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Carbon storage change in a partially forestry-drained boreal mire determined through peat column inventories

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To study the impact of forestry drainage on peat carbon storage, we cored paired quantitative peat samples from undrained and drained sides of an eccentric bog. Five pairs of 0 to ≤ 100-cm-deep surface-peat cores, and a pair of profiles representing the full peat deposit provided stratigraphic evidence of marked loss of surface peat due to drainage. For the drained side cores, we found a relative subsidence of 25–37 cm of the surface, and a loss of about 10 $\mathrm{kg_{DW}\ m^{-2}}$, corresponding to 131 ± 28 $\mathrm{g\ C\ m^{-2}\ a^{-1}}$ (mean ± SE) for the post-drainage period. Similar peat loss was also found in the full deposit profiles, thus lending credibility to the whole-column inventory approach, even though the decrease (9 $\mathrm{kg_{DW}\ m^{-2}}$) was relatively small in comparison with the total carbon storage (233 and 224 $\mathrm{kg_{DW}\ m^{-2}}$ for the undrained and drained sides, respectively).

Introduction

Peatland drainage and carbon cycling

Boreal peatlands are globally among the most significant long-term terrestrial sinks of carbon (Post *et al*. 1982, Strack *et al*. 2008), and their carbon (C) dynamics have become a matter of broad scientific interest. While there is a lot of accurate data on the C dynamics of natural mires, the effects of drainage on C dynamics and balance of boreal peatlands are more uncertain. Drainage of mires for agriculture clearly turns the peat into a net source of C (Maljanen *et al*. 2004). However, the possible impacts of forestry-drainage on peat soil CO_2 balances and C storages are a more complicated issue. Considerable variation has been found in the soil net greenhouse gas balances of drained forest sites in different trophic and climatic conditions (Alm *et al*. 1999a, 2007a).

Monitoring of C flows and its shortcomings

There are several approaches to determine the C balance of forestry-drained peatlands. Most of the current knowledge is based on measurements of instantaneous fluxes of CO_2 and CH_4 using closed chambers or micrometeorological eddy-covariance (EC) tower techniques (Alm *et al*. 2007b). Net gas balance of a peatland is the result of input and output components, e.g. litter accumulation, biomass decomposition and soil respiration. CO_2 chamber systems provide accurate soil respiration data during the measured periods, but estimating C balances of the peatland

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forest soils is not directly possible using this method. Several important factors, such as dissolved organic carbon (DOC), must be assessed separately. According to Aitkenhead and McDowell (2000), DOC export from temperate and boreal terrestrial catchments may range from 1 to 50 g m^{-2} a^{-1}, with the largest values connected with high runoff or high degree of paludification. The average DOC leaching from all forested catchments in Finland is estimated at 5–6 g m^{-2} a^{-1} (Kortelainen and Saukkonen 1998). Sallantaus (1992) reports that forestry drainage has significantly increased the output rates of DOC from paludified catchments: on the average from 8.0 to 14.1 g m^{-2} a^{-1} on drained fen catchments and from 12.4 to 16.6 g m^{-2} a^{-1} on drained bog catchments.

Estimates of C input into peatland forest soils, based on studies of litter production and decomposition, are hampered by broad uncertainties (Laiho *et al.* 2008). Some studies have suggested that forestry-drained peatlands are C sinks while the increased wood, root and litter biomass appears to compensate for the declining moss production and increasing soil respiration (e.g. Cannel *et al.* 1993, Minkkinen *et al.* 1999). On the other hand, gas exchange measurements indicate increased C emissions from the peat of drained sites (Martikainen *et al.* 1995, Alm *et al.* 1999b, Silvola *et al.* 1996).

The recent gas exchange studies of Minkkinen *et al.* (2007) and Ojanen *et al.* (2010) from altogether 71 drained peatland sites indicate values of heterotrophic soil respiration ranging from 200 to 900 g C m^{-2} a^{-1}. Considering the C input estimates of peatland forest soils of 300–400 g m^{-2} a^{-1} (Laiho 2006, Laiho *et al.* 2008), some of the peatland sites may act as C sinks and others as C sources. Besides between-site variability, the large interannual variability is a further serious source of uncertainty for the monitoring-type studies, which are rarely carried out for periods long enough to cover the full range of possible conditions. For example, temperature during the thawed-out season is known to profoundly affect the rate of soil respiration (Ojanen *et al.* 2010).

Peat inventory and the present study

Peat inventory analyses provide an alternative approach for carbon balance studies. Even though the study sites must meet rather specific preconditions, the approach will give direct answers to the central question: What is the net change of the carbon store of a particular peat deposit?

The aim is to measure the total C storage at a single site before and after the drainage or to compare carbon storages of statistically representative samples of undrained and drained mires. The obtained C mass difference is the total C storage change through the time. To observe real changes, a long enough time interval, preferably some decades, must have passed since the ditching. Principally, there are three different settings in which such changes can be studied.

