

Atmospheric impact of abandoned boreal organic agricultural soils depends on hydrological conditions

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Drained agricultural peat soils are significant sources of carbon dioxide (CO₂) but also small sinks for methane (CH₄). Leaving these soils without any cultivation practice could be an option to mitigate GHG emissions. To test this hypothesis, we measured, over a three year period, net CO₂ exchange and fluxes of CH₄ for five agricultural peat soils that had been abandoned for 20–30 years. Annually, the sites were either small net sinks or sources of CO₂ and CH₄ (–7.8 to 530 g CO₂-C m⁻² and –0.41 to 1.8 g CH₄ m⁻²). Including N₂O emissions from our previous study, the net (CH₄ + CO₂ + N₂O) emissions as CO₂ equivalents were lower than in cultivated peat soils and were lowest in the wet year. Therefore, high GHG emissions from these soils could be avoided if the water table is maintained close to the soil surface when photosynthesis is favoured over respiration.

Introduction

Pristine, water-saturated peat soils store large amounts of carbon because the rate of biomass production in photosynthesis is greater than the rate of decomposition (Gorham 1991, Alm *et al.* 1997, Turunen 2008). The carbon accumulation rate in undrained boreal and subarctic peatlands is, according to Turunen and Moore (2003), 13–20 g m⁻² yr⁻¹. Pristine peatlands have negligible emissions of nitrous oxide (N₂O), (Martikainen *et al.* 1993), but they are sources of methane (CH₄) (Lai 2009, Saarnio *et al.* 2009). Drainage, fertilization, ploughing, irrigation, harvesting, liming and compaction of soil by machines

modify the soil properties of managed peatlands and thereby change their carbon and nitrogen cycles (e.g. Martikainen *et al.* 1993, Regina *et al.* 1998, Lohila *et al.* 2004, Ball *et al.* 2008). Managed boreal peat soils are generally substantial net sources of CO₂ (Kasimir-Klemmedtsson *et al.* 1997, Mosier *et al.* 1998, Maljanen *et al.* 2001, 2004, Lohila *et al.* 2004) and N₂O (Kasimir-Klemmedtsson *et al.* 1997, 2009, Maljanen *et al.* 2003a, Regina *et al.* 2004, Rochette *et al.* 2010) but low sources, or even sinks, for atmospheric CH₄ (Kasimir-Klemmedtsson *et al.* 1997, 2009, Maljanen *et al.* 2003b, Regina *et al.* 2007).

The use of organic soils in agriculture is among the most problematic land-use options

when considering atmospheric impact. For example, in Finland 8% of the total greenhouse gas (GHG) emissions originate from agriculture. Agricultural soils cover about 6% of the land area in Finland. Organic agricultural soils cover only 13% of the agricultural soils (Myllys and Sinkkonen 2004) and 0.6% of the total peatland area in Finland (Turunen 2008), but they are mainly responsible of the GHG emissions originating from agriculture (Statistics Finland 2010). In Sweden, 6%–8% of total GHG emissions originate from cultivated peatlands which represents 8.6% of the total arable land area (Berglund and Berglund 2010). Therefore, an important question is how to reduce the GHG emissions from these managed organic soils covering only a relatively small area. One option would be to cease all agricultural activities like ploughing, fertilization, harvesting on these problematic soils, but how this would change the GHG emissions from these soils is poorly understood. Cropland ecosystems lose large amounts of nutrients with the harvested crop each year, which must be replaced by fertilization. Peat soil also needs to be limed to keep the soil pH high enough for crops (Myllys 1996). Secondary vegetation succession starting after abandonment could incorporate more carbon into the ecosystem. Grasses and herbs dominate in field vegetation for decades during secondary succession (Törmälä 1982), and open ditches are the first habitat for pioneer tree species (birch, willows) (Hytönen 1999). In abandoned systems, there could thus be an increase in the energy flow to decomposers (Törmälä 1982). On the other hand, a decrease in soil pH without regular liming could reduce the decomposition rate. Decomposition and CO₂ emissions could also decrease as a result of lower soil aeration after ploughing has ended, and after increase in water-table level if the ditch network is not maintained any more after abandoning the site (Yavitt *et al.* 1997).

We hypothesize that when former organic agricultural soils are maintained without any management for several decades, they lose less CO₂ than cultivated peat soils as a result of a reduction in the soil respiration rate and increased photosynthesis after plant succession. After gradual deterioration of the drainage

ditches, a rise in the water-table level would decrease decomposition of soil organic matter and favour carbon accumulation in the ecosystem. However, there is a risk that CH₄ emissions would increase with the increasing water-table level (e.g. Tuittila *et al.* 2000). To study these hypotheses, we measured annual CO₂ balances and CH₄ fluxes from five abandoned agricultural soils for three years which, along with previous data on their N₂O fluxes (Maljanen *et al.* 2012), completes the picture of changes in GHG emissions.

Material and methods

Study sites

CO₂ exchange and CH₄ fluxes were measured from June 2002 to June 2005 for five abandoned organic agricultural fields (AB1–AB5, Table 1). The fields were located within 700 m of each other in Kannus, western Finland (63°54'N, 23°56'E). The length of the growing season in Kannus is about 180 days and the soil is usually covered with snow from November to mid-April. The mean annual temperature is 2.4 °C and the annual precipitation is 561 mm. The sites, originally pristine peatlands, had been drained in the 1950s and used for cultivation of perennial grasses and cereals (crop rotation) for decades before they were abandoned 20–30 years prior to the current study. The crop rotation (perennial grasses/cereals) is a normal practise in Finland. During the agricultural phase, some mineral soil had been mixed with the peat, and normal NPK fertilization (40–100 kg ha⁻¹ N, 17–35 kg ha⁻¹ P and 33–80 kg ha⁻¹ K according to Lampinen 1978 and Rainiko 1978) was used in order to improve the soil properties for cultivation. No fertilization or ploughing activities have been carried out since the agricultural use ended, and the sites were naturally vegetated. The dominant plant species (mean coverage more than 10%) were *Juncus filiformis* and *Deschampsia cespitosa* at sites AB1 and AB2; *Elymus repens* and *Poa pratensis* at site AB3; *Deschampsia cespitosa*, *Epilobium angustifolium* and *Rubus arcticus* at site AB4 and *Epilobium angustifolium*, *Deschampsia cespitosa* and *Agrostis capillaris*

at site AB5. There were no trees growing in the middle of the fields, but some birch and willow shrubs were growing by the ditches.

Soil chemical and physical characteristics and weather data

At each site, five soil samples (239 cm³) were taken from the depths of 0–10 and 10–20 cm. Soil pH_(H₂O) was measured from dried soil samples using a 1:2.5 v:v soil:solution suspension. The bulk density of the soil was calculated as the ratio of dry mass (dried at 105 °C) to volume of the sample. The organic matter content was determined as loss-on-ignition (at 550 °C for 8 h). The content of total soil C was determined with a LECO CHN-1000 or LECO CHN-2000. The total N of the soil samples was determined by the Kjeldahl method, and the total concentrations of P and K using HCl extraction of ignition residues. Decomposition status of the peat was determined according to the von Post humification scale (von Post 1922).

Temperatures of the unfrozen soil were measured manually (Fluke 51 II Digital Thermometer) at the depths of 2, 5, 10 and 20 cm during gas sampling. At site AB3 (located in the middle of the sites), soil temperature (depths 5 and 20 cm) was monitored continuously using Campbell 107 soil temperature sensors and a data logger. Air temperature and precipitation data were collected by the Finnish Meteorological Institute at Toholampi weather station near the study sites (Fig. 1 and Table 2). The water-table level (WT) was measured in groundwater wells,

and the depth of soil frost was measured at each site using frost-depth gauges filled with methylene blue–H₂O solution. The distance of WT from the soil surface is indicated by a negative value.

The cellulose decomposition test was carried out during two summers and one winter from 6 June to 11 September 2003 (98 d), from 15 October 2003 to 7 May 2004 (205 d), and from 7 May to 15 September 2004 (131 d). Pieces of birchwood cellulose (5 × 10 cm) were dried at 105 °C, stabilized for two hours at room temperature and weighed. Three pieces were inserted into a plastic net (mesh size 1 mm), and three replicate nets were buried in the peat at each site at the depths of 0–5, 5–10 and 10–15 cm. After the *in situ* incubation period, the ingrown roots and mosses were cleaned off, and the pieces were dried and weighed and the cellulose decomposition rate was calculated from the weight loss.

