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ORIGINAL ARTICLE

Carbon loss estimates from cultivated peat soils in Norway: a comparison of three methods

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Abstract Drainage and cultivation of peat soils stimulates soil organic matter (SOM) mineralization, which substantially increases CO_2 emissions from soils. Large uncertainties are associated with this CO_2 flux, and little data are available, especially in Norway. The objective of the present research was to estimate C losses from cultivated peatlands in West Norway by three independent methods: (1) long-term monitoring of subsidence rates, (2) changes in ash contents, and (3) soil CO_2 flux measurements. Subsidence of cultivated peat soils averaged about 2.5 cm year^{-1}. We estimated that peat loss and compaction were respectively responsible for 38% and 62% of the total subsidence during a 25-year period after drainage. Based on this estimate the corresponding C loss equals 0.80 kg C m^{-2} year^{-1}. The observed increase in mineral concentration of the topsoil of cultivated peat is proportional to their C loss, providing no mineral particles other than lime and fertilizers are added to the soil. Using this novel approach across 11 sites, we estimated a mean C loss of 0.86 kg C m^{-2} year^{-1}. Soil CO_2 flux measurements, corrected for autotrophic respiration, yielded a C loss estimate from cultivated peat soils of 0.60 kg C m^{-2} year^{-1}. The three methods yielded fairly similar estimates of C losses from Norwegian cultivated peatlands. Cultivated peatlands in Norway cover an estimated 63,000 ha. Total annual C losses from peat degradation were estimated to range between 1.8 and 2 million tons CO_2 year^{-1}, which equals about 3–4% of total anthropogenic greenhouse gas emissions from Norway.

Keywords Soil loss · Peat subsidence · Peat compaction · Soil CO_2 flux

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Introduction

Peat soils cover about 2–3% of the global land surface, but store approximately one-third of the total organic C, which is about equal to the total amount of C stored in the atmosphere or in all terrestrial biomass (Joosten and Clarke 2002). Due to cold climate, peat soils are mostly found in arctic and sub-arctic regions. In Norway, peat soils cover nearly 24,000 km^2 or 7% of the land area (International Peat Society).

It has been known for a century that drainage and cultivation of peat soils lead to subsidence and C loss as CO_2. This loss has mainly been considered as an agricultural problem, especially when the peat is overlying bedrock or mineral soil unsuitable for cultivation. More recently, the effects of peat drainage and cultivation on soil CO_2 emissions have become a major concern. The CO_2 efflux from Swedish cultivated peat soils was reported to reach up to 70 ton CO_2 ha^{-1} year^{-1} (Kasimir-Klemdtsson et al. 1997). Although this value is particularly high, other studies report substantial rates such as 22 ton CO_2 ha^{-1} year^{-1} in Norway (Grønlund et al. 2006), and between 15 and 27 ton CO_2 ha^{-1} year^{-1} in Finland (Maljanen et al. 2001). While the emissions are potentially large, the uncertainty on these estimates is also quite large.

Historically, two field methods have been used to estimate C losses from cultivated peat soils: (1) subsidence rate measurements (Kasimir-Klemedtsson et al. 1997), and (2) direct gas flux measurements. Both methods suffer from uncertainties. Peat subsidence after drainage and cultivation results from the combined effects of compaction and soil loss through soil organic matter (SOM) mineralization. In theory, the exact C loss from peat can be calculated from initial and final peat depths, C concentration profiles and bulk density profiles. In practice, such data are never available, which calls for estimates of the relative contributions of compaction versus that of C loss.

Direct CO_2-flux measurements are generally limited to few locations and conducted during a short period of time such as one year (e.g. Maljanen et al. 2001; Grønlund et al. 2006). In addition, net ecosystem CO_2 flux measurements require information on plant biomass accretion or yield exports to infer changes in peat organic C (Kasimir-Klemdtsson et al. 1997). If total soil respiration is measured, then both yield measurements and allometric relationships with gross photosynthesis are necessary (e.g. Grønlund et al. 2006). The uncertainty on the CO_2 flux is often large, sometimes exceeding ten times the estimated average value (Nieveen et al. 2005).

