, calculations of the volumetric content of carbon based on the bulk density and carbon content of the algal mat in a certain period (Table 2) (10000cm^2 × 10 mm × bulk density g cm^{-3} × C content %) revealed an increase in carbon content during the summer and decrease towards autumn

Table 2 Characteristics of the uppermost 10 mm thick algal mat and underlying 15 mm thick peat layer in the mud-bottom hollow in May, August and November correspondingly

	Algal mat	Peat
Bulk density g/cm^3	0.087 ± 0.01	0.051 ± 0.015
	0.12 ± 0.01	0.057 ± 0.009
	0.076 ± 0.008	0.044 ± 0.009
C content, %	42.5 ± 0.83	43.5 ± 0.06
	42.7 ± 0.78	41.8 ± 0.15
	45.8 ± 0.31	46.5 ± 0.16
N content, %	1.29 ± 0.04	0.65 ± 0.09
	1.35 ± 0.15	1.41 ± 0.14
	1.44 ± 0.04	1.67 ± 0.3
C/N ratio	32.9 ± 1.35	66.9 ± 8.87
	31.6 ± 4.07	29.6 ± 2.95
	31.8 ± 0.89	28.5 ± 3.47

(Figure 4). This refers to carbon loss from the topmost 10 mm thick algal mat in the mud-bottom hollow from May to November by 21.7 ± 56 g C m^{-2}. Corresponding calculated thinning of the originally 10 mm thick mat is by 0.59–0.62 mm.

In the underlying peat layer after the decrease in summer, C content increased again by more than 5% until November (Table 2). Seasonal changes in the calculated volumetric carbon content in the 15 mm thick peat layer were smaller than in the algal mat but in general followed the same trend (Figure 4). From May to November the carbon loss from peat layer equates to 25.8 ± 63 g C m^{-2} and thinning of the originally 15 mm peat layer corresponding to the calculated carbon loss is 1.16–1.26 mm. In total, calculated carbon loss from the uppermost 25 mm thick layer of the mud-bottom hollow from May to November is 47.5 ± 84 g C m^{-2} and the corresponding reduction in the thickness of the studied layer is 1.75–1.88 mm. These values are comparable with the results obtained from the direct measurements of strings and pins length and calculated carbon losses presented above.

Seasonal changes in C/N ratio

Commonly the C/N ratio is used to characterize the dynamics of the decomposition processes. If the potential change in N content is ignored, the changes in the C/N ratio could be interpretated as the change in carbon content (Malmer and Holm, 1984). Seasonal changes in the C/N ratio in samples from mud-bottom hollows showed only small changes in the algal mat but an almost twofold decrease in the underlying peat layer from May to August corresponding to 40–50% loss of original carbon (Table 2). Taking into account the bulk density and carbon content of the algal mat and underlying peat layer, this means carbon loss from the uppermost 25 mm thick mud-bottom hollow layer by 266.5 ± 84.2 g C m^{-2} and corresponding thinning by 11–28.4 mm. This is a much bigger carbon loss and corresponding thinning of the uppermost surface layer than that revealed by other methods presented above, and therefore is obviously overestimated and not realistic.

Seasonal changes in nitrogen volumetric content

Changing nitrogen content in the algal mat and especially in the underlying peat layer (Table 2) indicates that the N content should not be taken as almost constant when interpreting the changes in C/N ratio. Calculated changes in the nitrogen volumetric content revealed important seasonal changes in the algal mat as well as in the underlying peat layer (Figure 5). In the algal mat, after an increase in the N content in summer this decreased again by autumn; in the peat layer after an important increase in the N content from May to August only a relatively small reduction took place in autumn.

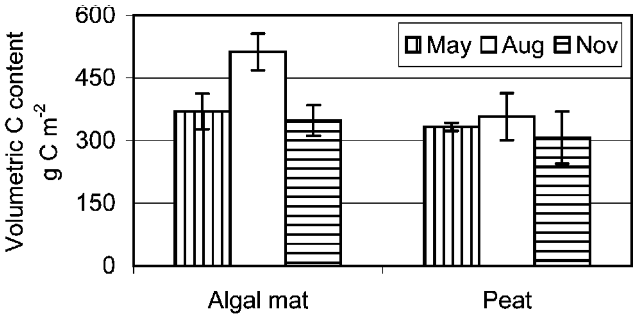

Figure 4 Calculated seasonal changes in the volumetric carbon content in 10 mm thick algal mat and underlying 15 mm thick peat layer per 1 m^2 of mud-bottom hollow surface.

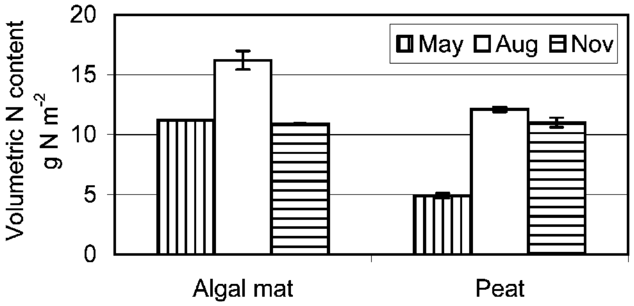

Figure 5 Calculated seasonal changes in the volumetric nitrogen content in 10 mm thick algal mat and underlying 15 mm thick peat layer per 1 m^2 of mud-bottom hollow surface.

