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Bare soil and reed canary grass ecosystem respiration in peat extraction sites in Eastern Finland

By N. J. SHURPALI*, N. P. HYVÖNEN, J. T. HUTTUNEN, C. BIASI, H. NYKÄNEN, N. PEKKARINEN and P. J. MARTIKAINEN, *University of Kuopio, Department of Environmental Sciences, Bioteknia 2, P.O. Box 1627, FI-70211 Kuopio, Finland*

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ABSTRACT

This paper reports chamber measurements of ecosystem respiration (ER) from reed canary grass (*Phalaris arundinacea* L.) (RCG) cultivation made during 2004 and 2005 and respiration rates from an adjacent, bare peat extraction site. Annually, the RCG site released 1465 g in 2004 and 1968 g CO_2 m^{-2} in 2005. The peat extraction site, however, emitted 498 g in 2004 and 264 g CO_2 m^{-2} in 2005. Heterotrophic respiration accounted for about 45% of the RCG ER. Temperature explained 75–88% of the variation in 2005 RCG heterotrophic respiration. Autotrophic respiration was the dominant component of ER and it followed a similar seasonal pattern as the living (green) biomass. RCG heterotrophic respiration was related to soil temperature in interaction with soil volumetric water content and seasonal rainfall distribution. It explained 79 and 47% of the variation in the bare soil respiration from the peat extraction site during 2004 and 2005 snow free periods, respectively. Compared to other ecosystems, emissions from RCG were lower indicating that the RCG is a promising after use option in organic soils.

1. Introduction

Natural peatlands are an important sink for atmospheric carbon dioxide. Nearly 30% of the world's soil carbon pool is found in northern peatlands (Gorham, 1991). The net accumulation of carbon in these ecosystems is attributed to the imbalance between primary production and decomposition processes, controlled by vegetation, climate and hydrology. The long-term apparent rate of carbon accumulation in pristine mires of Finland is estimated to be 18.5 g m^{-2} yr^{-1} (Turunen et al., 2002). However, during some dry years, peatlands have been found to lose carbon (Shurpali et al., 1995; Alm et al., 1999; Waddington and Roulet, 2000).

Owing to a large natural abundance of peatlands, mankind has used these peat resources for various purposes. In Finland, for example, there are 10.4 Mha of peatlands and more than 50% of these are drained mainly for forestry, agriculture and peat extraction (Vasander et al., 2003). As a result of drainage, the depth of oxygen penetration in the peat matrix increases resulting in enhanced rates of aerobic decomposition of soil organic matter. In many cases, the peatland carbon cycling has been drastically altered favouring a net loss of carbon to the atmosphere (Ahlholm and Silvola, 1990; Nykänen et al., 1996; Silvola et al., 1996; Maljanen et al., 2002; Waddington et al., 2002; Lohila et al., 2004; Maljanen et al., 2004) in contrast to natural peatlands which have been gaining C since the last glacial period (Laine et al., 1996; Turunen, 2003). Attempts to mitigate CO_2 emissions through cultivation of barley and grass species on drained organic soils have indicated that these land use types continue to emit large amounts of carbon into the atmosphere (Nykänen et al., 1995; Maljanen et al., 2001; Lohila et al., 2004).

As a part of the Kyoto protocol, signatory member countries are required to report greenhouse gas (GHG) emissions from major land use classes and to reduce emissions below the 1990 levels during the 2008–2012 commitment period. A major part of the CO_2 emissions results from combustion of fossil fuels. One of the strategies adopted for mitigating GHG emissions due to fossil fuel combustion is to increase the share of bioenergy in the total energy consumption. Consequently, cultivation of bioenergy crops such as reed canary grass (RCG) is gaining a lot of attention in Finland as one of the potential land use practices on drained organic soils to offset the large emissions resulting from peatland drainage. Reed canary grass is well suited to Nordic conditions (Venendaal et al., 1997; Lewandowski et al., 2003). It thrives well under low soil pH and water-logged conditions, and it is cold tolerant. It is capable of accumulating large amounts of atmospheric carbon in biomass within a short growing season, characteristic of boreal regions. There is a wealth of data on the rates of RCG biomass production under different environmental conditions. However, there is hardly any scientific information

*Corresponding author.
e-mail: narasinha.shurpali@uku.fi
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on the impact of cultivation of bioenergy crops on the environment. To our knowledge, there are no studies that report inter and intraannual trends in net ecosystem carbon exchange from reed canary grass cultivation.