Plant cover characteristics

The total coverage of the understorey plants and the composition of the dominant plant species were recorded in early August 2002, 2003 and 2004. Above-ground plant biomass was collected at the end of July 2003 and 2004 using a 20 × 20 cm frame with six replicate cuttings. Samples were dried at 105 °C and the amount of biomass (g m⁻²) was calculated. The growth dynamics of the predominant plant species (*Deschampsia cespitosa*, *Elymus repens*, *Agrostis capillaris* and *Juncus filiformis*) were measured using marked plants, whose size and number of leaves were determined. Leaf area (LA) was calculated by

Table 1. Site characteristics measured in 2002 (soil sampling depth 0–20 cm). PD = peat depth, BD = bulk density, OM = organic matter content, C = carbon, N = nitrogen, CD = cellulose decomposition, P_{tot} = total phosphorus, K_{tot} = total potassium and pH = measured from 1:2.5 v:v soil:H₂O suspension, H = degree of decomposition (von Post 1922).

Site	PD (cm)	BD (g cm ⁻³)	OM (%)	C:N	N (%)	CD ^{a)} (% d ⁻¹)	P _{tot} (mg g ⁻¹)	K _{tot} (mg g ⁻¹)	pH _{water}	H
AB1	30	0.38	52	18.8	1.2	0.30	1.5	1.6	4.9	8–9
AB2	20–30	0.40	43	19.0	0.9	0.32	0.1	1.1	5.0	8–9
AB3	30	0.38	44	18.3	1.0	0.25	0.2	1.7	5.9	8–9
AB4	30	0.30	61	16.3	1.7	0.33	0.2	0.7	4.5	9
AB5	80	0.42	41	19.2	1.1	0.47	0.1	2.5	4.3	10

^{a)} Mean value from three periods in 2003–2004.

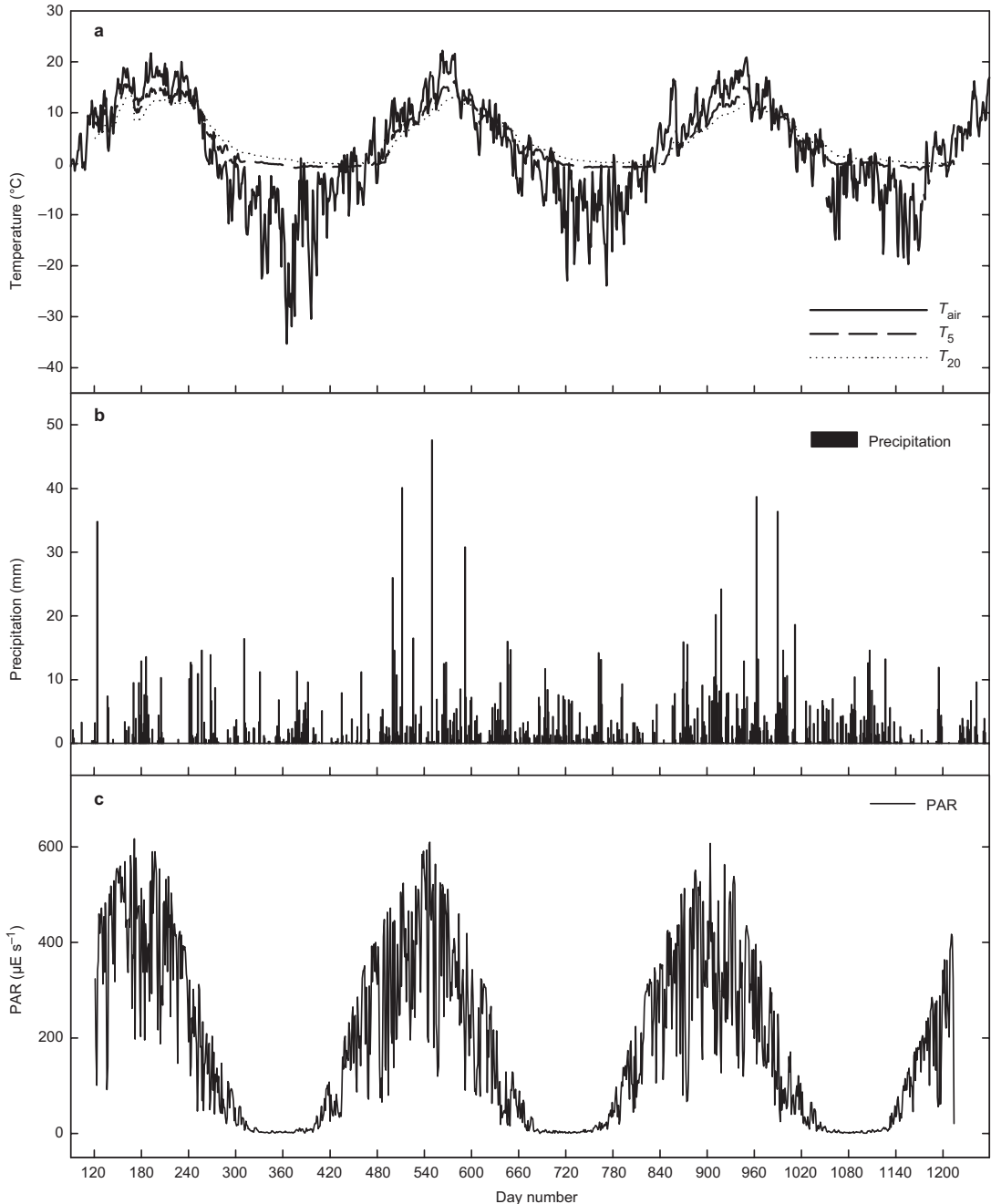


Fig. 1. (a) Daily mean soil (at 5 and 20 cm depth) and air temperatures at the study site AB3, (b) daily precipitation, and (c) mean daily photosynthetically-active radiation (PAR) at the Toholampi weather station.

multiplying the number of leaves inside the frames by their length and width (Wilson *et al.* 2007). The coverage of all other plants measured in the late summer was used to estimate the total

leaf area inside the frames. LA was measured six times during the growing season in 2002, and 12 times in 2003 and 2004, and the gaps between the measurements were interpolated.

CO₂ exchange and CH₄ fluxes during the growing season

Weekly CO₂ exchange measurements were carried out from July 2002 until October 2004 during the growing seasons using a chamber method (Alm *et al.* 1997). The instantaneous net CO₂ exchange was measured with a transparent chamber (60 × 60 cm, height 30 cm) with a thermostat, which was placed over an aluminium frame (58 × 58 cm) pre-installed in the soil. There were four replicates for each site. To ensure gas tightness, there was a groove in the upper edge of the frame which was filled with water. A portable infrared gas analyzer (EGM 3 or EGM 4, PP Systems, USA) was used to measure the change in the CO₂ concentration in the chamber during an incubation period of three minutes under stable irradiation conditions. CO₂ concentration readings were recorded at 15-s intervals. After a measurement with full irradiation, the chamber was shaded with one or two mesh fabrics, and the measurement was repeated under this reduced irradiation. The light intensity (PAR) and air temperature (T_a) inside the chamber were recorded during the incubation period. The total respiration (R_{eco}) of the plant–soil system was measured as described above in the dark by covering the chamber with an opaque lid. In addition to the four vegetated plots, one frame at each site was kept free of above-ground vegetation in order to measure soil respiration (R_{soil}). The CO₂ flux was calculated from the linear part of the CO₂ concentration slope in the light and in the dark (Alm *et al.* 1997).

CO₂ uptake from the atmosphere to the ecosystem is indicated here with a negative, and release of CO₂ to the atmosphere with a positive

sign. An estimate of GPP (gross primary production) was calculated as the sum of CO₂ fluxes measured under light and dark conditions (Alm *et al.* 1997). The measurement in the dark was used as an estimate of the total respiration (R_{eco}), and net ecosystem exchange (NEE) was then calculated as:

$$\text{NEE} = \text{GPP} - R_{\text{eco}} \quad (1)$$

For calculation of the diurnal NEE values, statistical response functions were constructed separately for each site for the growing seasons of 2002, 2003 and 2004 in order to reconstruct the hourly values for GPP and R_{eco} on the basis of climatic data (Table 3). The response functions for GPP and R_{eco} or R_{soil} were as follows:

$$\text{GPP} = Q \times I \times \text{LA} / (k + I) \quad (2)$$

$$R_{\text{eco}} \text{ or } R_{\text{soil}} = \exp(b_0 + b_1 T_5 + b_2 \text{WT}) \quad (3)$$

The dependence of GPP on irradiation, I , ($\mu\text{mol m}^{-2} \text{s}^{-1}$) takes the form of a rectangular hyperbola function (e.g. Frolking *et al.* 1998), where Q is the asymptotic maximum, and k is the half saturation constant. The additional parameter LA in Eq. 2 is the leaf area ($\text{cm}^2 \text{cm}^{-2}$). In Eq. 3, T_5 is the soil temperature at the depth of 5 cm, and WT is the water-table depth (cm) assuming negative values when the water table is below soil surface. The diurnal estimates of GPP and R_{eco} were reconstructed using hourly time-series data for T_5 , LA, WT and I from the beginning of May until the end of October each year.