In the present paper, we argue that a third method for estimating C losses from cultivated peat soils should be considered. This method is based on the progressive increase in peat mineral content after drainage and cultivation, as measured over long time period by Sorteberg (1983). Organic matter loss can be computed, assuming that it is the essential driver for the concomitant increase in soil mineral content. Here we will detail this method and discuss its associated hypotheses.

The overall objective of the present research was to estimate total C losses from Norwegian cultivated peat soils. The first objective was to refine rate estimates by confronting three different and independent methods: (1) from subsidence measurements, (2) from changes in peat mineral contents and (3) from soil CO_2 flux measurements. The second objective was to translate these rates into total cumulative losses over Norway using existing soil databases.

Material and methods

Soil database

The agricultural soil database of the Norwegian Institute for Agricultural and Environmental Research contains soil analyses from 65% of the farms in Norway with a mean sampling density of 0.8 samples ha^{-1}. In addition to chemical analyses, soil samples are classified in 12 texture classes for mineral soils and two classes for organic soils. The organic soil classes include (1) mixed organic-mineral soil with 20–40% SOM and (2) organic soil with >40% SOM. The SOM content is calculated from the bulk density of the air dried sifted soil by means of pedotransfer functions for Norway as reported by Øien (1988).

Assuming equal sampling density on organic and mineral soils within each county, the area coverage of organic soils is calculated from the share of samples with organic soils and the cultivated area within the county. County estimates were then aggregated to regional and national levels.

Databases and field measurements

The location of the fields included in this study is presented in Fig. 1. Peat subsidence rates were estimated separately for Smøla Island for the 1951–2004 period, and across 11 fields located in five different counties for the 1952−1982 period. Here we will refer to the first set of measurements as “Smøla” and the latter as “5-county”. The Smøla dataset was built on (1) data reported by Hovde (1987) for the 1951–1983 period, (2) data reported by Frøseth and Celius (1991) for 1988, and (3) original

Fig. 1 Map with the location of the sites for C loss measurements in addition to county boundaries and names. Black bullets indicate 5 county study sites and the white bullet the gas flux site

measurements conducted in 1993 and 2004 and reported here for the first time. The Smøla measurements were conducted at five different fields. If not mentioned otherwise, "Smøla" refers to the average of these five fields. The fields were drained before 1950, and most of them also in 1979. The crop was mostly grass, but in some years potatoes, vegetables and barley. The detailed Smøla dataset was used to separate the soil-loss versus compaction components of subsidence. This factor was then applied on the 5-county subsidence estimates, as recomputed from Sorteberg (1983). The 5-county peat subsidence data from Sorteberg (1983) were collected at 1,336 points (Table 1). The two fields on Smøla Island included in the 5-county dataset were different from those used for the above mentioned repeated Smøla measurements.

Peat ash content data were also obtained from Sorteberg (1983) and therefore cover the same time period as the 5-county subsidence data (Table 1). Data were reported for 11 fields, whereof 10 fields coincide with the above-mentioned subsidence-measurement fields. A total of 148 samples were analysed for initial ash content and 193 samples for final content. Initial ash content was not available at the fields Søgne and Tysvær II and was therefore estimated as the mean value of initial ash contents of the other 9 fields.

The 5 counties included in this study contributed with about 50% of the total area of cultivated peat soils in Norway (Table 2). Rogaland, the county with the largest cultivated peat area, was also represented with the highest number of sites and observation points.

Soil CO_2 efflux measurements were conducted at Bodø in Nordland County in Northern Norway, as reported by Grønlund et al. (2006). The peat deposit has a decomposition degree of H3–H4 (Von Post 1922) and an average depth of 70 cm. The underlying mineral soil is a marine sediment of loamy texture. The saturated hydraulic conductivity is moderately slow and the ash content is low. Detailed soil description is provided by Grønlund et al. (2006).