Firstly, sites at which relevant measurements had been properly made some decades ago can be revisited to assess the present-day situation. In Finland, such data are available through the peatland inventory database of the Geological Survey of Finland (Pitkänen *et al.* 2011, Simola *et al.* 2012).

Secondly, the peat carbon pools may be compared between undrained and drained mires. Minkkinen and Laine (1998a) made an attempt to compare the peat bulk masses of natural and drained mire sites that originally represented the same mire type. As it is, their approximative stratigraphic matching of the data could not guarantee that the compared inventories represented equal periods of peat accumulation. Thus their results, indicating a considerable increase in the peat C stores in the drained sites remain questionable. Mäkilä and Goslar (2008) studied peat accumulation in drained and undrained mires using radiocarbon-dated peat sections. Their data for the past 300 years indicate higher values in undrained mires, the difference between drained and undrained sites being on average 3.2 kg C m^{-2}.

Thirdly, there are partially-drained peat bogs making it possible to compare the peat profiles from adjacent undrained and drained parts of the same mire. This type of a setting is described in the present paper. The approach has been tried earlier a few times (Anderson *et al.* 1992, Sakovets and Germanova 1992, Minkkinen *et al.* 1999) with somewhat controversial results, again, owing to lacking control of the full comparability of the sites.

We made peat and C mass comparison of peat profiles on a partially drained eccentric bog, on which the ditches run parallel to the natural water flow. As judged by surface topography and vegetation, the drainage effects at this site seem to be rather strictly confined to the ditched part. Further, our goal was to analyze the accuracy and repeatability of quantitative whole-profile peat inventory.

Study site and methods

Site characteristics

Rahesuo mire is a fairly large eccentric raised-bog complex with a total area of 750 hectares (7.5 km^2) situated in Ilomantsi, eastern Finland (62°52´N, 31°10´E; Fig. 1). Most of the bog complex has been drained, but in its western part about 30 ha remains in a natural condition. The dominant original mire types were ridge-hollow pine bog and tall-sedge fen. The exact ditching year could not be verified from documentary sources, so we determined it by the post-drainage growth increase of local Scots pine (*Pinus sylvestris*) trees. Based on the year-rings of six individual pine trees, the ditching took place in 1971–1972.

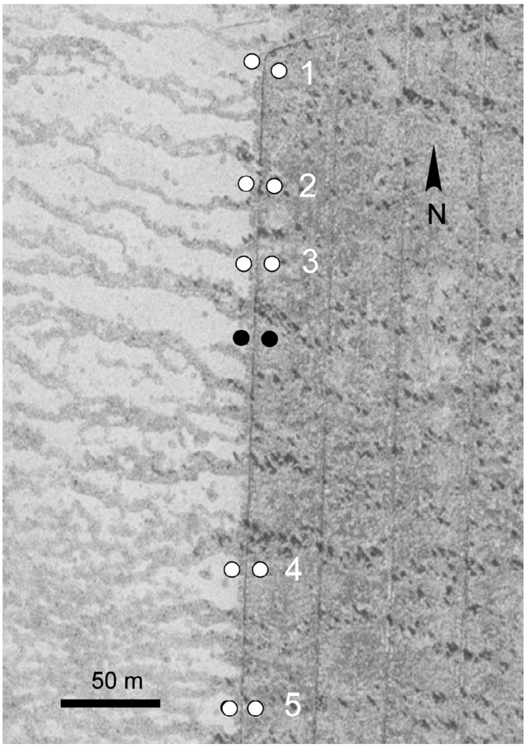

Fig. 1. An aerial photograph of Rahesuo. The hummock-hollow pattern and the drainage ditch system are visible (drainage direction and natural water flow are towards the north). The coring points for the full profile peat inventory are indicated with black dots, and those for the short surface cores with white, numbered dots (copyright Maanmittaushallitus).

The natural part is almost open, with only scattered small pine trees, while on the drained part the pines grow more densely, mainly on the former ridge surfaces, reaching a maximum height of about 5 m; even here the timber stock is less than 10 m^3 ha^{-1}. In forestry, such peatland drainage result is considered economically unfeasible. The site is representative of those 8000 km^2 of peatlands out of 49 000 km^2 drained that are already left out of forestry. Surface vegetation of the natural mire in the study area is a regular mosaic of wet hollow or lawn surfaces and drier ridges. The vegetation cover of the drained part is profoundly changed because of the drier conditions on the surface, but the original ridge-hollow topography is still discernible. We calculated indicator species values (*see* Dufrene and Legendre 1997) from the data of plant species cover of 20 vegetation plots (1 m^2) distributed on the ridges and hollows in both the natural and drained area. The indicator species values represent abundance of species in a certain habitat in proportion to abundance in the whole data (Table 1). In the drained area, typical forest mosses were met on the ridge hummocks. The hollow surfaces in the drained area were characterized by *Polytrichum strictum* and *Mylia anomala*, in place of the characteristic *Sphagnum* spp. of the natural hollow vegetation.