The carbon balance of an ecosystem is a net function of the C uptake by the vegetation (gross photosynthesis) and combined C release from the soil and vegetation (ecosystem respiration). We report in this paper 2 yr measurements of ecosystem respiration from a cutaway peatland cultivated with RCG and soil respiration from an adjacent bare peat extraction site in eastern Finland.

2. Materials and methods

2.1. Study sites

This study was conducted in the Linnansuo cutover peatland complex (62° 30′ N, 30° 30′ E) located in the rural area of the city of Joensuu in eastern Finland. The complex lies on the border of southern and mid boreal climatic zones. Based on the 30 yr normal (1971–2000) climatic data, the mean annual temperature and precipitation in the region are 2.1 °C and 669 mm, respectively (Drebs et al., 2002). The maximum and minimum temperatures of −10.6 and 16.0 °C occur during the months of January and July, respectively. July and August are the wettest months with 80–90 mm of rainfall, while February, March and April, on an average, receive the lowest amount of precipitation mostly in the form of snow with about 35 mm during each month. The preparation of peatlands for peat extraction in the Linnansuo complex, including their drainage by ditching, was initiated in 1976. Peat extraction began in 1978 (Vapo Ltd. Energy, 2003). In 2001, however, when the residual peat thickness ranged between 20 and 85 cm, peat extraction ceased and cultivation of bioenergy crops began.

We selected two sites from this complex in the beginning of 2004 for ecosystem respiration measurements (Fig. 1). The first subsite (hereafter referred to as RCG site) is 15-ha in area and it is cultivated with reed canary grass (*Phalaris arundinacea* L.). Thin patches of fire moss (*Ceratodon purpureus Hedw.*) are found scattered as minor understory vegetation. These patches are more conspicuous in places where the RCG growth is poor. Prior to the cultivation of reed canary grass, this site was abandoned after peat extraction. Cultivation on this abandoned site began in 2001. The preparation of the site for cultivation included deepening of the drainage ditches. These ditches divide the area into 20 m-wide strips. The strips with 20–85 cm thick residual peat layer were tilled, limed and fertilized with a per hectare surface application of 59.5 kg N, 14.0 kg P and 45.5 kg K. These strips were then sown with the seeds of a low-alkaloid, hardy reed canary grass variety 'Palaton'. As a part of the agronomic practices in the region, the cultivation of reed canary grass on such abandoned organic soils follows a 10-yr rotation cycle. Except for the beginning of the rotation cycle, the soil is not tilled at all. Fertilizers are applied every year. Whether the soil needs additional lime is decided depending upon the soil pH and crop performance in the preceding year. The crop is harvested every spring since the third growing season. The fresh weight crop