Mean annual temperature and precipitation for the studied sites is presented in Table 3. Despites large distances, the mean temperatures are rather similar

Table 1 Sites for measurements of peat subsidence, bulk density and ash content

Site	County	Observation points	Initial depth (m)	Subsidence total (cm)	Years	Bulk density (g cm$^{-1)}$	Number of ash samples	Ash content (g 100 g^{-1})	
								Initial	Final
Søgne[c]	Vest-Agder	69	3.37	67	27	0.171	23	n.d.	7.7
Klepp	Rogaland	195	1.84	36	29	0.288	25	5.4	14.6
Time[b,c]	Rogaland	192	1.66	29	27	n.d.	0	n.d.	n.d.
Tysvær I	Rogaland	58	3.24	57	28	0.212	8	3.9	9.1
Tysvær II[c]	Rogaland	110	2.74	66	24	0.23	14	n.d.	10.0
Tysvær III	Rogaland	129	2.28	57	29	0.26	5	8.9	15.0
Fjell	Hordaland	122	4.27	74	30	0.209	6	4.7	8.6
Radøy	Hordaland	62	1.75	42	28	0.231	5	3.4	7.9
Meland[a]	Hordaland	147	n.d.	n.d.	n.d.	0.221	24	4.5	9.5
Smøla I	Møre and Romsdal	120	3.61	108	30	0.147	39	2.2	8.7
Smøla II	Møre and Romsdal	111	2.44	38	30	0.156	36	4.6	9.6
Steinkjer	Nord-Trøndelag	168	1.97	39	28	0.158	8	3.0	10.1
Mean			2.65	56	28	0.208		4.5	10.1
St.d.			0.83	22		0.043		1.9	2.5

[a] Estimated depth and subsidence

[b] Estimated density

[c] Estimated ash concentration

Table 2 Counties included in the 5-county study, distribution of cultivated soil related to number of field and observation points

County	% of cultivated soil		Studied areas		
	Organic	Total cultivated	Sites	Number of fields	Observation points
Vest-Agder	5	2	Søgne	1	69
Rogaland	19	9	Klepp, Time, Tysvær	5	684
Hordaland	12	5	Fjell, Radøy, Meland	3	331
Møre og Romsdal	6	6	Smøla	2	231
Nord-Trøndelag	7	9	Steinkjer	1	168
Sum	51	30		13	1,483

and vary from 4.3°C in Bodø to 7.6°C in the fields in Hordaland (Fjell, Radøy and Meland). The variation in precipitation is larger, from 960 to 2,150 mm year^{-1}, with the highest precipitation in the sites with the highest temperatures.

Calculation of loss from of peat subsidence

Peat subsidence results from both compaction and peat loss processes. In theory, the peat loss component is equal to:

$$peat_{loss} = BD_{ini} \times Z_{ini} - BD_{fin} \times Z_{fin}, \quad (1)$$

where BD is density, Z is depth, and *ini* and *fin* subscripts stand for initial and final conditions. In practice, however, this formula is generally not applicable because: (1) the depth is not always reported as carefully as the subsidence itself, and (2) the change in bulk density is not uniform across the peat and rarely available throughout the depth of the peat profile. Instead, here we will try to separate loss from compaction components based on repeated

Table 3 Mean annual temperature and precipitation of the studied sites

Site	°C	mm
Søgne	7.0	1,380
Klepp, Time	7.2	1,260
Tysvær	7.4	1,630
Fjell, Radøy, Meland	7.6	2,150
Smøla	5.7	1,155
Steinkjer	4.4	960
Bodø	4.3	1,020
Mean/sum	6.2	1,365

subsidence measurements and the shape of the subsidence curve. The initial phase of consolidation largely dominates the subsidence process for several years after drainage. For this reason, subsidence as a proxy for C loss can only be used multiple years after drainage (Berglund 1989 in Kasimir-Klemdtsson et al. 1997). We followed this principle by breaking the subsidence curve obtained at Smøla in two distinct phases: (1) rapid subsidence following a drainage event, and (2) reduced and constant-rate subsidence multiple years after drainage. We used this second range of data to estimate rates of C losses. The hypotheses associated with this method will be presented in the discussion section of this manuscript.