Because the drainage ditches in this part of Rahesuo run almost parallel to the natural water flow direction (perpendicular to the ridges; Fig. 1), the drying effect apparently extends only a few meters to the natural side of the outermost ditch. We took our paired sample cores from large well-defined hollows that were clearly discernible on both sides of the marginal ditch (Figs. 1 and 2). Such extensive hollows should provide an ideal setting for this type of

Fig. 2. View of the coring location of the full profile cores: the cores were taken about 7 m away from the ditch from the undrained (left-hand-side arrow) and drained sides (right-hand-side arrow). Photo: Aki Pitkänen

study because in the natural condition they are dominated by hydrophilic sphagna that grow as a very level horizontal surface and maintain a high water table (Seppälä and Koutaniemi 1985). The hollows are relatively stable and the age of individual hollows may be 2000–3000 years (Karofeldt 1998). Thus, the growth and decomposition rate of the *Sphagnum* peat should have remained fairly similar across a single hollow, and cores taken within a particular hollow even some tens of meters away from each other should be well comparable. Owing to the originally horizontal surface of such a hollow it is possible to measure precisely the subsidence caused by partial drainage and thus determine the corresponding horizontal levels in the compared profiles.

Table 1. Indicator values of plant species (according to Dufrene and Legendre 1997) of the hollow and hummock microhabitats on the natural and drained sides of our coring location. The significances (*p*) of the indicator values from the Monte Carlo permutations (4999 runs) are shown.

Species	Indicator value	*p*
Natural hollow		
Sphagnum balticum	92.1	< 0.001
Carex limosa	100.0	0.001
Scheuchzeria palustris	100.0	0.001
Drained hollow		
Mylia anomala	87.5	< 0.001
Polytrichum strictum	100.0	< 0.001
Natural hummock		
Vaccinium microcarpon	77.2	0.003
Sphagnum fuscum	70.7	0.011
Empetrum nigrum	63.1	0.013
Rubus chamaemorus	56.9	0.030
Drained hummock		
Dicranum spp.	100.0	< 0.001
Pleurozium schreberi	100.0	< 0.001
Betula nana	74.8	0.005
Vaccinium uliginosum	69.0	0.014

Methods

As representative sampling sites we chose large hollows that are dissected by the marginal drainage ditch and are still well discernible even on the dried side. In one hollow, we cored the entire peat column — two replicates from both sides of the ditch — for quantitative total peat inventory analyses. Five additional hollows along a 300-m-long section of the marginal ditch were cored in order to compare the uppermost peat sections (0–100 cm) on both sides (Fig. 1).

At each coring site, we levelled the subsidence of the dried-side coring site relative to the undrained one with aid of a transparent water-filled hose. At the full profile coring site, we levelled the mire surface along a 160-m-long transect parallel to the strings and perpendicular to the ditches.

For the total peat inventory analysis, we sampled two parallel volumetric peat profiles from both the undrained (UNDR) and the drained

(DRA) part of the selected hollow on 26 June 2009. The coring sites were both about 7 m away from the marginal ditch (so the two sites were about 15 m apart), and the distance between the parallel cores from each site was less than 1 m. The uppermost 0–100 cm was cored with a box sampler (80 × 80 × 1000 mm) and the lower parts of the profiles down to the mineral soil were sampled with a Russian pattern side-cutting peat sampler (50 × 500 mm). The coring design is shown in Fig. 3. In the field, each recovered core was immediately sliced into contiguous 10-cm samples which were placed in air-tight plastic bags. In the laboratory, each sample was weighted as fresh (wet weight) and after drying in 105 °C (dry weight, DW). The dry subsamples were homogenized by grinding, and the ignition residue (ash weight) was determined from smaller subsamples after incineration at 550 °C. The dry bulk densities (DB) of the samples were calculated by dividing the dry weight of each subsample by its known initial volume. Values given for the dry bulk density (DB; g_{DW} l^{-1}) and ash content (ash bulk, AB; g l^{-1}, and ash percentage of dry weight) are arithmetic means for each pair of the subsamples from the two parallel cores.

The five additional pairs of surface peat samples were taken with the box-corer, symmetrically from both sides of the marginal ditch, about 15 m from each other and down to the same absolute depth on both sides; about 0–100 cm from the undrained and 0–70 cm from the drained side. Surface levelling performed at each site enabled precise horizontal matching of the two cores, and by visual comparison of them in the field it was possible to identify identical, unaltered strata in the basal parts of each pair. The top part of each core was sampled from above a clear stratigraphic horizon found at the same level in both cores, typically an interface between strongly decomposed (dark) and weakly decomposed (light) *Sphagnum* peat observed in the undrained core at around 60 cm depth and, accounting for the subsidence, around 30 cm in the drained one (Fig. 4). The samples were taken to the laboratory for DB and AB determinations.

Stratigraphical depth is expressed as depth below the peat surface at each of the sampling points, UNDR and DRA. For simplicity, we indicate the individual 10-cm samples by their basal levels, so $\text{UNDR}_{220\text{ cm}}$ refers to the 210–220-cm sample from the undrained site, whereas $\text{DRA}_{0\text{–}150\text{ cm}}$ refers to the total inventories in the uppermost 150 cm of the drained site.