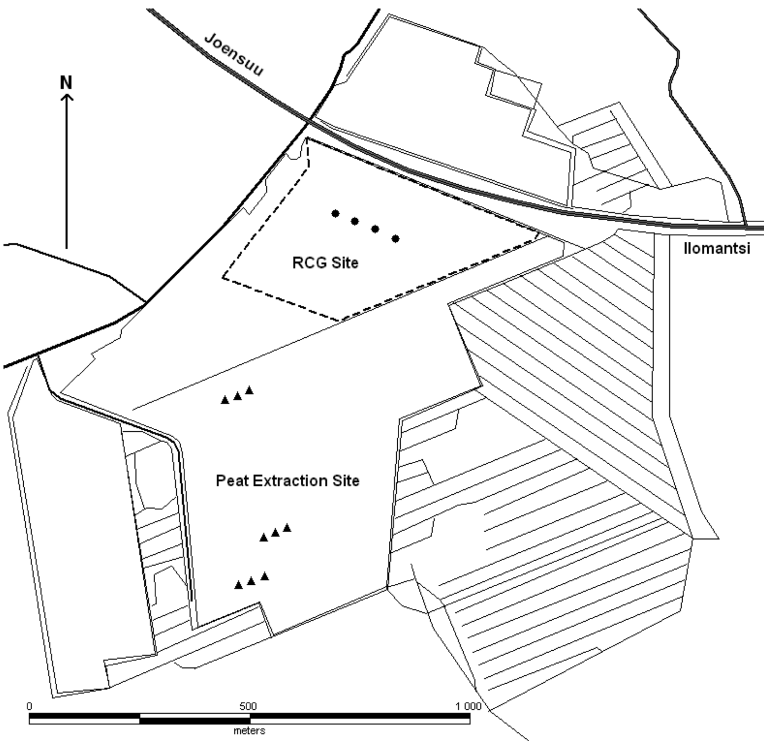

Fig. 1. A map showing the Linnansuo peatland complex in Eastern Finland. The study sites are located south-southwest of the Joensuu–Ilomantsi highway. The measurement plots in the reed canary grass cultivation area (RCG site) are shown by solid circles. Each plot has three replicate chamber locations. The peat extraction site is to the south of the RCG site. The chamber locations in the peat extraction site are represented by solid triangles. Note that areas in the map shown in light grey colour are different peat extraction areas in the complex.

Table 1. Mean values of the physical and chemical properties (with standard deviations in parenthesis and the number of analysed samples) of the surface peat in the reed canary grass (RCG) and peat extraction sites at Linnasuo peatland complex in eastern Finland.

Property	RCG site		Peat extraction site	
pH	4.3–6.3	3	4.2–4.3	3
Bulk density (g cm^{-3})	0.42 (0.19)	4	0.18 (0.05)	9
Mg (mg kg^{-1})	1340 (960)	4	240 (20)	9
Ca (mg kg^{-1})	3420 (1530)	4	1320 (110)	9
K (mg kg^{-1})	550 (400)	4	$<$100	9
Total P (mg kg^{-1})	270 (60)	4	270 (50)	9
C/N	40.3	4	40.2	9

yield was 4.8, 3.7 and 2.0 tonnes ha^{-1} in spring 2004, 2005 and 2006, respectively.

The second subsite, hereafter referred to as 'peat extraction site', is adjacent to the RCG site and it is still under active peat extraction. The drainage ditches divide this site also into 20 m-wide strips. The mineral soil beneath the peat is visible in some parts of this site. Hence the peat extraction is expected to cease after some more seasons of operation. The peat characteristics at both RCG and peat extraction sites are described in Table 1.

2.2. Measurements of ecosystem respiration

The total ecosystem respiration (ER) was measured once or twice a month during the snow-free season in 2004 and 2005, between the second half of April and middle of November. It was measured with a closed chamber technique combined with a portable infrared gas analyser (Alm et al., 1999; Nykänen et al., 2003) at both sites. In the RCG site, 12 cylindrical collars (diameter 58 cm) were inserted into the peat to a 20 cm depth in the beginning of the 2004 growing season. The collars were distributed in four plots located at 50 m intervals along one strip, with three replicate collars in each plot (Fig. 1). The collars had water grooves for air-tight connection with the chambers during the ecosystem respiration measurements. In the beginning of each respiration measurement, aluminium chamber (diameter 54.5 cm, height 43 cm) equipped with an electrical fan was placed in a water groove of the collar for data collection at a 10 s interval during the 3-min measurement period. A portable infrared gas analyser (LI-6200 Portable Photosynthesis System, LI-COR, Inc., Lincoln, NE, USA), operating with a flow rate of about 1 L min^{-1}, was used for measurement of the mixing ratio of CO_2 inside the chamber. The chamber height was adjusted over the growing season with additional collars to account for the increase in the plant height. The total ecosystem respiration was calculated from the linear change in the chamber CO_2 concentration during the measurement periods. Of the total number of measurements made during 2004 and 2005, 92.9 and 93.9% of the data were evaluated to be of good quality for RCG and peat extraction sites, respectively.