We will therefore assume that loss happens at a constant rate after drainage in phase 2, while compaction is a fast process essentially at work during the initial years following drainage, i.e. phase 1. Assuming that the loss component can be isolated and quantified and all changes in bulk density are caused by compaction, the SOM loss can be estimated from the bulk density during phase 2:

$$\mathrm{OM_{loss}} = \mathrm{Subsidence_{loss}} * \mathrm{BD_{phase2}} \tag{2}$$

Calculation of C loss from changes of mineral contents

The ash content (i.e. the mineral content) of the plough layer of cultivated peat soils increases steadily after drainage (Sorteberg 1983). This increase results from (1) the loss of organic matter within a homogeneous peat layer where the mineral fraction become more concentrated due to the mineralization and loss of the surrounding organic matrix and (2) application of lime and mineral fertilizers.

Calcium and magnesium are assumed to be the main components in lime and fertilizers that is accumulated in peat soil. Accumulation of other elements like phosphorous and potassium are assumed to be negligible because of leaching and uptake by plants.

The initial fraction of minerals (MF_{ini}) can be expressed as:

$$MF_{ini} = \frac{M_{fin} - M_{fert}}{M_{fin} - M_{fert} + OM_{fin} + OM_{loss}} \tag{3}$$

where M_{fin} is the final mass of mineral particle in the 20-cm layer, M_{fert} is the added Ca and Mg, OM_{fin} is the final mass of organic matter in the 20-cm layer, and OM_{loss} is the loss of organic matter between the initial and final sampling. Equation 3 can be rewritten as:

$$OM_{loss} = \left(M_{fin} - M_{fert}\right) \times \left(\frac{1}{MF_{ini}} - 1\right) - OM_{fin}, \tag{4}$$

The sum of OM_{fin} and M_{fin} is the final mass of soil in the soil layer:

$$OM_{fin} + M_{fin} = BD_{fin} \times Thick, \tag{5}$$

where BD_{fin} is the final bulk density and *Thick* the layer thickness.

M_{fin} and OM_{fin} can be expressed as

$$M_{fin} = MF_{fin} \times BD_{fin} \times Thick \tag{6}$$

$$OM_{fin} = \left(1 - MF_{fin}\right) \times BD_{fin} \times Thick \tag{7}$$

where MF_{fin} is the measured final mineral content.

Combining (4), (6) and (7) gives:

$$OM_{loss} = \left(MF_{fin} - MF_{fert}\right) \times \left(BD_{fin} \times Thick\right) \times \left(\frac{1}{MF_{ini}} - 1\right) - \left(\left(1 - MF_{fin}\right) \times BD_{fin} \times Thick\right), \tag{8}$$

where MF_{fert} is the mass fraction of added fertilizer. Equation 8 contains only measured parameters. If data on MF_{ini} are lacking, MF_{fin} in similar uncultivated soil or peat subsoil can be used as a substitute.

Carbon, calcium and magnesium contents of peat soils were obtained from soil profile description analyses of peat soils in Norway, which includes both cultivated and uncultivated soils. The C fraction of SOM is estimated as the C fraction of the loss of ignition. Increase of mineral content due to liming is estimated from analyses of exchangeable Mg and Ca, as the difference between cultivated and uncultivated soils. Because of few observations in the soil profile database for the regions represented in this study, the estimates were calculated for the whole country. However, we assume that the mean values for these parameters do not differ drastically among regions in Norway.

CO_2 flux measurements

The CO_2 flux measurements for a cultivated peatland in Bodø in North Norway have been reported by Grønlund et al. (2006). Three plots were investigated, two plots with perennial grass and one plot with ryegrass. Gas samples were collected in closed chambers (25 × 25 cm) in the period August 2003–November 2004; with 2-week intervals (no samples in the period of snow cover from December to March). The net ecosystem C loss was estimated through mass balance between the outputs, i.e. the measured gross respiration and the measured yield export, and the input, i.e. gross photosynthesis. This later flux was estimated from literature-derived coefficients for similar species in high-latitude ecosystems: (1) a ratio between net plant productivity and above-ground net plant productivity (NPP/ANPP) of 1.4 (Pietola and Alakukku 2005), and (2) a ratio between net plant productivity and gross plant productivity (NPP/GPP) of 0.55 (Moore et al. 2002), as explained in detail in Grønlund et al. (2006).