CH₄ fluxes were measured throughout the three years, every second or third week (Fig. 2). During the snow-free periods, fluxes of CH₄

Table 2. The mean seasonal temperatures and precipitation (from 1 May to 31 October and from 1 November to 30 April) in Kannus, and their comparison (%) to the long term average (1971–2000) (Drebs *et al.* 2002).

	May–October				November–April			
	Mean temp.		Precipit.		Mean temp.		Precipit. ¹⁾	
	(°C)	(%)	(mm)	(%)	(°C)	(%)	(mm)	(%)
2002–2003	10.3	101	283	81	–7.7	145	190	90
2003–2004	9.6	94	479	137	–4.3	81	241	115
2004–2005	10.5	103	555	155	–3.5	66	247	118

¹⁾ Mostly as snow.

were measured with a static chamber method using aluminium frames as described above, and an opaque aluminium chamber (60 × 60 cm, height 30 cm) equipped with a fan. This method

was used also for CO₂ (R_{eco}) outside growing season during snow free periods. Gas samples (40 ml) were drawn from the headspace of the chambers with 60 ml polypropylene syringes

Table 3. Parameters for the response functions to calculate gross primary photosynthesis (GPP), ecosystem respiration (R_{eco}) and soil respiration (R_{soil}) for the growing seasons of 2002, 2003 and 2004. Units: mg m⁻² h⁻¹ for GPP, R_{eco} , R_{soil} ; $\mu\text{s m}^{-2}$ for l ; cm² cm⁻² for LA; °C for T_s , and cm for WT (negative values when below soil surface).

Site	AB1	AB2	AB3	AB4	AB5
GPP = [Ql/(k + l)] × LA					
2002					
Q	361 ± 43.2	529 ± 62.3	191 ± 19.9	333 ± 40.5	251 ± 59.4
k	269 ± 91.4	252 ± 90.1	188 ± 66.1	272 ± 89.1	340 ± 214
r^2	0.74	0.65	0.62	0.69	0.42
2003					
Q	154 ± 12.7	422 ± 44.6	403 ± 55.5	493 ± 58.7	565 ± 45.8
k	261 ± 69.9	369 ± 101	463 ± 148	263 ± 91.6	163 ± 49.7
r^2	0.67	0.51	0.34	0.23	0.56
2004					
Q	307 ± 29	384 ± 28.8	440 ± 41.1	243 ± 25.5	388 ± 34.3
k	400 ± 88.8	198 ± 51.7	285 ± 82.2	337 ± 89.9	461 ± 96.6
r^2	0.48	0.47	0.56	0.18	0.67
Ln $R_{\text{eco}} = b_0 + b_1 \times T_s + b_2 \times \text{WT}$					
2002					
b_0	5.30 ± 0.07	5.56 ± 0.12	5.99 ± 0.06	5.43 ± 0.16	5.82 ± 0.13
b_1	0.11 ± 0.01	0.06 ± 0.01	0.07 ± 0.01	0.05 ± 0.01	0.04 ± 0.01
b_2	0.002 ± 0.001	-0.01 ± 0.002	–	-0.01 ± 0.003	-0.004 ± 0.002
r^2	0.88	0.80	0.79	0.73	0.48
2003					
b_0	5.67 ± 0.11	6.13 ± 0.10	5.89 ± 0.12	6.54 ± 0.07	5.78 ± 0.12
b_1	0.05 ± 0.01	0.04 ± 0.01	0.08 ± 0.01	–	-0.07 ± 0.01
b_2	-0.01 ± 0.002	-0.01 ± 0.001	-0.01 ± 0.002	-0.01 ± 0.001	-0.01 ± 0.002
r^2	0.80	0.74	0.74	0.52	0.62
2004					
b_0	5.26 ± 0.16	5.44 ± 0.12	5.61 ± 0.12	5.77 ± 0.11	5.24 ± 0.15
b_1	0.12 ± 0.01	0.12 ± 0.01	0.13 ± 0.01	0.10 ± 0.01	0.12 ± 0.01
b_2	-0.02 ± 0.004	-0.01 ± 0.002	-0.01 ± 0.002	-0.01 ± 0.002	-0.01 ± 0.002
r^2	0.51	0.69	0.72	0.68	0.72
Ln $R_{\text{soil}} = b_0 + b_1 \times T_s + b_2 \times \text{WT}$					
2002					
b_0	4.96 ± 0.18	5.56 ± 0.78	4.24 ± 1.45	4.81 ± 0.59	4.59 ± 0.69
b_1	0.06 ± 0.02	-0.004 ± 0.04	0.03 ± 0.05	0.04 ± 0.03	0.01 ± 0.04
b_2	-0.01 ± 0.003	-0.01 ± 0.01	-0.01 ± 0.02	-0.01 ± 0.01	-0.01 ± 0.01
r^2	0.93	0.37	0.46	0.78	0.45
2003					
b_0	4.30 ± 0.56	5.14 ± 0.40	4.79 ± 0.32	4.74 ± 0.41	3.98 ± 0.30
b_1	0.06 ± 0.04	0.05 ± 0.01	0.07 ± 0.02	0.03 ± 0.03	0.09 ± 0.02
b_2	-0.03 ± 0.01	-0.01 ± 0.001	-0.01 ± 0.004	-0.02 ± 0.01	-0.01 ± 0.004
r^2	0.80	0.61	0.79	0.73	0.83
2004					
b_0	3.23 ± 0.47	3.39 ± 0.25	3.14 ± 0.54	3.81 ± 0.11	3.77 ± 0.11
b_1	0.12 ± 0.03	0.12 ± 0.02	0.10 ± 0.04	0.08 ± 0.03	0.18 ± 0.02
b_2	-0.04 ± 0.02	-0.03 ± 0.01	-0.04 ± 0.01	-0.04 ± 0.002	-0.01 ± 0.01
r^2	0.61	0.89	0.70	0.70	0.90

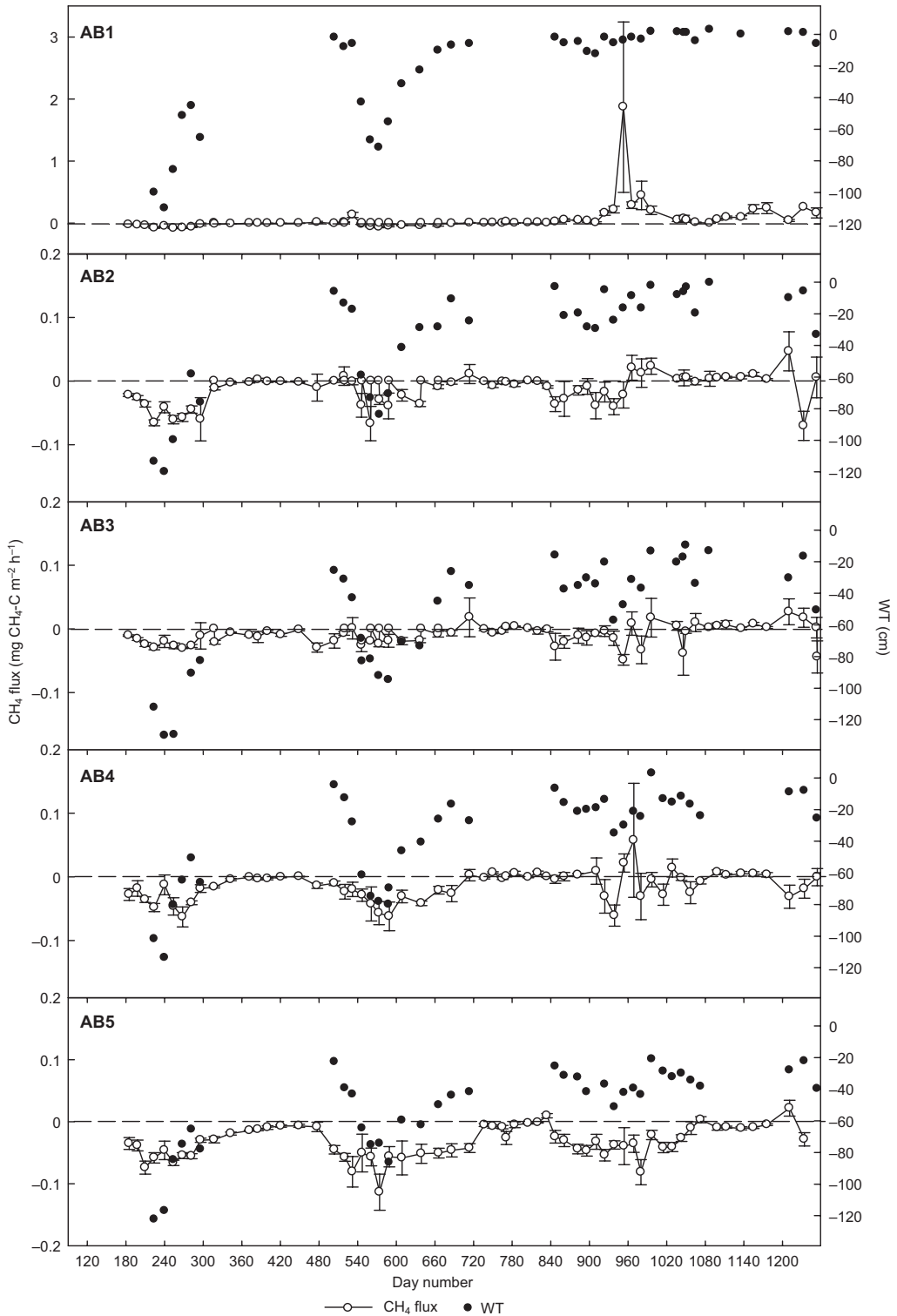


Fig. 2. Methane (circles) dynamics ($\text{mg CH}_4\text{-C m}^{-2} \text{h}^{-1}$) and water table depth (WT, distance from the soil surface, dots) on abandoned organic agricultural soils from July 2002 to June 2005. Negative and positive flux values indicate uptake and emissions of CH_4 by the ecosystem, respectively.