In the peat extraction site, permanent collars could not be used for the respiration measurements due to active peat extraction during the summer. Thus, in the beginning of each measurement, a cylindrical chamber made of sheet metal (diameter 31 cm, height 30–32 cm) was pushed directly into the peat to a depth of 5.0 cm, while the rest of the measurement proceeded as in the RGC site described above. In the peat extraction site, measurements were made along three strips using three replicate chambers per strip situated about at 30 m intervals from each other (Fig. 1).

2.3. Soil respiration measurements

To determine the contribution of soil respiration to total respiration in the RCG site, the root-trenching method was used. In spring 2005, 16 collars made of PVC (of 10 cm diameter) were vertically inserted into the soil to a depth of 15 cm deep (representing major part of the rooting zone), thereby severing the roots. The aboveground vegetation was removed thereafter and also a day prior to every respiration measurement campaign. Respiration rates were measured continuously over the growing season (approximately twice a month) by a portable IRGA using the closed static chamber technique. Briefly, an opaque respiration chamber was fitted over the collar to form an airtight seal. Then, the increase in CO_2 concentration was recorded every five seconds for a period of 3 minutes, at a flow rate of about 300 ml min^{-1}. The CO_2 flux (mg CO_2 m^{-2} h^{-1}) was calculated from the slope of the headspace CO_2 concentration against time curve.

The soil respiration contribution (SRC, in %) to ecosystem respiration was calculated using the following equation:

$$\mathrm{SRC} = \mathrm{Soil\ respiration/Ecosystem\ respiration} \times 100$$

After trenching the decomposition of the residual dead roots left in the collars may result in overestimated soil respiration rates (Hanson et al., 2000). To assess the extent of overestimation, data on soil respiration rates from the year 2006 with similar climatic conditions and negligible contribution from root decomposition were compared with data from 2005. The patterns of soil respiration rates after DOY 200 were similar in both years, indicating the general comparability of the data sets. However, the soil respiration rates from 2005 prior to DOY 200 were on an average 22% higher (with a standard deviation of 14%), most likely due to the decomposition of trenched roots or maintained activity from severed roots. The early season data in 2005 (prior to DOY 200) were therefore accordingly corrected.

2.4. Winter emission measurements

During the snow covered season in 2004, ecosystem respiration was measured with the snow-gradient method (Sommerfeld et al., 1993; Koizumi et al., 1996; Alm et al., 1999; Maljanen et al., 2004) from the same sampling locations as those during the snow free period. Gas samples of 20 ml were taken from the depth of 10–20 cm below the snow surface with gas-tight plastic syringes (Terumo Europe, Leuven, Belgium), attached to a 3.2 mm diameter metal pipe. Gas samples were also simultaneously collected to monitor the CO_2 concentration in the ambient air. CO_2 concentrations in the samples were then analysed in laboratory within 24 h of sampling with a gas chromatograph (HP 5890 Series 2) equipped with a thermal conductivity detector (TCD). Snow porosity was also concurrently measured from each sampling point by taking 15–20 cm surface snow cores with a 103 mm (inner) diameter PVC tube. These snow samples were weighed in the field laboratory for calculation of porosity using the density of ice (0.9168 g cm^{-3}). The CO_2 flux through the snow to the atmosphere was calculated using Fick's first law of diffusion as indicated in the following equation,

$$J_g = D_g(\mathrm{d}C_g/\mathrm{d}z)f$$

where J_g is the diffusive flux for a gas, g along a concentration difference (dC_g) below z cm of snowpack with an air-filled snow porosity (*f*). The value of the CO_2 diffusion coefficient, D_g, used in the above equation was 0.139 cm^2 s^{-1} (Sommerfeld et al., 1993).

2.5. Biomass and other supporting measurements

Aboveground plant and root biomass of RCG were sampled twice a month. The sampling was conducted along a transect which was, prior to sampling, assessed to be representative for the cultivation. We used this approach because the RCG cultivation showed distinct growth patterns, with less biomass growth in the middle of the strips and better growth at the edges, due to uneven fertilizer distribution. At sampling, the plants were completely harvested from 25 × 25 cm plots ($n = 9$) by clipping at the stem base, and separated into living, green biomass and dead standing biomass. From six out of the nine plots a soil core was additionally taken for belowground root biomass determination. The soil core was sampled to a depth of 15 cm depth, thus up to the maximum rooting depth of the plants [in general, roots from the 10–15 cm deep layer contributed less than 2% to the total (0–15 cm depth) root biomass], by using a metal soil corer (of 7 cm diameter). In the laboratory, roots were collected and carefully washed over a 0.2 mm sieve. Only the white, living roots were sampled. Both aboveground plant parts and roots were then oven-dried at 60 °C for 24 h and weighed. The living biomass including green plant parts and roots is presented in g m^{-2}.