Results

Cultivated peat soils in Norway

Based on the share of soil samples, organic soils can be estimated to 6.2% of the cultivated area in Norway (63,000 ha) (Table 4). Due to climatic conditions, the frequency of organic soils is highest in the western and northern parts of the country and lowest in the south-east. Our sample-proportion method yields a conservative estimate of organic soil acreage in Norway. Indeed, crops with highest fertilization requirements are more frequently cultivated on mineral than on organic soils. The actual sampling density is therefore probably higher on mineral soils, which could lead to an underestimation of organic soil acreages with this method. Organic soils have earlier been estimated to cover 15–20% of cultivated land in Norway based on the cultivation statistics (Sorteberg 1983; Johansen 1997). The true area is likely lower because of conversion to mineral soils and abandonment of some cultivated peatlands with drainage problems.

Table 4 Cultivated organic soils in different regions in Norway

Region	Total acrage (ha)	% of total cultivated peat soil in Norway	% of total cultivated soil in the region
East	10,574	17	2.2
South	4,195	7	13.1
West	27,028	43	11.0
Mid	8,448	13	5.2
North	12,708	20	13.5
Total	62,953	100	6.2

Peat subsidence

The annual subsidence in the Smøla measurements was highest the first years after drainage, in the periods 1951–1966 and 1976–1983 (Fig. 2). In these periods, compaction is likely to be the dominant component. In the periods 1966–1976 and 1983–2004 the annual subsidence is approximately constant and can be considered a direct estimate of the soil loss component of the subsidence. The rate of subsidence per meter of peat was relatively similar in the periods 1966–1976 and 1983–2004 (Fig. 2).

Loss components of the total subsidence were estimated from the repeated subsidence measurements

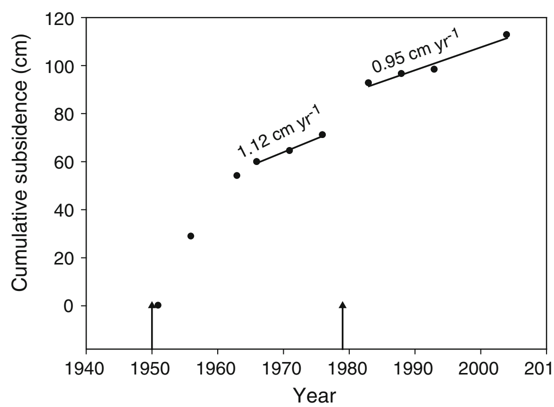

Fig. 2 Cumulative peat subsidence following drainage at Smøla Island. The field was drained about 1950 and at the end of the 1970s (arrows)

Table 5 Repeated subsidence measurements of 5 subfiels on Smøla Island

Sub-field	Depth 1951 (m)	Cumulative subsidence (cm)							Annual subsidence (cm)			
		1956[a]	1966[a]	1976[a]	1983[a]	1988[b]	1993[c]	2004[c]	1951–1976	1951–2003	1966–1976	1983–2004
1	3.37	12	37	45	70	74	78	91	1.8	1.72	0.80	1.02
2	3.52	23	47	51	91	94	95	110	2.04	2.07	0.40	0.90
3	3.63	20	49	59	79	82	84	105	2.36	1.97	1.00	1.22
4	3.98	38	78	92	102	106	107	117	3.68	2.21	1.40	0.71
5	3.88	51	88	108	121	127	127	140	4.32	2.65	2.00	0.92
Mean	3.68	29	60	71	93	96	98	113	2.84	2.13	1.12	0.95
St.d.	0.25	16	22	28	20	21	20	18	1.10	0.34	0.61	0.19

[a] *Source*: Hovde (1987)

[b] *Source*: Frøseth and Celius (1991)

[c] *Source*: This study

presented in Fig. 2 and Table 5. Mean annual subsidence rates averaged 2.84 cm year^{-1} and 2.13 cm year^{-1} for the 1951–1976 and 1951–2004 periods, respectively. The mean annual subsidence rates during periods of negligible compaction averaged 1.12 cm year^{-1} and 0.95 cm year^{-1} for the 1966–1976 and 1983–2004 periods, respectively. The mean annual SOM loss for the whole period (1951–2004) can be estimated to 1.04 cm year^{-1} as the mean subsidence for the two periods (1966–1976 and 1983–2004). The loss component of the subsidence was estimated to 38% (1.12 cm year^{-1}/2.84 cm year^{-1}) for the first period (1951–1976) and to 49% (1.04 cm year^{-1}/2.13 cm year^{-1}) for the whole period (1951–2004). As the first period corresponded approximately to the time period and duration of the 5-county dataset (1952–1982), the 38% loss component was used for calculating C loss from the 11 fields.