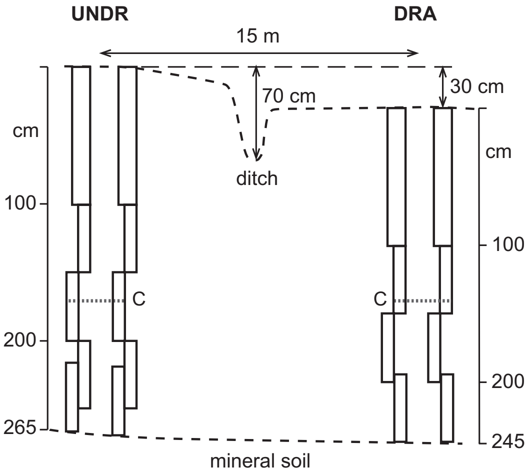

Fig. 3. A diagram showing the sampling arrangement at the full profile coring site. Sample cores taken with the 1-m box corer at the top and with a 0.5-m Russian corer at deeper levels. Depth scales (from surface downwards) given at the margins: left for UNDR = the natural side, and right for DRA = the drained side; the relative positions for the scales based on levelling. A charcoal layer (C) found in both sites is indicated.

When comparing the full peat columns, we used the ash percentage curves to identify the corresponding levels in the UNDR and DRA profiles. As an alternative method, we tried to use the cumulative ash inventories, calculated from the surface downwards. This approach was based on the (eventually discarded) working hypothesis that the ash component is sufficiently immobile to serve as an unvarying measure for the subsidence processes in initially similar peat profiles. For conversion of dry weight into carbon we have used the value 50% for C (dry weight) according to Minkkinen and Laine (1998b) the C content of peat in Finnish mires is 50%–60% of the dry weight.

A paired *t*-test was used to test the difference in peat dry weights between the stratigraphically matched surface sections of the UNDR and DRA surface cores. Before that the data were found to be normally distributed using a Kolmogorov-Smirnoff test.

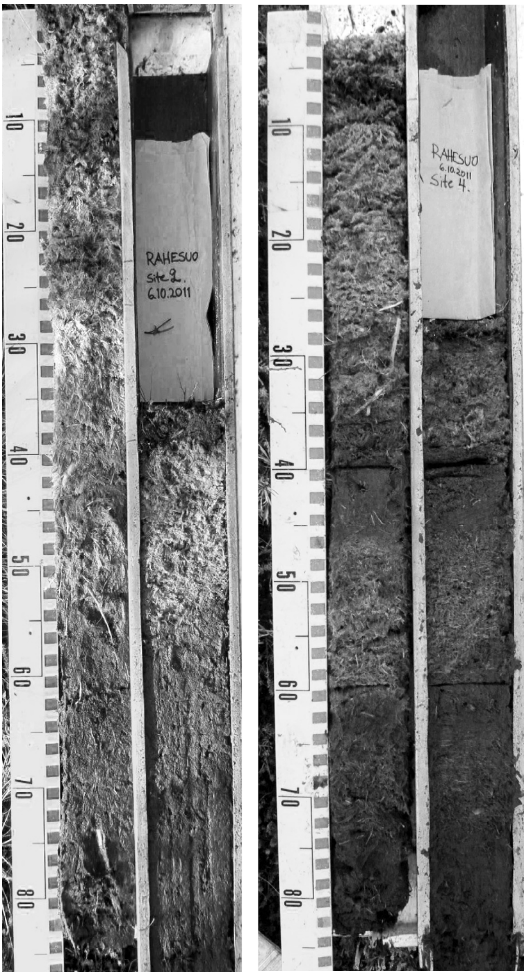

Fig. 4. Two examples of the short peat-core pairs (undrained on the left, drained on the right). Vertical matching according to levelling of the coring site surfaces. In both pairs there is a dark layer of peat with higher humification degree at around 60 cm depth according to the undrained site scale. The top parts above this level were sampled for comparative weight analyses. This and other stratigraphic similarities between the cores show that the drainage-related changes are rather clearly confined to the uppermost peat strata.

Results

Surface subsidence and peat quality changes

Surface levelling at the full-profile coring site, along the 160-m-long transect (at right angles across the marginal ditch), indicated that slight subsidence, or dipping of the surface towards the marginal ditch was evident on the undrained side up to about 20 metres from the ditch. Farther away the hollow surface was 40 cm higher than on the drained side. Only 5 meters away from the ditch margin the surface level of the undrained side was 30 cm higher than on the drained side. At all the coring sites, the measured surface level difference between the two cores was 25–37 cm. Thus, in regard of the observed total of 40 cm, a slight subsidence is indicated even for our undrained-side cores. On both sides, the water table appeared to remain fairly close to the surface agreeing with the poor drainage result: on the undrained side, 2–10 cm and on the dried one only slightly deeper, 5–15 cm below surface (observations in September 2008, June 2009, August and September 2010).