(Becton Dickinson) equipped with three-way stopcocks 5, 10, 15 and 25 minutes after the chambers were installed on the frames. The samples were analyzed with a gas chromatograph (Shimadzu GC-14B or Hewlett-Packard 5890) equipped with a flame ionization (FI) detector for CH₄, and thermal conductivity (TC) detector for CO₂ (Maljanen *et al.* 2001). Standards of 1.98 μl l⁻¹ CH₄ and 396 μl l⁻¹ CO₂ were used for hourly calibrations. The gas flux rates were calculated from the linear change in the gas concentrations in the headspace of the chamber.

CH₄ and CO₂ fluxes during winter with snow

During winter, when the snowpack depth was more than 15 cm, the CH₄ and CO₂ fluxes were determined using a gas gradient technique (Sommerfeld *et al.* 1993). Gas samples for the concentration analyses were drawn from the snow pack into the syringes using a stainless steel probe (diam. 3 mm). Samples were taken inside the collars and from several depths from 2 cm above the soil surface to 5 cm below the snow surface to verify linearity. Gas concentrations were analysed within 24 hours of sampling with a gas chromatograph as described above. Annual CH₄ and CO₂ flux rates during the winter period were calculated for each site separately using time-weighted average values for measured emissions.

Additional gas flux data and GWP calculations

Published N₂O flux data from the same sites and same period (Maljanen *et al.* 2012) were used to calculate the total atmospheric impact of CO₂, CH₄ and N₂O fluxes as CO₂ equivalents using the GWP approach (100 year time horizon) according to Solomon *et al.* (2007). The annual emissions of CH₄ were multiplied by 25 and those of N₂O by 298 to convert these emissions to CO₂ equivalents. Similar calculations were made for published data from grass leys with low management intensity (Maljanen *et al.* 2001, 2003a, 2003b, 2004, Lohila *et al.* 2004, Regina *et al.* 2004, 2007) and cultivated barley fields with fre-

quent management (Maljanen *et al.* 2001, 2003a, 2003b, 2004) on organic soils in Finland. The grass leys were ploughed and sown every 3–4 years and the barley fields annually; both were also fertilized (NPK) annually.

Statistical methods

Parameters for the photosynthesis functions were calculated using a non-linear regression, and coefficients for the respiration functions using a stepwise linear regression. CH₄ flux rates were not normally distributed and therefore correlations between the CH₄ flux rates and environmental parameters were calculated using Spearman's rank correlation (r_s). The differences in cellulose decomposition rates were tested with a paired *t*-test. All tests were performed using SPSS ver. 17 (SPSS Inc.)

Results

Soil characteristics

At the depth of 0–20 cm, soil pH_(H₂O) varied from 4.3 to 5.9, and the soil C:N ratio from 16.3 to 19.2 (mean = 18.3). All the soils were rather well decomposed, in von Post scale (*H*) from 8 to 10 (Table 1). The organic matter content in the same peat layer varied from 41% to 61%, and the peat bulk density between 0.30 and 0.42 g cm⁻³ (Table 1). The mean cellulose decomposition rate (average from all depths) varied between the sites from 0.18% d⁻¹ to 0.67% d⁻¹ during the summer periods (burial times 98 to 131 days) and from 0.02% to 0.33% during the winter (burial time 205 days). Cellulose mean decomposition values in 2003 and in 2004 were 0.55% d⁻¹ and 0.34% d⁻¹, respectively, but they did not differ statistically.

Weather conditions

The 2002 growing season was warm and dry. The average temperature during the summer months (from June to August) was 16.0 °C and the maximum temperature, measured in July,

was 28 °C. The following winter was cold; the lowest air temperature recorded at the end of December 2002 was -40 °C (Fig. 1a). The 2003 growing season was cooler and wetter; the average temperature from June to August was 13.6 °C. The following winter was milder; temperatures dropped to below -20 °C only a few times. The third growing season (2004) was wet (Fig. 1b) and slightly warmer than that of 2003. The mean temperature from June to August was 13.8 °C and the precipitation (304 mm) was 100 mm above the long-term average (for years 1971 to 2000, Drebs *et al.* 2002). The following winter was milder; air temperature remained above -20 °C. The mean temperatures and precipitation levels during the growing seasons (from May to October) and winters (November to April) are listed in Table 2.

In 2002, soils started to freeze early in the late November but in the following years, soil frost developed later. The maximum soil-frost depth varied from 4 to 17 cm. Soils thawed between late April and early May. The maximum soil temperature, 19.6 °C (at a depth of 5 cm), during the three year period was measured in July 2003 and the minimum, -2.4 °C, in March 2004. During winter, soil temperature remained close to -0.5 °C at all sites (Fig. 1a).

The water-table (WT) level was lowest during the dry, first growing season, and highest during the wet, third growing season. The WT varied from 128 cm below the soil surface to 5 cm above the soil surface, being on average 46 cm below the soil surface between May and October (Fig. 2).

Vegetation characteristics

Predominant plant species varied between the sites. The total coverage of plants in the third growing season was close to 90%, whereas in the first growing season it was clearly lower (Table 4). The maximum leaf area in the study plots was also lowest in 2002 and highest in 2004. Plant biomass was not measured in the first growing season but it was greater in the wet, third growing season than in the previous year. The above-ground biomass varied from 27 to 269 g C m⁻². The below-ground biomass was

not measured, but the total biomass for perennial grasses was estimated to be 2.5 times their above-ground biomass (Törmälä 1982, Pietola and Alakukku 2005), and it ranged from 38 to 376 g C m⁻² (Table 4).

Ecosystem respiration (R_{eco}) and soil respiration rates (R_{soil})

The maximum R_{eco} values during the growing season were about 1000 mg CO₂-C m⁻² h⁻¹, whereas during winter, the respiration rates were low, from 20 to 50 mg CO₂-C m⁻² h⁻¹ (Fig. 3). The R_{eco} during the growing season correlated with soil temperature (at 5 cm depth) and WT level and, therefore, these variables were used in the response functions (Table 3) for calculating diurnal R_{eco} . The modelled R_{eco} rates were at their lowest during the dry growing season (184 days) of 2002 (from 831 to 1057 g CO₂-C m⁻²), highest in 2003 (from 937 to 1570 g CO₂-C m⁻²) and slightly lower during the 2004 growing season (from 760 to 1460 g CO₂-C m⁻²). Winter respiration rates (from 1 November to 30 April, 181 days) were from 92 to 221 g CO₂-C m⁻².

Soil respiration rates (R_{soil}) were on average of 50%, 40% and 20% of R_{eco} during the first, second and third growing seasons, respectively. The annual modelled R_{soil} rates were at their highest during the second year and at their lowest during the wet third year (Table 4).

CO₂ exchange and CO₂ balance

The gross primary production (GPP) was strongly dependent on photosynthetically active radiation (I) during the growing season. Leaf area also correlated with GPP and was used in the response function as described above (Table 3). The modelled GPP rates during the growing seasons ranged from 642 to 1094 g CO₂-C m⁻² (Table 4 and Fig. 4). The modelled GPP values were highest during the wet growing season of 2004 and lowest during the dry and warm growing season of 2002. GPP increased with higher WT levels ($r^2 = 0.84, 0.97, 0.99, 0.95$ and 0.99 at sites AB1-AB5, respectively), thus high soil moisture favoured photosynthesis

(Fig. 5 and Table 5). Calculated instantaneous GPP values (measured R_{eco} + NEE) in full irradiation conditions were significantly higher at high WT level than at low WT level (Table 5). There was also a positive correlation between the precipitation sum and GPP. When precipitation during the growing season increased from 300 mm (dry year) to 550 mm (wet year), GPP increased on average by a factor of 1.3. The total (above + below ground) biomass measured outside the gas sampling plots in 2003 and 2004 did not correlate well with the GPP or NEE.