Other key parameters for calculating C loss from peat subsidence in the 5-county study are (Tables 1 and 6): (1) mean subsidence of 56 cm, (2) mean final bulk density of 0.21 g cm^{-3}, and (3) C fraction of SOM of 51 g 100 g^{-1}. The estimated total loss averaged 44 kg SOM m^{-2}, i.e. 22 kg C m^{-2}, and the annual loss 0.80 kg C m^{-2} for 28 years (Table 7).

Changes in mineral content

The parameters for calculating C loss from changes in mineral content are presented in Tables 1 and 6. Mean values for initial and final mineral fractions were 4.5 and 10.1 g 100 g^{-1}, respectively (Table 1). The mean values for CaO + MgO content of uncultivated and cultivated peat were respectively 0.58 g 100 g^{-1} and 1.02 g 100 g^{-1} (Table 6). The difference, 0.44 g 100 g^{-1} can be an estimate of the mineral increase due to liming and fertilization. The final mineral fraction corrected for added Ca and Mg is 9.6 g 100 g^{-1} for the 11 fields in the 5-county measurements. Total loss based on changes in mineral contents was estimated to 47 kg SOM m^{-2} and 24 kg C m^{-2} and the mean annual losses to 0.86 kg C m^{-2} (Table 7).

CO_2 flux measurements

The net C loss based on CO_2 flux measurements in Bodø was calculated to be 0.6 kg C m^{-2} year^{-1} as the balance between gross respiration (1.16 kg C m^{-2} year^{-1}) plus yield removed (0.38 kg C m^{-2} year^{-1}) minus the estimated gross photosynthesis (0.94 kg C m^{-2} year^{-1}). Details on

Table 6 Carbon, calcium and magnesium contents of Norwegian peat soils

	n	Mean (g 100 g^{-1})	CV (%)
C[a]	27	51	14
CaO + MgO			
Uncultivated	111	0.58	134
Cultivated	20	1.02	50

Number of observations (n), mean values, and coefficients of variation (CV) are reported

[a] C fraction computed from SOM loss of ignition

Table 7 Estimated soil organic matter (SOM) and C losses from cultivated peatlands

Method	Data set	Total loss		Annual loss (kg C m^{-2} $year^{-1}$)
		kg SOM m^{-2}	kg C m^{-2}	
Subsidence	5 county (28 years)	44	22	0.80
Mineral content	5 county (28 years)	47	24	0.86
CO_2 flux	Bodø, Nordland county			0.60

measurements and calculations are provided in Grønlund et al. (2006).

Discussion

The three contrasting methods proposed in the present study to estimate C losses from drained and cultivated peat soils in Norway yielded similar values: 0.80, 0.86 and 0.60 kg C m^{-2} $year^{-1}$, for the subsidence, change-in-ash-content and CO_2-flux methods, respectively (Table 7). Differences in estimated C losses might not depend exclusively on the method, but also on the location and the period of the study. Methods applied at the same site, i.e. long-term monitoring of subsidence rates and changes in ash contents, yielded remarkably similar estimates. The lower estimate obtained by the soil-CO_2-flux method might be due in part to a different research location, more to the North. Although the climate of Bodø is not very different from other Norwegian coastal sites presented in this study (Table 3), it is slightly colder, which might have contributed to slightly reducing the SOM mineralization rate. The estimated losses are consistent with similar estimates obtained in Nordic countries and Central Europe (Maljanen et al. 2001; GEFOS 1998). Our estimates are well within reported C losses from cultivated peatlands, which range from 0.22 to 3.1 kg C m^{-2} $year^{-1}$ (Freibauer et al. 2004). As expected for Norwegian boreal regions, our estimates are in the lower range of what was estimated by Armentano and Menges (1986) (in Neufeldt 2005) for temperate regions: from 0.79 to 1.13 kg C m^{-2} $year^{-1}$, and a little bit above estimates for Germany of 0.29 to 0.67 kg C m^{-2} $year^{-1}$ (Behrendt et al. 1994 in Neufeldt 2005).