The topmost peat on the undrained side of the cored hollows consisted of poorly decomposed *Sphagnum* peat, with mixed and variously decomposed layers of *Sphagnum*, *Eriophorum* and *Carex* peat deeper down (Table 2). On the dried side, the top consisted of a thin layer of well-decomposed matter (moor humus). Comparison of the paired profiles clearly indicated that the subsidence-related decomposition and compression were confined to the uppermost peat strata only: below about 60 cm in the undrained cores (about 30 cm in the drained ones) the strata appeared virtually identical and unaltered (Fig. 4). In each of the full-profile cores, we observed a thin charcoal layer on the undrained side at 170 cm, and on the drained one at 140 cm, i.e. at the same absolute level thus taken as a synchronous marker level for the cores.

The full column cores: correlation by ash stratigraphies

In all the full-column profiles, the ash percentage curves show a sharp inflection near the bottom, while ash content in the basal parts was much higher than above. At both sites (UNDR and DRA), the two replicates show this inflexion in the same level (Fig. 5A and B). Thus the level $\mathrm{UNDR}_{250\ \mathrm{cm}}$ corresponds with $\mathrm{DRA}_{220\ \mathrm{cm}}$. Considering the 30-cm subsidence of the peat surface at DRA, these depths are actually at the same horizontal level, by which the two series

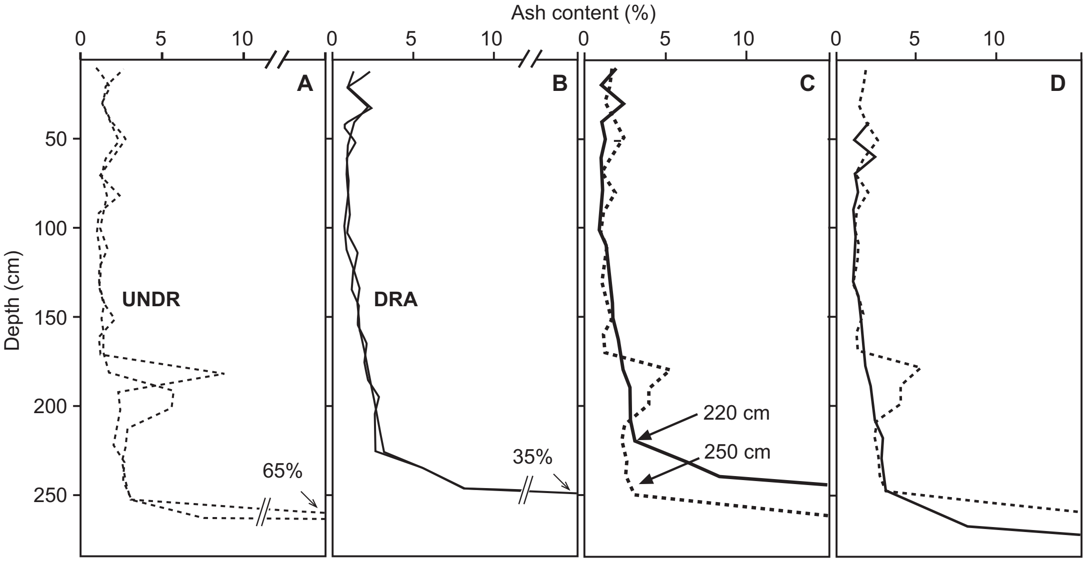

Fig. 5. Ash percentage profile pairs of the replicates, and stratigraphic correlation of the two sites based on ash percentage values. (**A**) The undrained side, UNDR; (**B**) the drained side, DRA; (**C**) averages of the UNDR (dashed line) and DRA (solid line) ash percentage profiles, placed at the same surface level in both curves. The bends in the curves (indicated with arrows) were determined as corresponding stratigraphic levels. (**D**) A good match of the ash percentage profiles of UNDR and DRA is obtained when the corresponding stratigraphic levels of UNDR and DRA shown in **C** are fitted together.

can be matched (Fig. 5C and D). Overall, the ash percentage curves above the matching level appear rather similar, except for some variation and higher values within $\mathrm{UNDR}_{180\text{–}200\ \mathrm{cm}}$ (Fig. 5A). A slight sloping of the mineral soil bottom towards DRA is evident, as the peat layer below $\mathrm{DRA}_{220\ \mathrm{cm}}$ is about 10 cm thicker than that below $\mathrm{UNDR}_{250\ \mathrm{cm}}$ (Fig. 3).

Peat DB, cumulative mass, and carbon loss

The lowermost 70 cm in both profiles were highly similar, which is demonstrated by the almost identical course of the cumulative mass inventories (*see* Fig. 6); the cumulative mass for $\mathrm{UNDR}_{250\text{–}180\ \mathrm{cm}}$ is 62.8 kg m^{-2}, and that for

Table 2. Characteristics of the visually-matched levels in the upper parts of the undrained (UNDR) and drained (DRA) coring sites: degree of peat humification (von Post scale 0–10) and relative abundances of identifiable plant remains. Taking into account the levelled subsidence of DRA relative to UNDR, 30 cm is added to the sample depths of DRA; the actual depths are shown in parentheses.