Supporting data collected simultaneously with the respiration measurements included manual measurements of air and soil surface temperature. Continuous data on the local air temperature and rainfall were not available for use in the description of the seasonal climatic conditions at the study sites. Also, we needed these data for extending the observed respiration temperature relationship to time periods when respiration was not measured. Therefore, we used the continuous hourly records of air temperature and rainfall from the Mekrijärvi research station located about 30 km to the east of the study sites. Volumetric water content was measured continuously by time domain reflectometer probes (CS616 Water Content Reflectometer, Campbell Scientific Ltd., Logan, Utah, USA) installed at 2.5 cm below the surface in the RCG cultivated site. Snow depth from the RCG site was continuously monitored by sonic ranging sensor (SR50 Sonic Ranging Sensor, Campbell Scientific) mounted at a height of 3.5 m on an instrument tower in the RCG area. The 30-min averaged data were recorded by a CR10X-datalogger (Campbell Scientific Ltd., Logan, Utah, USA).

2.6. Estimation of annual C losses and statistical analyses

For estimation of the annual C losses, the year was divided into two parts—snow-free period and winter. We employed the presence of snow on the ground or lack thereof as a criterion for characterizing the length of the two seasons. Days from DOY 114 to 320 in 2004 and from 109 to 321 in 2005 with no visible snow on the ground constituted the snow free period, while the remaining days were considered to be a part of the winter season. For the snow-free season calculations, concurrently measured data on temperature and ecosystem respiration from RCG site and soil respiration from the peat extraction site were fitted in a non-linear regression analysis with an exponential function (of the form: $y = a \times \exp^{bx}$, where a and b are the fitted coefficients, y is the estimated respiration and x is the soil surface temperature in °C) to yield the coefficients needed to simulate respiration data during missing periods. The measurements covered a wide temperature range. Using the coefficients obtained from the temperature response, we calculated hourly emission rates using records of hourly temperatures. The hourly emission values were summed to yield daily and seasonal values. For the winter season, we used mean emissions values of 16.6 mg m^{-2} h^{-1} for the RCG site and 8.2 mg m^{-2} h^{-1} for the peat extraction site based on measurements made during the 2004 winter as described above. We used the SPSS package (SPSS for Windows, Release 14.0.1, 18 November 2005) for statistical analyses and SigmaPlot (SigmaPlot for Windows Version 10 Build 10.0.0.54) for preparing the illustrations in the manuscript.

3. Results and discussion

3.1. Climatic conditions during 2004 and 2005

Shown in Fig. 2A and B are daily air temperature and precipitation patterns during 2004 and 2005. The daily minimum of −24.1 and −18.5 °C occurred during early January in 2004 and late February in 2005, respectively (Fig. 2A). The air temperature reached maximum values during early August in both years