The method based on changes in mineral content produced the highest C loss estimate across field sites. This can be due to two potential sources of overestimation (Table 8). First, the results would be overestimated if the peat is inhomogeneous and the mineral content increases with soil depth. This potential problem is particularly true under large C losses from shallow peat soils. In such conditions, the mineral soil is progressively reached, and ploughing the remaining shallow peat layer further increases the mineral content of the surface soil. In our analysis, the initial depth was about 2.5 m and the final depth around 2 m. These soils appear deep enough to avoid reaching mineral-enriched layers through progressive peat loss and ploughing. The second source of overestimation is the surface addition of non-fertilizer mineral material such as sand for increasing bearing capacity and application of shell sand, which is occasionally used for liming in Norwegian coastal areas. In addition, total calcium and magnesium contents should be used instead of exchangeable, but such data were not available for this study. On the other hand, underestimation of actual C loss rates would result from significant peat mineralization in horizons subjacent to the plough layer. These sources of bias underscore that the method based on changes in the peat mineral content can only yield a rough estimate of the actual loss. However, we believe that this method has merit and would deserve being further investigated for two reasons. First, in our limited study peat loss estimates obtained with this method are in excellent agreement with the traditional subsidence-based method. Second, this method is easy and cheap, and does not necessarily require prior knowledge on peat soil evolution, such as the subsidence method does. If nearby non-drained peat soils exist, it is quite reasonable to assume that the initial mineral content of the drained peat was similar to the present mineral content of the undrained peat. By contrast, it is not reasonable to assume that specific drained peat soils had the same original depth as nearby undrained peat soils, because of the known depth heterogeneity of peat deposits throughout the landscape. So, mineral content is both easier to measure than subsidence and current proxies for initial conditions can be used. The methods needs to

Table 8 Summary of hypotheses and associated sources of bias for the three C-loss estimation methods

Method	Estimate (g C m^{-2})	Main hypotheses	Sources of bias	
			Underestimation	Overestimation
Change in mineral content	860	(1) Homogeneous peat (2) Decomposition happens in the plough layer (3) All mineral addition is from lime and fertilizers	(1) Decomposition in deeper peat layers	(1) Inhomogeneous peat: the mineral soil is progressively reached (2) surface addition of non-fertilizer mineral material (e.g. sand for bearing capacity)
Subsidence	800	(1) Compaction is fast, and negligible after a few initial years (2) Decomposition per m soil happens at a constant rate throughout the duration of drainage (3) Decomposition itself does not change bulk density	(1) Decomposition is faster in the years immediately after drainage	(1) Compaction remains substantial throughout the duration of drainage
CO_2 flux	600	(1) Decomposition per m soil happens at a constant rate throughout the duration of drainage (2) Gross photosynthesis can be estimated from yields and literature data on GPP to yield ratios	(1) Decomposition is faster in the years immediately after drainage	

be further tested. Using silica content instead of total ash could be a better indicator of the concentration of minerals in the soil.

The subsidence method yielded an intermediate estimate for C loss from drained and cultivated peat soils. A main uncertainty in the present study is the estimation of the loss and compaction components of the subsidence, where compaction is assumed to become negligible 15 years after drainage. In reality, compaction probably proceeds at a reduced rate long after drainage operations, especially due to the use of heavy field machinery. On the other hand, soil loss (i.e. SOM mineralization) is likely to be the fastest during the first years after drainage due to more degradable SOM matter and the more aerobic conditions associated with a lower water table and a more efficient drainage system during the initial years. So, both the long term compaction and the initial rate of peat mineralization are likely to be underestimated. However as a mean for the whole period these errors potentially cancel each other.