Matched sample pair	UNDR (cm)	DRA + 30 cm	Humification	
1	25	36 (6)	3	*Sphagnum. balticum* >> *S. majus* > *S. angustifolium*
2	35	40 (10)	3	*S. balticum, S. majus* > *S. angustifolium, S. jensenii*
3	45	46 (16)	4	*S. majus* > *S. balticum* > *S. angustifolium*
4	52	52 (22)	5–6*	*Sphagnum*** >> *Ericacean shrubs* > *Eriophorum vaginatum*
5	58	58 (28)	5	*S. magellanicum* > *S. angustifolium* >> *S. balticum* >> *Ericacean shrubs* > *E. vaginatum*

* More humified at DRA, ** incl. sect. Cuspidata (high humification hindered reliable species identification).

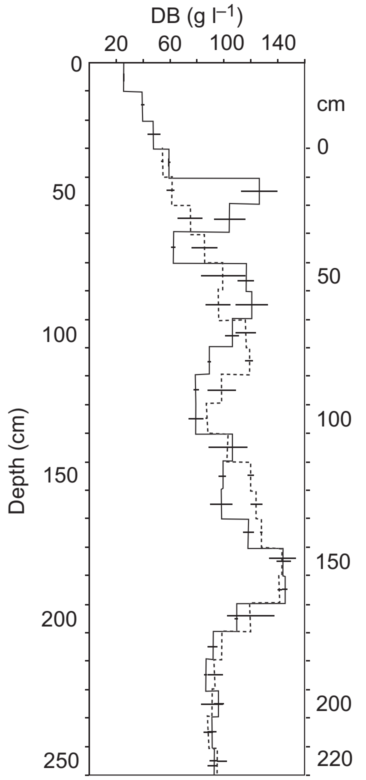

Fig. 6. The average DB values of the stratigraphically correlated UNDR (solid line) and DRA (dashed line) peat profiles. Depth scale for UNDR on the left and for DRA on the right. Horizontal bars indicate the difference between the two parallel samples. Note that in both profiles the lowermost 80-cm sections are virtually identical.

$DRA_{220–150}$ is 63.0 kg m^{-2}. In the upper parts, the two profiles somewhat differ, the DRA slices having generally higher DB values. Thus, the cumulative mass increases faster in the DRA core. However, the total dry mass inventory for $DRA_{220–0\ cm}$ remains lower than that for the $UNDR_{250–0\ cm}$.

The cumulative dry peat mass in $UNDR_{250–0\ cm}$ is 233 ± 3 kg m^{-2}, while the corresponding mean value for $DRA_{220–0\ cm}$ is 224 kg m^{-2} (Fig. 7). This suggests a peat mass loss of 9 kg_{DW} m^{-2} or about 4 kg C m^{-2} in the post-drainage period. Assuming that the mire was drained nearly 40 years ago, the average annual carbon loss is about 100 g m^{-2} a^{-1}. If we take the supposedly synchronous charcoal layers observed in both profiles (UNDR at 170 cm and DRA at 140 cm; Fig. 3) as a new basal level, we get second estimates for the peat DM inventories: 147.8 ± 3.5 and 136.5 ± 1.1 kg m^{-2}, respectively, indicating a loss of 140 g C m^{-2} a^{-1}.

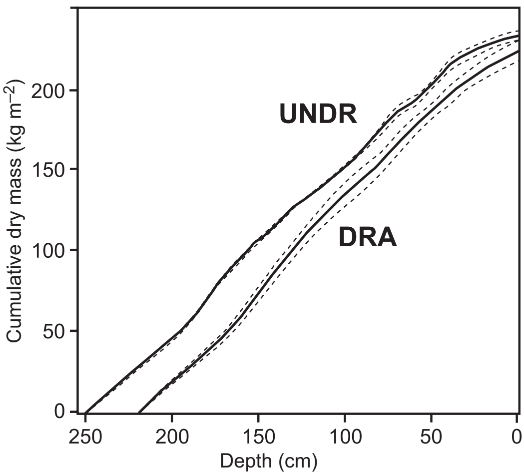

Fig. 7. Cumulative dry bulk masses of UNDR and DRA from the bottom up to the surface. The depth scale indicates for both profiles the depths below their respective surfaces ($UNDR_{0–250\ cm}$, $DRA_{0–220\ cm}$). Dashed lines show the individual cores, thick lines the averages.

Ash loss

The corresponding stratigraphic sections $UNDR_{0–90\ cm}$ and $DRA_{0–60\ cm}$ were found to contain markedly different quantities of ash; 1220 g m^{-2} in UNDR and only 670 g m^{-2} in DRA, which indicates a considerable loss of mineral matter from the uppermost peat at the drained site (all sample variation considered, the loss is in the range 350–550 g m^{-2}).