Discussion

The results of the *Drosera* method confirmed the assumptions that peat accumulation is retarded in mud-bottom hollows. Algae forming their surface decompose more easily as compared to *Sphagna*, and in the long term do not result in the accumulation of organic matter. However, the *Drosera* method does not allow detection of potential peat loss by erosion or oxidation. Peat loss by windblow and water erosion could be important in gullies on blanket mires (Tomlinson, 1982; Tallis, 1997; Large and Hamilton, 1991) where the corresponding maximum rate of surface lowering could reach 30 mm yr^{-1} being on average 5–6 mm yr^{-1} (Anderson, 1997). However, in relatively small mud-bottom hollows with an almost flat surface formed by a dense algal mat on a negligible slope of the bog surface, water erosion is likely to be minimal or absent and no sign of it has been observed. Therefore in mud-bottom hollows detected peat loss should be caused mainly by peat oxidation favoured by relatively high temperature at and just under the dark bare peat surface (Karofeld and Toom, 1999). Nevertheless, the lengthening of measuring strings and pins should be interpreted not only as a result of peat oxidation but also as an integrated value of peat accumulation and decomposition.

The difference in the results during the same year was likely determined more by heterogeneity between the sites and not so much by possible difference between strings and pins. The results from different years are not directly comparable because of different exposure periods. Recalculation of the results to the 100-day period should be taken with care since during the measurement period the decomposition rate differs. Decomposition processes are strongly influenced by temperature. So the biggest length increment of strings was measured in 1999 with the shortest exposure period but with the highest mean air temperature (+16.7°C) during the period 15 May–15 August. In 2000, the exposure period was longest, but the lowest mean air temperature (+14.8°C) of three years resulted in the smallest increase in the strings and pins length (meteorological data: personal communication with A. Kimmel, Head of Tooma Mire Station). Because in 1999, with the highest mean air temperature, pins were not used, this could be one explanation for the difference between the results from strings and pins.

As a result of two processes – lowering of mud-bottom hollows surface by 1.95 mm yr^{-1} (Figure 3) and peat accumulation 0.9–1.7 mm yr^{-1} (Ilomets *et al.*, 1995) in surroundings with *Sphagnum* mosses – the surface of mud-bottom hollows becomes lower in time. The formed depressions can be overgrown or, if existing for a longer period, they may initiate formation of new hollows (Karofeld, 1999) and thus have a major role in the differentiation of bog surface microtopography.

Calculations of the volumetric carbon and nitrogen content in the algal mat and underlying peat layer in mud-bottom hollows revealed important seasonal changes. The main increase in the C content in the algal mat from May to August may indicate intensive CO_2 fixation in photosynthesis. In autumn, photosynthesis is retarded but decomposition processes under the surface may continue, resulting in the C loss. In the underlying peat layer a small increase in the C content from May to August is most likely caused by the downwash of fresh organic particles and DOC from the algal mat above (Figure 4). As shown by Charman *et al.* (1999) the downward transport of dissolved organic matter is probably more important than thought earlier. In autumn, the peat layer stays warmer for a longer time compared to the surface, thus keeping decomposition processes active leading to the reduction in the carbon content of peat. The net result is that this leads to the loss of organic matter and carbon from the surface layer of mud-bottom hollows.

In northern mires an average net accumulation rate of carbon is *c.* 20 g C m^{-2} yr^{-1} (Gorham, 1991; Tolonen and Turunen, 1996; Vitt *et al.*, 2000). In this context the mud-bottom hollows are exceptional features in bogs, because as confirmed by the different methods of measurement the peat accumulation is stopped there and owing to the peat oxidation their surface layer is lowering by 1.95 ± 0.75 mm yr^{-1}. It was revealed that the carbon loss from the uppermost 25 mm thick layer of mud-bottom hollows is *c.* 50–60 g C m^{-2} yr^{-1} compared to C accumulation in *Sphagnum*-covered areas about 70 g m^{-2} yr^{-1} (Ilomets, 1996). However, the actual rate of carbon loss from the unit area of mud-bottom hollows is most likely even bigger than calculated above for the uppermost 25 mm layer, whereas owing to the relatively high temperature under the mud-bottom hollows decomposition processes occur also in deeper peat layers.

Minor changes in the C/N ratio of the algal mat could indicate that both carbon and nitrogen are fixed and mineralized to the same extent (Henrichs and Farrington, 1987). If the source for carbon content increase is the binding of CO_2 in photosynthesis, then the blue-green algae and bacteria on the surface of mud-bottom hollows able to fix the atmospheric nitrogen may be responsible for the increase in nitrogen content during summer (Figure 5). In autumn the growth of algae stops and nitrogen will be mineralized and partly downwashed into deeper layers causing the increase in peat volumetric N content.

Mud-bottom hollows cover a large part of the area of some bogs in the Boreal zone and they appear to be exeptional features in carbon-accumulating bogs. Because of the cessation of peat accumulation, accelerated decomposition processes resulting in organic matter and carbon loss and increased emission of decomposition gases from the surface of mud-bottom hollows, they play a major role in the differentiation of bog surface microtopography and carbon budget. With predicted climatic changes and temperature increase in northern areas, mud-bottom hollows may become significant natural sources of greenhouse gases.

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