The modelled net ecosystem CO_2 exchange during the growing seasons varied from a net sink of $-122 \text{ g CO}_2\text{-C m}^{-2}$ to a net emission of $383 \text{ g CO}_2\text{-C m}^{-2}$. When the winter emissions were included, the annual net CO_2

exchange ranged from -7.8 (sink) to 530 (emission) $\text{g CO}_2\text{-C m}^{-2} \text{ yr}^{-1}$ (Table 4). Based on the three-year mean (mean \pm SD = $306 \pm 161 \text{ g CO}_2\text{-C m}^{-2}$), the ecosystems were annual net sources of CO_2 .

CH₄ flux rates

The sites were either weak sinks for or sources of CH_4 , with an average (\pm SD) rate for the five sites of $-0.018 \pm 0.516 \text{ g CH}_4\text{-C m}^{-2} \text{ yr}^{-1}$. Most of the sites acted as small sinks for CH_4 during the first and second years. During the third year, site AB1 emitted $1.8 \text{ g CH}_4\text{-C m}^{-2}$ and site AB3 emitted $0.03 \text{ g CH}_4\text{-C m}^{-2}$ as a result of high water-table levels (Fig. 2 and Table 6). The other

Table 4. Summary of mean water table depth (WT), annual soil respiration (R_{soil}), ecosystem respiration (R_{eco}), gross primary production (GPP) and net ecosystem CO_2 exchange (NEE) during three years (June 2002–May 2003, June 2003–May 2004 and June 2004–May 2005). Negative sign indicates CO_2 uptake by the ecosystem and positive sign its emission to the atmosphere. Above-soil biomass (SBM) was measured in the middle of July and the total biomass (BM) was estimated as C. Total coverage is the total coverage of plants inside the frames for the gas exchange measurements.

	AB1	AB2	AB3	AB4	AB5	Mean
2002–2003						
WT (cm)	–70	–93	–109	–79	–91	–88
R_{soil} ($\text{g CO}_2\text{-C m}^{-2}$)	558	588	371	567	428	502
R_{eco} ($\text{g CO}_2\text{-C m}^{-2}$)	954	954	1179	939	1009	1007
GPP ($\text{g CO}_2\text{-C m}^{-2}$)	–666	–651	–840	–642	–606	–681
NEE ($\text{g CO}_2\text{-C m}^{-2}$)	287	303	339	297	403	326
Total coverage (%)	42	43	85	48	65	57
2003–2004						
WT (cm)	–29	–39	–58	–40	–55	–44
R_{soil} ($\text{g CO}_2\text{-C m}^{-2}$)	535	551	629	575	455	549
R_{eco} ($\text{g CO}_2\text{-C m}^{-2}$)	1030	1362	1606	1290	1332	1324
GPP ($\text{g CO}_2\text{-C m}^{-2}$)	–719	–832	–1094	–919	–833	–879
NEE ($\text{g CO}_2\text{-C m}^{-2}$)	310	530	511	325	499	445
SBM (g C)	55	27	104	55	30	54
BM ¹⁾ (g C)	77	38	145	77	42	145
Total coverage (%)	55	55	86	67	62	65
2004–2005						
WT (cm)	–2	–14	–28	–18	–35	–19
R_{soil} ($\text{g CO}_2\text{-C m}^{-2}$)	109	186	398	231	291	243
R_{eco} ($\text{g CO}_2\text{-C m}^{-2}$)	877	1115	1655	1289	1175	1222
GPP ($\text{g CO}_2\text{-C m}^{-2}$)	–885	–1000	–1205	–971	–1028	–1018
NEE ($\text{g CO}_2\text{-C m}^{-2}$)	–7.8	115	450	318	147	204
SBM (g C)	194	269	203	134	137	187
BM ¹⁾ (g C)	272	377	284	188	192	262
Total coverage(%)	80	80	100	94	85	88

¹⁾ Estimated biomass C calculated from measured shoot biomass and with shoot:root ratio of 2.5:1 (according to Pietola and Alakukku 2005).

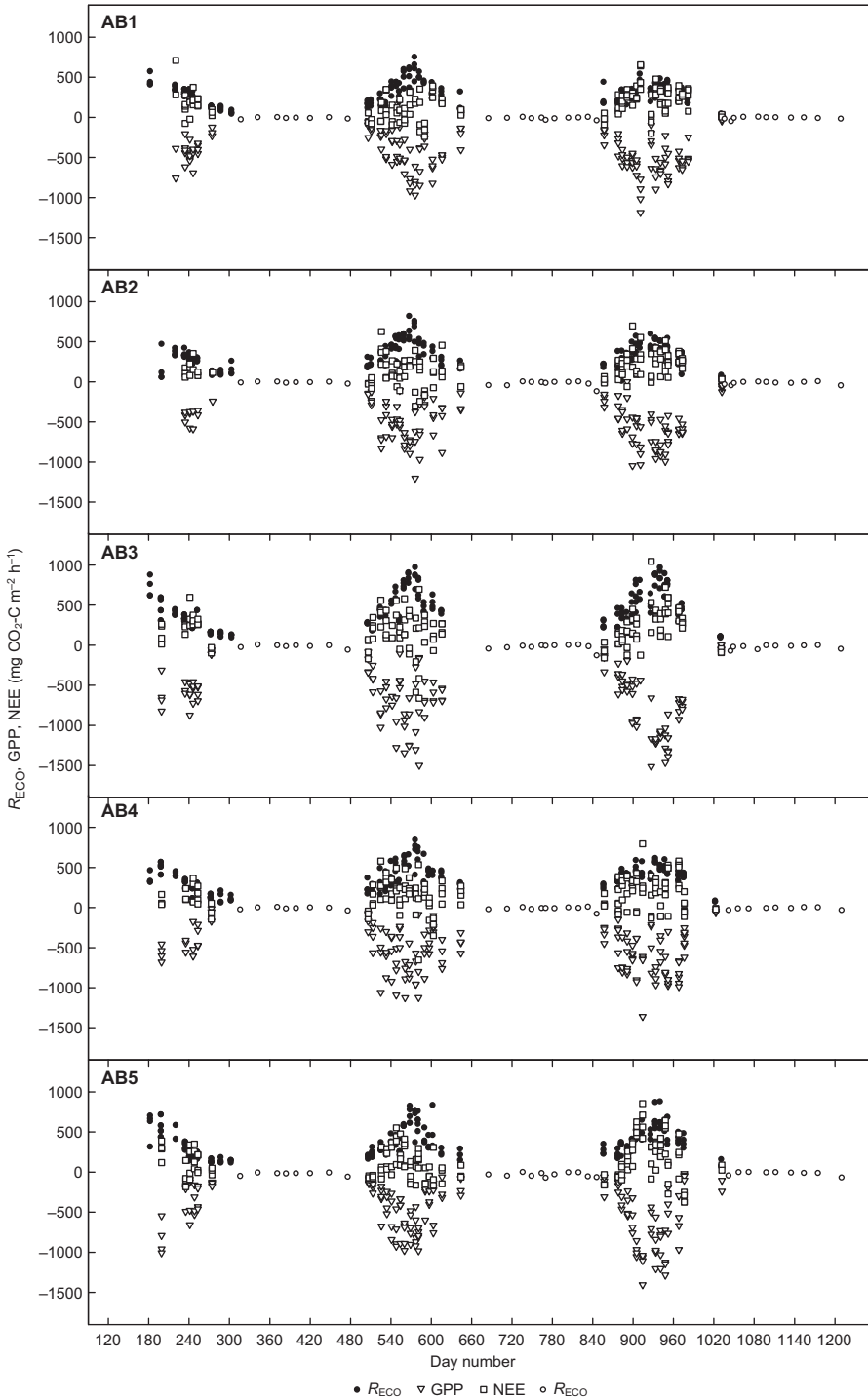


Fig. 3. Instantaneous CO₂ fluxes measured in all subplots using chambers and an IRG analyzer. Black dots are ecosystem respiration rates (R_{Eco}) measured with an IR analyzer during the growing season and circles are ecosystem respiration rates measured with GC outside the growing season. Triangles are net ecosystem exchange rates (NEE) measured with a transparent chamber in a full light, and squares are calculated values of the gross primary production ($\text{GPP} = \text{NEE} + R_{\text{Eco}}$). Negative sign indicates uptake by the ecosystem and positive emission to the atmosphere.