The short-core samples

Already in the field it became evident that the five sample pairs consistently showed a marked impact of the drainage on the very uppermost peat strata (Fig. 4). Leveling indicated rather regular subsidence of the drained side at each coring location, on the average 31 cm (range 23–37 cm), which by visual inspection coincides with equally regular shrinking of the uppermost peat strata in the drained-side cores (Fig. 4). Peat bulk analyses showed that the subsidence is mainly due to loss of matter of the uppermost peat layer. A consistent loss of organic matter was verified for all the drained-side samples (Fig. 8), corresponding to 131 ± 28 g C m^{-2} a^{-1} (mean ± SE). The dry mass loss in the corresponding surface sections of the UNDR and DRA cores was statistically significant (paired *t*-test: $t_4 = 4.908, p = 0.008$).

The UNDR and DRA profiles also differed with regard to their bulk densities. The average DB of $UNDR_{0–60\ cm}$ is 55 g l^{-1}, while in the roughly-corresponding 0–30 cm of DRA the value is 79 g l^{-1}. Thus, besides the proven losses of material, peat compaction is also contributing to the observed surface subsidence. It is worth noticing that the short-core result of carbon loss is practically the same as that obtained from the whole-column C loss assessment, thus lending credibility even for the latter approach, in which the observed decrease was fairly small relative to the total carbon storages compared.

Discussion

Rahesuo as a study site

We wish to emphasize the particular drainage conditions at our study site in Rahesuo, where an extensive bog is partially drained so that the ditches run precisely along the natural water flow. This offers quite a rare setting to study the effects of drainage on peat stores as well as the validity and reproducibility of quantitative peat column inventories. The short-core sample pairs from this unusual site that we were able to study, provided clear evidence of the profound effects of drainage on the uppermost peat strata, and enabled assessment of the relative roles of the two main processes involved in surface subsidence, namely peat decomposition and compression. Furthermore, the short-core samples provided good support for the more tediously performed, but also more generally applicable total-column analysis approach (cf. Pitkänen *et al*. 2011, Simola *et al*. 2012).

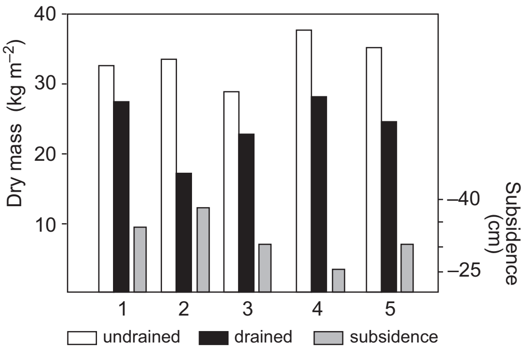

Fig. 8. Comparison of the peat masses of the matched short-core pairs 1–5.

It may be reasonable to ask: how representative is Rahesuo of the more than 50 000 km^2 of forestry-drained peatlands in Finland? For one thing, as concerns forestry, the site is a failure, but so is a fairly large proportion of all forestry-drained peatlands (Keltikangas *et al*. 1986, MMM 2011); at present, some 8000 km^2 of forestry-drained peatlands have been dropped from active forestry, and some further thousands of square kilometers may be abandoned as non-profitable in the next 10 to 30 years, after the first post-drainage tree stand is logged. On the other hand, the drainage effects as such appear quite ordinary and typical (surface subsidence, vegetation changes).

It has been proposed (e.g. Laiho 2006, Laine *et al*. 2006, Lohila *et al*. 2011) that on successfully forested drained peatlands, the increased litter production by the growing tree stock would compensate for eventual decomposition losses in the soil. However, our studies of pine seedling root collar burial depths (Pitkänen *et al*. 2012) actually showed at properly forested sites (timber stock > 150 m^3 ha^{-1}) somewhat smaller apparent C accumulation rates than at sites with smaller timber volumes. Furthermore, in a study of total peat mass changes involving re-analysis of 37 old inventory sites (Simola *et al*. 2012), we found an average net C decline, but no correlations between the C balance and timber stock.

In summary, the Rahesuo site would appear representative of the drainage-related changes. In Rahesuo, such changes can be quantitatively assessed, whereas they are notoriously difficult or quite impossible to quantify at most of the similarly impacted peatland sites.

Ash loss

Our initial working hypothesis was that the ash would be quantitatively retained even in the subsided (partly decomposed and partly compressed) peat after drainage, and thus it might be possible to use the cumulative ash inventories as a yardstick to compare profiles before and after the drainage. The observed ash loss, 350–550 g m^{-2} on the drained side, strongly argues against the idea of using the cumulative ash weights for correlation of stratigraphic levels between peat profiles. In addition, random differences between the ash content series, such as within the generally well matching lower parts of our UNDR and DRA profiles (cf. $\mathrm{UNDR}_{200\text{–}180\ \mathrm{cm}}$; Fig. 4) further disqualifies the method.