The compaction component of peat subsidence is expected to increase with peat depth, while loss component is expected to be less depth dependent. As a consequence, the loss component fraction of the subsidence is likely to decrease with increasing peat depth. Our estimate of the loss component (38%) was calculated from measurements on 3.5-m-deep peat formations. The mean depth of the 5-county peat formations was shallower, i.e. about 2.5 m, and the loss component could therefore be underestimated. This can be a possible explanation for the lower estimate from the subsidence measurements than from the changes of mineral contents. A loss component of 41% would have given identical results for the two methods.

Our estimate that a little less than half of the subsidence is due to peat mineralization is compatible with the available literature information. Several studies suggest that compaction out-weights mineralization in subsidence processes (Minkkinen and Laine 1998; Dirks et al. 2000). In New Zealand, compaction of drained peat soils was reported to account for 63% and SOM loss for 37% of subsidence (Schipper and McLeod 2002). However, SOM mineralization can out-weight compaction in certain conditions (Eggelsmann 1976; Murayama and Abubakar 1996). Our results confirm a traditional assumption in Nordic countries that the loss and compaction components of the subsidence are approximately equal, providing the peat has been drained for at least 50 years. Recently, Leifeld et al. (2005) estimated the long-term C balance of Swiss peat formations from literature values for peat subsidence rates coupled to a literature assumption of 70% oxidative loss in peat subsidence (from Eggelsmann 1976). Such assumptions are currently necessary because of the lack of reliable data on historical losses of C from peat soils. Here we suggest that our method based on changes in mineral content could help providing the necessary data even when historical records of peat subsidence have not been kept.

The CO_2-flux method gave the lowest estimate of C loss form mineralizing peat. The main source of bias is towards underestimation (Table 8). Indeed, this method provides data only on a limited time period. Underestimation is expected if mineralization decreases with time and data are collected long enough after drainage. However, the CO_2-flux method presents additional advantages as compared to the two other methods. Measurement of gas fluxes provides information on the temporal variability of CO_2 loss. It can also be combined with other greenhouse gases like CH_4 and N_2O. Such measurements are however more expensive than the indirect methods and many replicates are necessary for large scale estimates.

Carbon loss from cultivated peatland is a significant source for greenhouse gas emission in Norway. Our results from the 5 county measurements suggest mean emission estimates of 8–8.6 tons C ha^{-1} $year^{-1}$ and 29–31 tons CO_2 ha^{-1} $year^{-1}$ in South, Western and Mid Norway. These regions contribute with about 63% of all cultivated peat soils in Norway (Table 4). Eastern Norway, which has not been represented in this study has higher summer temperatures and could therefore have a higher degradation and C loss. Northern Norway has been represented by gas flux measurements, showing a flux of 6 tons C ha^{-1} $year^{-1}$ and 22 tons CO_2 ha^{-1} $year^{-1}$. As this figure represents only one locality and two summer seasons, it can not be considered a true estimate of CO_2 flux from cultivated peat in Northern Norway. On the other hand, because of lower temperatures, C loss for peat can be expected to be lower in Northern Norway. The regions represented in the 5-county measurements in this study are therefore likely to have emission rates between Eastern and Northern Norway. An estimated mean emission from these regions could therefore act as a rough estimate for the whole country. As the total area of cultivated peatlands in Norway is estimated to 63,000 ha, the estimate for the total annual loss is about 500,000–550,000 tons C $year^{-1}$, which is equivalent to 1.8–2.0 million tons CO_2 $year^{-1}$. This value amounts to about 3–4% of the total national anthropogenic greenhouse gas emission. Provided that no more pristine peatlands are cultivated, this figure will decrease in the long run as drained peatlands progressively become mineral soils under the action of SOM mineralization. This might have already happened in SW Germany, where peat restoration has only minor mitigation potential due to the small surface of cultivated peatlands (Neufeldt 2005). In the mean time, there is great interest in preventing this transformation of peat formations into mineral soils and thereby contributing to GHG mitigation through peatland restoration. Our results are therefore in line with recent reports, which indicate that peatland restoration is one of the most important land-use measures to mitigate the effects of anthropogenic GHG emissions (e.g. Freibauer et al. 2004).

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