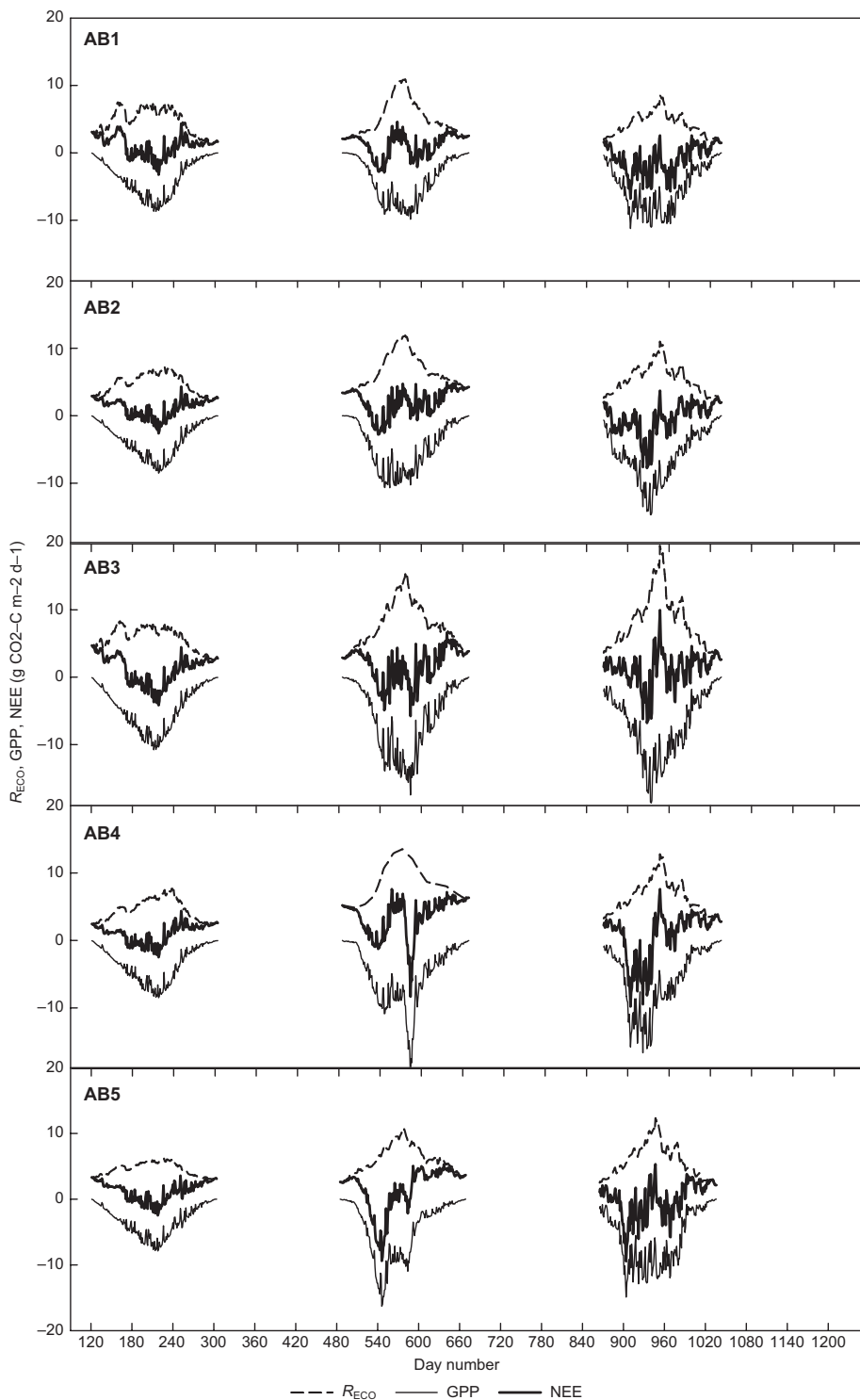


Fig. 4. Modelled values of the ecosystem respiration (R_{eco} , dashed line), gross primary production (GPP, solid thin line) and net ecosystem uptake (NEE, solid thick line) for the abandoned organic agricultural soils during the growing seasons of 2002, 2003 and 2004. Negative sign indicates uptake by the ecosystem and positive emission to the atmosphere.

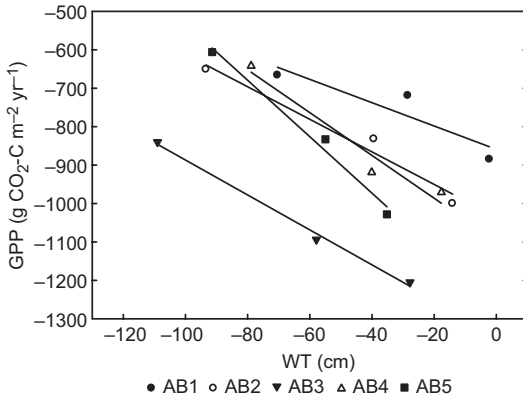


Fig. 5. Gross primary production (GPP) on abandoned agricultural peat soils during three growing seasons plotted against water table level (WT) during the growing season.

sites remained net sinks for CH_4 during these years. The highest annual CH_4 uptake rate ($0.41 \text{ g CH}_4\text{-C m}^{-2}$) was measured at site AB5 in 2003 (Table 6).

Methane fluxes correlated with the WT level (Fig. 2) and soil temperature (at the depth of 5 cm) at all sites. CH_4 uptake decreased with higher WT level ($r_s = -0.188, p = 0.030$; $r_s = -0.444, p < 0.001$; $r_s = -0.241, p = 0.004$; $r_s = -0.292, p < 0.001$; $r_s = -0.276, p = 0.002$; at sites AB1 to AB5, respectively). CH_4 uptake decreased with decreasing soil temperature at the depth of 5 cm ($r_s = 0.130, p = 0.046$; $r_s = 0.332, p < 0.001$; $r_s = 0.270, p < 0.001$; $r_s = 0.268, p < 0.001$; $r_s = 0.559, p < 0.001$; at sites AB1 to AB5, respectively).

Table 5. Mean gross photosynthesis \pm SD ($\text{mg CO}_2 \text{ m}^{-2} \text{ h}^{-1}$) measured under conditions of full irradiation ($I > 700 \mu\text{s s}^{-1} \text{ m}^{-2}$) and at the mean water-table level (cm, distance from the soil surface as a negative value) during measurement days at each site during the growing seasons of 2002, 2003 and 2004. The values with a common letter do not differ significantly at $p \geq 0.05$ (Tukey's test).

	Mean GPP			<i>F, p</i>	WT			<i>F, p</i>
	2002	2003	2004		2002	2003	2004	
AB1	1660 \pm 350 ^a	2050 \pm 850 ^{ab}	2410 \pm 670 ^b	5.32, 0.007	-93 ^a	-46 ^b	-10 ^c	98.3, < 0.001
AB2	1750 \pm 320 ^a	2170 \pm 910 ^{ab}	2470 \pm 790 ^b	3.72, 0.028	-118 ^a	-47 ^b	-28 ^c	79.1, < 0.001
AB3	2130 \pm 470 ^a	2780 \pm 1290 ^a	3230 \pm 1440 ^a	2.78, 0.670	-136 ^a	-61 ^b	-34 ^c	112, < 0.001
AB4	1970 \pm 400 ^a	2450 \pm 1030 ^{ab}	2850 \pm 860 ^b	3.91, 0.024	-113 ^a	-52 ^b	-26 ^c	30.8, < 0.001
AB5	1870 \pm 1170 ^a	2250 \pm 1120 ^{ab}	2780 \pm 1460 ^b	4.32, 0.017	-128 ^a	-59 ^b	-40 ^c	78.1, < 0.001

Table 6. Annual net exchange of CH_4 , N_2O and CO_2 ($\text{g m}^{-2} \text{ yr}^{-1}$) on abandoned organic agricultural soils during three years (June 2002–May 2003, June 2003–May 2004 and June 2004–May 2005). The GWP_{tot} is the total warming effect (sum of CH_4 , CO_2 and N_2O) as CO_2 equivalents. CH_4 flux is multiplied by 24 and N_2O flux by 298 to express fluxes as CO_2 equivalents ($\text{g CO}_2 \text{ eq. m}^{-2} \text{ yr}^{-1}$) for 100-year time horizon (Solomon et al. 2007). Negative sign indicates uptake by the ecosystem and positive sign emission to the atmosphere.