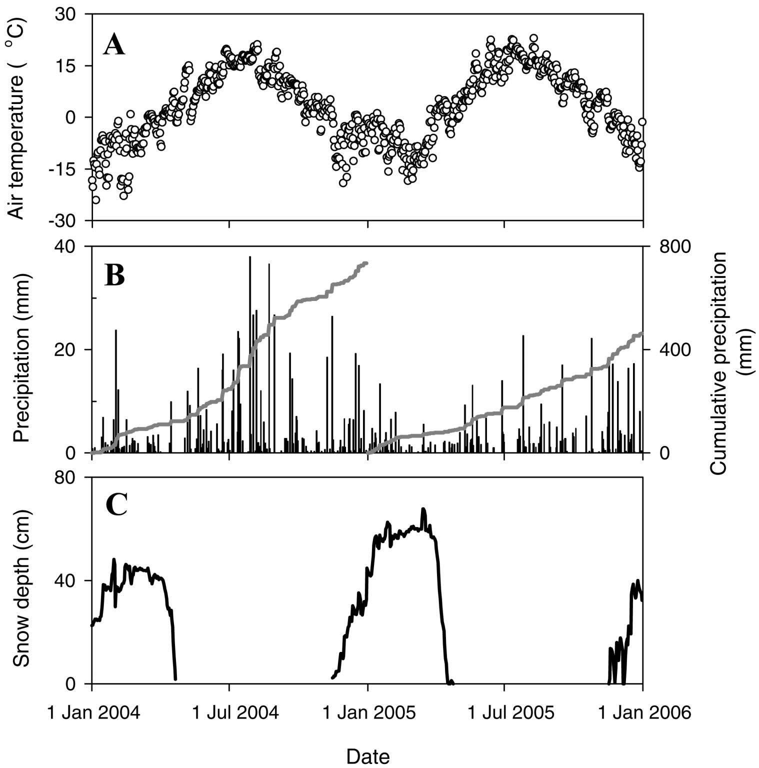

Fig. 2. Daily distributions of (A) air temperature, (B) precipitation and (C) snow depth during 2004 and 2005. Cumulative precipitation is also shown as dark grey lines in panel (B).

(21.2 °C in 2004 and 22.9 °C in 2005). The year 2004 was wet, while 2005 was drier. In 2004, 302 mm of rain fell in the months of July and August combined. Compared to a regional annual precipitation of 669 mm, the total precipitation during 2004 was higher than the climatic normal amount by 10%, while it was nearly 31% lower during 2005 (Fig. 2B). Snow cover patterns during 2004 and 2005 are presented in Fig. 2C. The maximum snow depth during late February in 2004 was 46 cm, while it was 68 cm during mid March in 2005.

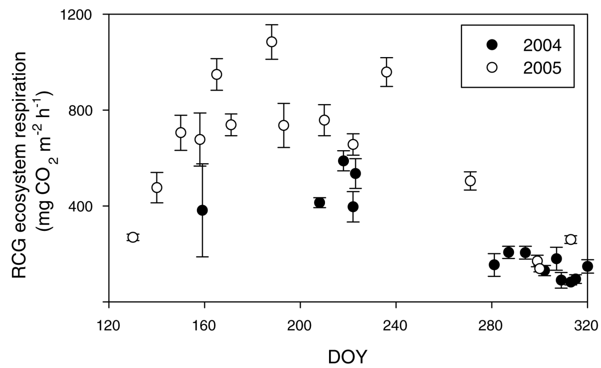

Fig. 3. Seasonal distributions of reed canary grass (RCG) ecosystem respiration during 2004 and 2005 at Linnansuo in eastern Finland.

3.2. *Ecosystem respiration during the snow free period – RCG site*

Seasonal distributions of daily ecosystem respiration from reed canary grass (RCG) cultivated area measured during 2004 and 2005 are presented in Fig. 3. ER was 380 mg m^{-2} h^{-1} during early June. Following this, ER reached a peak value of 630 mg m^{-2} h^{-1} in early August. Subsequently, ER declined and ranged from 80 to 150 mg m^{-2} h^{-1} during mid November.

In the drier and warmer year of 2005, measurements during the snow free period began as early as mid May. ER measured during this time was low (270 mg m^{-2} h^{-1}). ER peaked during early July with a peak emission of about 1090 mg m^{-2} h^{-1}. Following this, ER fluctuated and ranged from 660 to 960 mg m^{-2} h^{-1} until the end of August. Subsequently, ER decreased with the values ranging from 500 mg m^{-2} h^{-1} during late September to 140 mg m^{-2} h^{-1} during early November. The 2004 and 2005 ER patterns show distinct differences with respect to timing and magnitude of peak emissions. The peak CO_2 release during 2005 occurred about a month earlier and was nearly twice higher than the peak value during 2004. ER was higher during the dry 2005 season compared to the wetter season in 2004.