Based on the existing published data on the leaching and tree uptake of the main minerals (Ca, K, Mg, Al, and Si) from drained peat soils, we expected leaching to be quantitatively of rather minor significance (Sallantaus 1992, Laiho and Laine 1995, Laiho *et al*. 1999, Westman and Laiho 2003). Also, the data of Minkkinen *et al*. (1999) and Laiho *et al*. (1999) suggest relatively small differences in ash contents between drained and undrained surface peats. These studies may provide a biased view considering leaching of mineral matter, because they merely deal with the concentrations without regarding the effects of peat compaction on the site stratigraphy. Owing to post drainage subsidence of peat, the peat cores from drained sites contain material that is stratigraphically from deeper layers than equally thick peat layers sampled from undrained sites. In addition, capillary and evapotranspiratory transfer of solutes from the deeper peat strata may possibly compensate for the nutrient losses in the surface peat (Laiho *et al*. 1999).

The relatively high loss of ash matter in the DRA appears to be mainly due to leaching, while at this site the mineral nutrient uptake by trees (Laiho *et al*. 1999) would likely play an insignificant role. Unfortunately, there seem to be no published accounts of leaching of mineral constituents from drained peatlands in Finland since the study by Sallantaus (1992). The figures in Sallantaus (1992) suggest a gross leaching rate of about 2 g m^{-2} a^{-1} for P, Mg, N, K and Ca. Our data from Rahesuo indicate a mineral leaching rate in the range of 10–20 g m^{-2} a^{-1}, which is at least five times higher than that of Sallantaus (1992).

Surface subsidence and peat compaction

A major part of the immediate post-drainage peat subsidence is caused by compaction of the uppermost peat layer. Water drawdown instantaneously destroys the buoyancy of the previously waterlogged peat, which leads to volume collapse and decline in porosity of the surface layers. Further subsidence takes place gradually, mainly by the oxidation and decomposition of the peat (Paavilainen and Päivänen 1995). Also, the pressure from the growing tree mass may contribute to the peat compaction (Minkkinen and Laine 1998b). Minkkinen and Laine (1998b) compared the dry bulk density values of the surface peat layers (0–80 cm) of natural and drained pine bogs and reported a mean DB increase of 51 kg m^{-3} for 60-year-old drained sites in southern Finland.

Comparing the Rahesuo profiles the same way as Minkkinen and Laine (1998b) did, shows that the average DB of $\mathrm{DRA}_{0\text{–}80\ \mathrm{cm}}$ is only 15 kg m^{-3} higher than that in $\mathrm{UNDR}_{0\text{–}80\ \mathrm{cm}}$. Most of this increase is due to big differences within the top 30 cm (averages 37 *vs*. 63 kg m^{-3} in UNDR and DRA, respectively). Below the 30-cm level, the dry bulk densities do not markedly differ between the sites.

If it were just a matter of peat compaction without mass alterations, the observed 30-cm surface subsidence in DRA relative to UNDR would actually have led to much higher DB increase. Compaction of the top 1 m of the undrained peat ($\mathrm{UNDR}_{0\text{–}100\ \mathrm{cm}}$) by 30 cm should have increased the average DB of the corresponding $\mathrm{DRA}_{0\text{–}70\ \mathrm{cm}}$ from 80.8 to 116 kg m^{-3}. However, the found average DB in $\mathrm{DRA}_{0\text{–}70\ \mathrm{cm}}$ is only 84 kg m^{-3}, suggesting a significant loss of peat after the drainage.

Accuracy of the total-column inventories

The present case study demonstrates that the peat storage approach and inventory analyses are a feasible method to study the effects of draining on peatland C balance. Comparison of the total-column results indicates a definite but statistically insignificant loss of peat mass on the drained side. The insignificance may have resulted from the marked variation between the two replicates cored from both sides, and the fact that the found difference (9 kg m^{-2}) was only about 5% of the total masses of the profiles. However, the loss was corroborated significantly by the five short-core pairs, which could be matched both with horizontal levelling and with visual correlation of the peat strata, and which yielded closely similar result (9.4 kg m^{-2} loss on the drained site).

Volumetric accuracy of the sampling procedure is a very important factor, especially in the whole-profile inventory analysis, where the aim is to quantify relatively small differences between cores. Since the cumulative dry mass values obtained in the present study for comparison of the DRA and UNDR profiles are sums of average DB's of 10-cm subsample pairs, one could suspect that accumulating errors in sampling, drying and weighting would obscure the potential of comparing adjacent peat cores. Comparison of the cumulative mass values obtained from our replicate sample cores indicates rather small differences between the replicates (Fig. 7), 2.3% and 5.8% of the totals, for UNDR and DRA, respectively, suggesting that sampling errors are of low significance. Main source of the differences in the cumulative dry mass values may be horizontal variations in peat density, which may cause significant differences in the DB values of peat cores taken from spots as close as about one metre from each other (Tolonen and Ijäs 1982). This type of real between-core variation is evident even in our data (Figs. 6 and 7).

Our results indicate that the potential loss of peat mass induced by drainage occurs in the surface peat. Thus the deeper deposits, if included in cumulative mass assessment, are merely a potential error source. The error caused by random between-core variation can be reduced if it is possible to compare inventories of shorter core sequences. For this, sites with shallower peat depths would be applicable, or one should find reliable stratigraphic marker horizons in the upper parts of the profiles, such as charcoal layers or clear and corresponding changes in the ash percentages.

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