Site	AB1	AB2	AB3	AB4	AB5	Mean
2002–2003						
CH_4	-0.18	-0.23	-0.17	-0.20	-0.38	-0.23
CO_2	1050	1110	367	1090	1480	1020
N_2O	0.54	0.99	0.43	0.73	2.45	1.03
GWP_{tot}	1210	1400	490	1300	2200	1320
2003–2004						
CH_4	-0.12	-0.26	-0.12	-0.27	-0.55	-0.26
CO_2	1140	1940	1880	1190	1830	1960
N_2O	0.28	0.51	0.69	0.85	3.17	1.10
GWP_{tot}	1220	2090	2080	1440	2760	1920
2004–2005						
CH_4	2.41	-0.01	0.04	-0.08	-0.22	0.43
CO_2	-29	420	1650	1170	538	750
N_2O	0.15	0.42	0.32	0.33	1.08	0.46
GWP_{tot}	74	545	1750	1270	855	897

Total GWP of abandoned boreal organic agricultural soils

The global warming potential (GWP) of the sites, including C gases ($\text{CO}_2 + \text{CH}_4$), was calculated as CO_2 equivalents (Solomon *et al.* 2007). These gases together had a warming effect of 28 to 1940 g CO_2 eq. $\text{m}^{-2} \text{yr}^{-1}$, with a mean of 1121 g CO_2 eq. $\text{m}^{-2} \text{yr}^{-1}$ (time horizon of 100 years). Including N_2O emissions from Maljanen *et al.* (2012) resulted in a total mean (\pm SD) GWP of 1380 (\pm 677) g CO_2 eq. $\text{m}^{-2} \text{yr}^{-1}$ for these sites (Table 6).

Among the sites, AB1, for which the WT was close to the soil surface, had the lowest total GWP. The CO_2 balance mainly determined the total GWP, whereas CH_4 had only a minor effect (on average less than 0.1%, max. 3.2% of total GWP). The N_2O emissions (Maljanen *et al.* 2012) increased the GWP on average by 21%.

Discussion

Weather and vegetation characteristics

The three studied years differed greatly from each other with regard to precipitation and water table depth. The first growing season, 2002, was warm and dry; the second, 2003, cooler and wetter; and the third, 2004, very wet. Precipitation during the growing season of 2004 was almost twice the long-term average. Temperature and precipitation (mostly as snow) increased from the winter of 2002 to 2004. Vegetation coverage was at its lowest at the end of the dry growing season in 2002, indicating that drought limited plant growth. Vegetation cover recovered and consequently biomass increased during the following two growing seasons. There was two to ten times more plant biomass in 2004 than in 2003 (Table 3).

Even 20 to 30 years after ending all agricultural activities, the vegetation resembled more that of grass leys or meadows than mires. The plant biomass in 2004 was close to that of managed grass leys (Maljanen *et al.* 2001, 2004). The predominant species, e.g. *Deschampsia cespitosa*, *Juncus filiformis*, *Poa pratensis* and *Epilobium angustifolium*, are known to favour

soils with high N-content (Jylhänkangas & Esala 2002). The secondary succession of abandoned fields to forested areas is known to be slow (Törmälä 1982, Jukola-Sulonen 1983, Kiiirikki 1993). However, as described earlier, some scattered small birch trees and willow bushes were growing in the ditches.

Ecosystem and soil respiration rates

The R_{eco} and R_{soil} rates during the growing season and winter were lower than those reported for cultivated peat fields in Finland (Maljanen *et al.* 2001, 2004) but higher than those from natural peatlands (Alm *et al.* 1999a, Haapala *et al.* 2009). Measured R_{eco} and R_{soil} rates followed seasonal trends similar to those reported earlier for peatlands (e.g. Alm *et al.* 1997, Maljanen *et al.* 2001) and depended mainly on soil temperature and moisture. Both R_{eco} and R_{soil} rates were lower during the dry and warm growing season of 2002 than during the next, wetter growing season of 2003, indicating that low soil moisture limited ecosystem respiration in 2002, as has also been reported by Shurpali *et al.* (2009) for an organic soil covered with perennial grass. On the other hand, in 2004, the wet growing season and high WT levels also caused low respiration rates; R_{soil} was only half that in 2003. Mäkiranta *et al.* (2009) showed an optimum WT for R_{soil} in afforested agricultural peat soils and forestry-drained peatlands to be at about 60 cm. With higher or deeper water-table surface, wetness or drought apparently restricted soil respiration. High WT levels only slightly decreased R_{eco} since the moist conditions favoured photosynthesis and plant growth, which was seen as higher GPP and greater plant biomass and coverage in 2004 than in the previous years. The $R_{\text{eco}}:R_{\text{soil}}$ ratio was 2 in 2002, 2.4 in 2003 and 5.6 in 2004, showing that with increasing soil moisture R_{eco} increased more than R_{soil} . The autotrophic respiration can be estimated as $R_{\text{eco}} - R_{\text{soil}}$. The corresponding average values of the autotrophic respiration rates were -504, -775 and -979 g $\text{CO}_2\text{-C m}^{-2}$ for the years 2002, 2003 and 2004, respectively. This indicates that good water availability favours autotrophic respiration more than heterotrophic respiration (R_{eco}). The measured R_{soil} in 2002

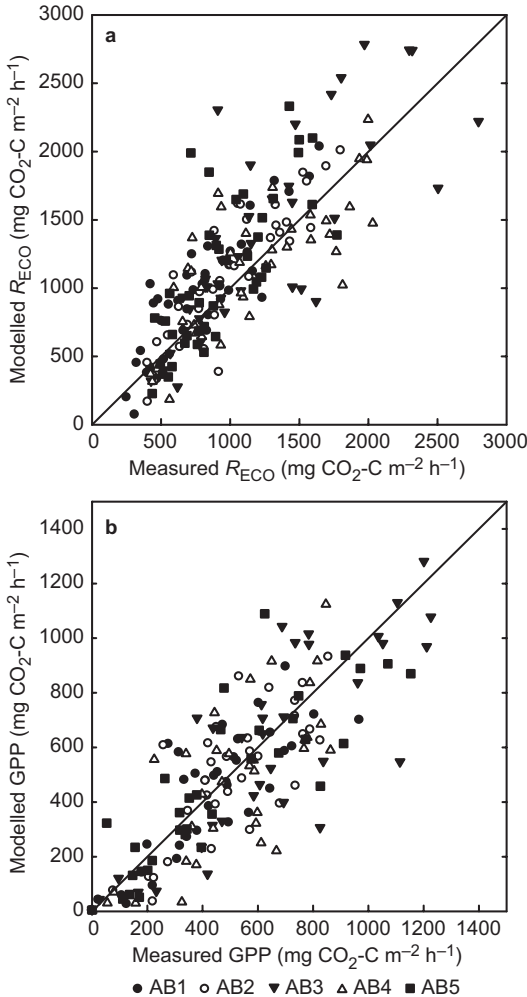


Fig. 6. Comparison of measured and modelled daytime (a) ecosystem respiration (R_{eco}) and (b) gross primary production (GPP) of abandoned agricultural soils (AB1–AB5). The line is indicating 1:1 agreement. R_{eco} and GPP are all shown as positive values.

could even be overestimated since the cutting of above-ground plants was done in June 2002 and a lot of degradable root material was then left in the soil (e.g. Alm *et al.* 2007).

Gross primary production (GPP) and net ecosystem CO_2 exchange (NEE)

The interannual variation in WT levels and associated variation in plant coverage and biomass explained the differences in the CO_2 balance

between the years (Fig. 5). GPP and R_{eco} models (Eqs. 2 and 3) fit well with the data (Fig. 6). During the first dry growing season, GPP at all sites was lower than during the following wetter growing seasons. The low WT level in 2002 resulted in low biomass production. The measured GPP values in the dry year 2002 were within the range measured in Finland for grass leys on peat soils with low management intensity (Maljanen *et al.* 2001, 2004), but in the following years they were 20%–40% higher than those for grass leys.

The annual net CO_2 exchange (NEE) varied from slightly negative (i.e. uptake), at $-8 \text{ g C m}^{-2} \text{ yr}^{-1}$ (wet year), to net emissions of $530 \text{ g C m}^{-2} \text{ yr}^{-1}$ (dry year). A similar climate-dependent trend has been found for perennial grass cultivated on boreal organic soil (Shurpali *et al.* 2009). In both cases, changes in GPP mostly depended on the hydrology of the soil. Zhou *et al.* (2011) further showed in a greenhouse experiment that the GPP of the perennial reed canary grass was sensitive to water availability. Alm *et al.* (1999b) also reported net CO_2 losses from a natural peatland as a result of reduced photosynthesis during a dry summer. The results in this study and those of Shurpali *et al.* (2009) showed that respiration in drained organic soil can be limited by low water availability. In wet years, the increase in GPP can more than compensate for the increase in C loss from increased soil respiration. However, if the soil water content is high enough, the respiration rate is reduced as a result of oxygen deficiency in the soil whereas GPP still increases, enhancing the net CO_2 uptake. The high GPP at sites AB1 and AB2 during the wet growing season could be associated with the *Juncus* species, in which aerenchyma allows for gas diffusion between shoots and roots (Dinsmore *et al.* 2009), i.e. transport of oxygen to the roots when the WT level is high. According to Law *et al.* (2002), photosynthesis in boreal forest ecosystems during a cloudy day can be higher than on sunny days, which also supports our results of high GPP during the rainy growing season.