3.3. *Components of RCG ecosystem respiration*

RCG Ecosystem respiration includes autotrophic respiration (growth and maintenance respiration rates of the aboveground and belowground plant parts and rhizosphere respiration; AR) and heterotrophic respiration (microbial decomposition of soil organic matter; HR). During the 2004 growing season, we measured the ecosystem respiration without partitioning approaches. However, starting from the 2005 season, in addition to ER measurements, independent heterotrophic respiration measurements were also made. Thus, with the HR data available during 2005, we could estimate the contribution of heterotrophic respiration to the ecosystem respiration. On a seasonal basis, HR amounted to 45% of ER with a standard deviation of 15% during the 2005 season. We noticed that the HR contribution to ER early in the season was rather high. This could be attributed to a possible contribution of the roots to the measured soil respiration as they were freshly trenched and they may have been still alive during this part of the measurement period. Also, decomposition of the residual, severed roots most likely increased respiration immediately after trenching. Therefore, we compared the fractional HR from 2005 and 2006 growing seasons (the 2006 season data are not included in this paper). After DOY 200, the fraction of HR in ER was nearly the same during both years with similar climatic conditions (on average 0.42 in 2005 and 0.46 in 2006). We thus applied the 2006 fractional contribution of HR for the period prior to DOY 200 to the results from 2005, considering the small differences found in average values.

According to our results, a little less than half of the ecosystem respiration originated from the soil. These results are in good agreement with the reported values on the proportion of soil respiration to overall CO_2 losses from cultivated areas (Lohila et al., 2003; Franzluebbers et al., 2002). However, a higher fraction of HR to ER (60%) has been reported from cultitvated peat soils (Lohila et al., 2003).

Under optimal soil moisture conditions, soil temperature is a reliable predictor of heterotrophic respiration (Fang and Moncrieff, 2001). However, several other abiotic and biotic factors such as soil moisture content, soil organic matter quantity and quality, root and microbial biomass, soil chemical and physical properties have also been shown to influence HR. Under dry conditions, intensity and duration of rainfall are considered important in governing soil respiration by the regulation of moisture content in the surface layers and through wetting and drying cycles (Yuste et al., 2003). As indicated in the section on seasonal climate above, the 2005 growing season received half the seasonal total amount compared to the previous year and the surface layer was dry.

Results of the analysis of regression of HR on soil temperature are shown in Table 2. We first fitted all seasonal HR and temperature data with an exponential growth curve. Soil temperature explained nearly 70% of the variation in the HR data. We then segregated the HR data into two groups—data measured on rainy days and days with no rain. Excluding the data from extremely low soil moisture conditions (soil moisture content less than 0.1 $m^3\ m^{-3}$) during periods with no rain, HR was found to be related to temperature by a highly significant exponential relationship (adjusted $R^2 = 0.88, p = 0.001$). Similarly, on rainy days, a significant exponential relationship existed between HR and temperature (Table 2). While these analyses suggest that soil temperature is a dominant factor controlling soil respiration rates in this ecosystem, the role of soil moisture content in regulating HR was not as conspicuous based on similar regression analyses involving HR and soil moisture content (see Table 3). A weak negative exponential relationship was evident when all data were considered in the regression analysis (Table 3). When the data were grouped into temperature groups, HR indicated a strong exponential decline in the 10–20 °C, range however the relationship was not significant as the number of data points included in the analysis was small.

Typical patterns of RCG aboveground (living green) and belowground biomass accumulation during a growing season are

Table 2. Results of the non-linear regression of RCG heterotrophic respiration on temperature ($y = a \times \exp^{bx}$, where y is the heterotrophic respiration in mg $m^{-2}\ h^{-1}$, x is the soil surface temperature in °C, a and b are the fitted coefficients).

Data type	SWC range[a]	N	a	b	Adjusted R^2	p-Value
All data	0.07–0.61	14	102.244	0.055	0.708	0.000
Data from days with no rain	0.10–0.61	7	103.725	0.062	0.882	0.001
Data from rainy days	0.21–0.56	6	67.757	0.081	0.754	0.016

[a]SWC stands for soil water content in $m^3\ m^{-3}$.