The average net CO_2 -C emissions during the first two years, excluding the net uptake during the wet growing season of 2004, were in the range reported for cultivated peatlands in

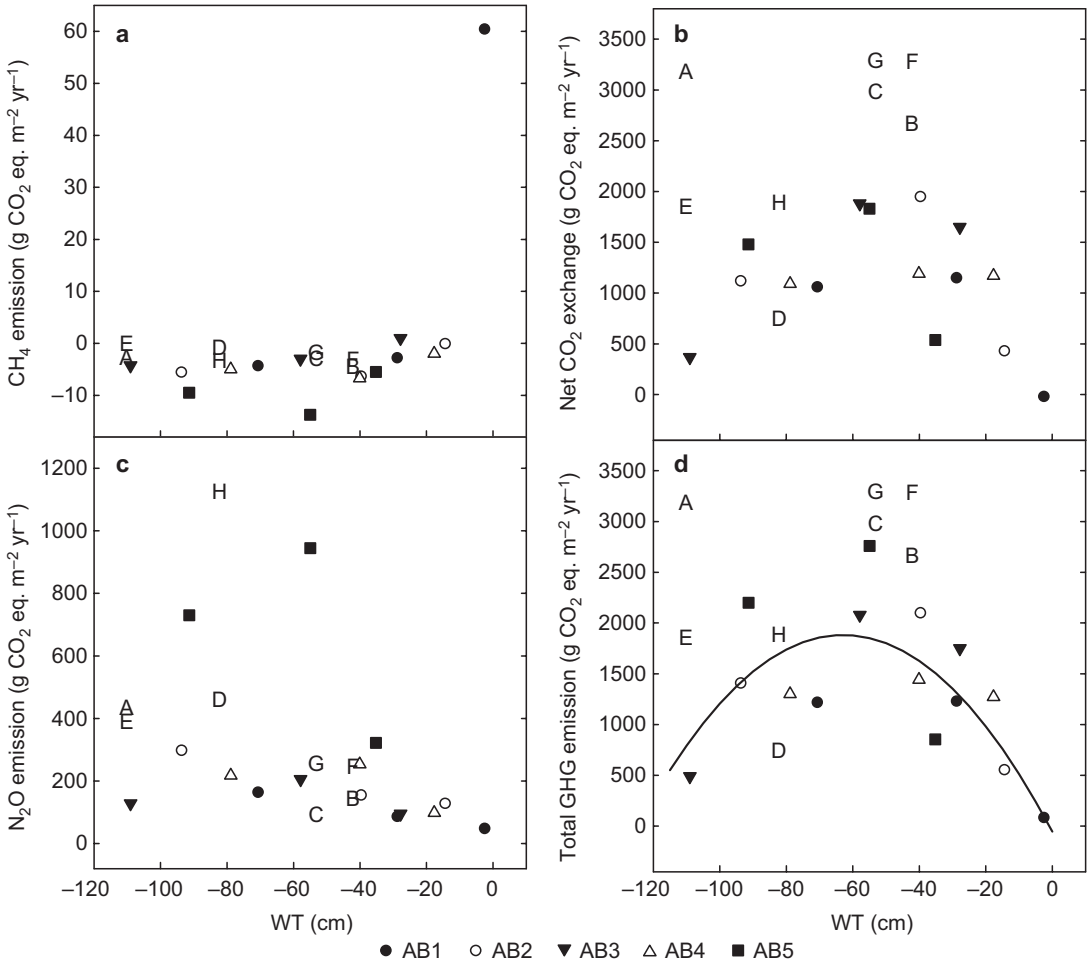


Fig. 7. The annual net exchange of (a) CO₂, (b) CH₄, (c) N₂O and (d) the total GHG emissions (GHG_{TOT}) for abandoned agricultural peat soils (AB1–AB5), calculated as CO₂ equivalents plotted against mean water table (WT). The curve is form of: $GHG_{TOT} = -53.8 + 61.2WT - 0.49WT^2$, ($r^2 = 0.92$). The capital letters show literature data for grass leys (A = Maljanen *et al.* 2001, 2003a, 2003b; B and C = Maljanen *et al.* 2004; D = Regina *et al.* 2004, 2007 and Lohila *et al.* 2004) and barley fields (E = Maljanen *et al.* 2001, 2003a, 2003b; F and G = Maljanen *et al.* 2004; H = Regina *et al.* 2004, 2007, Lohila *et al.* 2004) on organic soils in Finland.

Finland (Maljanen *et al.* 2001, 2004, Lohila *et al.* 2004). Abandonment of these organic agricultural soils did not turn them into carbon sinks. However, with high WT levels, emissions could be reduced (Fig. 7a and b). The present data also show that with deep WT levels (WT < 70 cm), net CO₂ emissions also decrease (Fig. 7b), but this occurs only in very dry conditions.

Methane fluxes

The mean CH₄ uptake rates during the first two

years were in the range or higher than those reported for well-drained cultivated peat soils (Maljanen *et al.* 2003b, 2004, Regina *et al.* 2007) or those for afforested agricultural peat soils in Finland (Mäkiranta *et al.* 2007). Here, during the first two growing seasons the WT level remained low and favoured CH₄ oxidation. After ceasing agricultural activities, CH₄ oxidizers in the peat are no longer disturbed by ploughing or fertilization (e.g. Mosier *et al.* 1998) but the deteriorating ditch system can lead, as reported here, to higher WT levels and a more anaerobic soil that supports CH₄ production and its emissions, as

during the wet, third growing season of 2004. However, contribution of CH₄ to total emissions was minor (Table 6), with CO₂ playing the main role. The current results support the earlier data showing that organic agricultural soils are mainly small sinks for CH₄ and net emissions occur only when the WT level is very close to the soil surface (Fig. 7a).

Mitigation of GHG emissions from organic agricultural soils

When calculated as CO₂ equivalents for a 100-year time horizon (GWP approach) (Solomon *et al.* 2007), the average net GHG emission from the abandoned organic agricultural soils was 1380 g CO₂ eq. m⁻² yr⁻¹ (range 74 to 2760). This value is 39% lower than that reported for intensively managed organic agricultural soils in the Nordic countries, 2300 g CO₂ eq. m⁻² yr⁻¹ (Maljanen *et al.* 2010). However, the range of values for abandoned organic soils is wide and the maximum value for abandoned sites exceeds the average values for agricultural soils in the Nordic countries (Maljanen *et al.* 2010). Our results show that leaving organic soils without management may be an somewhat uncertain way to mitigate GHG emissions, which are highly affected by weather conditions and natural water-table fluctuations. When published annual GHG data from organic agricultural soils in Finland reported in Maljanen *et al.* (2010) are plotted against the WT level, we can see that there is a non-linear relationship (Fig. 7d). The highest net GHG emissions occur in the WT range from 40 to 60 cm (Fig. 7d) and the emissions then decrease with lower or higher WT levels.

According to this study, the lowest net (CO₂ + CH₄) emissions occurred during the wet year with a high WT level. The N₂O emissions from these abandoned agricultural peat soils were also low in such conditions (Fig. 7c). Therefore, we suggest that by bringing the WT level (by actively blocking the ditches after ceasing agricultural activities) close to the soil surface, high GHG emissions can be avoided. However, there is a risk of CH₄ emissions if water table is high and the peat is totally water saturated (e.g. Wadlington & Day 2007, Saarnio *et al.* 2009).

Since natural vegetation succession on abandoned agricultural land is a slow process (e.g. Törmälä 1982), active afforestation would lead to full forest cover in a much shorter time (Hytönen 1999). Carbon sequestration in trees grown on these soils would offer a possibility for mitigation of the GHG emissions produced in the boreal region. A study by Lohila *et al.* (2007) showed that an afforested, formerly agricultural peat soil ecosystem, is close to neutral in CO₂ balance (source of 50 g CO₂-C m⁻²), i.e. sequestration of C to the tree stand compensates most of the CO₂ released from soil organic matter decomposition. On the other hand, afforested agricultural sites may still emit high amounts of N₂O (Maljanen *et al.* 2012). However, there are not enough data about the net carbon balances of abandoned and afforested sites to draw general conclusions regarding their GHG balances.

Concluding remarks

Abandoning organic agricultural soils (ceasing of all agricultural activities) may significantly decrease their GHG emissions. However, there is a high annual and spatial variation in GHG emissions. During the growing season, emissions from sites which were abandoned 20–30 years ago varied from high net emissions, similar to those from cultivated organic soils, to net GHG sinks. Weather conditions strongly affected the net GHG emissions. Both photosynthesis and respiration can be limited by low availability of water, but photosynthesis is favoured over respiration when the water table rises close to the soil surface in drained organic soils. Therefore, high GHG emissions from agricultural soils can be best avoided if the water table is maintained at a high level (WT depth less than 30 cm from the soil surface), e.g. by blocking the ditches after agricultural use has ended. There is a need for future studies on how these systems will develop. In the long run, the natural regeneration of abandoned sites may further increase the photosynthesis and therefore the C uptake by the ecosystem.

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