Table 3. Results of the non-linear regression of RCG heterotrophic respiration on temperature ($y = a \times \exp^{bx}$, where y is the heterotrophic respiration in mg $m^{-2}\ h^{-1}$, x is the volumetric soil moisture content in $m^3\ m^{-3}$, a and b are the fitted coefficients).

Data type	Temperature range (°C)	N	a	b	Adjusted R^2	p-Value
All data	−6 to 35	14	648.776	−2.485	0.336	0.017
Data from rainy days	6 to 27	6	1016.831	−3.560	0.569	0.051
Data from medium temperature range	10 to 20	4	616.329	−1.578	0.776	0.078

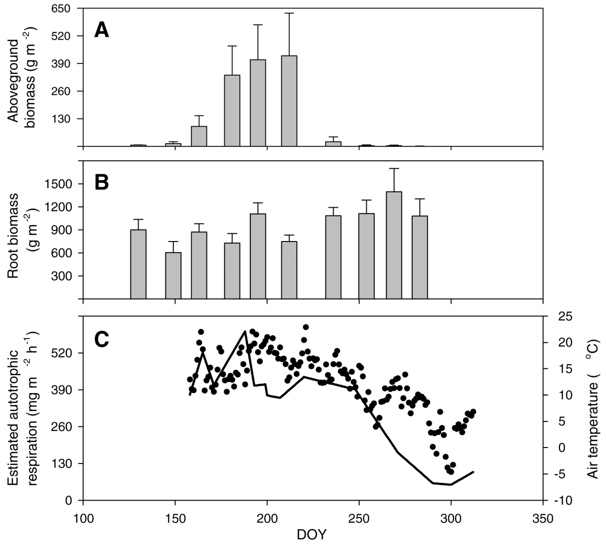

Fig. 4. Typical seasonal patterns of (A) aboveground living green biomass and (B) root biomass at the RCG site. (C) Autotrophic respiration (denoted by a line) and air temperature (denoted by closed circles) during the 2005 growing season at the RCG site at Linnansuo in eastern Finland.

shown in Fig. 4A and B. The estimated autotrophic fraction of ER and air temperature patterns during the 2005 growing season are also shown (Fig. 4C). Note that RCG is a perennial crop and hence it has high root biomass throughout the season with increasing root stocks over the years of cultivation. On the contrary, the living aboveground biomass reaches a maximum in July and August, representing peak vegetative growth and decreases thereafter with the onset of crop senescence. These biomass patterns reveal that the aboveground biomass accounts for about 30% of the total plant biomass during the peak growth period. Thus, the roots play a dominant role in biomass distribution through their prolonged longevity relative to aboveground biomass. But still, autotrophic respiration seemed to be more influenced by the living, green biomass, with decreasing activity in senescent tissues, although no correlation was found. Both aboveground and belowground respiration depend on recent photosynthesis. In the recent years, there has been a growing body of scientific evidence indicating that the root respiration is constrained by the allocation of photosynthates to the roots (e.g. Janssens et al., 2001; Högberg and Read, 2006). During spring and late autumn, the roots are most likely fuelled by carbon storages within their tissues.

In addition to the influence of green biomass, the data in Fig. 4C indicate a strong relationship between AR and air temperature. An exponential regression of AR on air temperature yielded an R^2 value of 0.77 ($p < 0.05$). AR in this discussion includes respiration both due to above- and below-ground plant biomass. Therefore, this temperature relation has no physiological relevance as the above- and below-ground plant parts have different temperature responses and are probably correlated better with temperatures within their own separate microenvironments. Leaf level gas exchange data, below-ground respiration measurements with and without roots and isotopic analyses would be needed to further partition AR into above-ground and root respiration components.

3.4. Bare soil respiration from the peat extraction site during the snow free period

In the peat extraction area, CO_2 emissions ranged from 57 to 136 mg m^{-2} h^{-1} in 2004 June (Fig. 5). Emissions fluctuated within a range of 102–200 mg m^{-2} h^{-1} in July. A peak emission of 207 mg m^{-2} h^{-1} was observed in the second week of August. ER ranged from 140 to 172 mg m^{-2} h^{-1} from mid August to mid September. ER then decreased to a range of 27–52 mg m^{-2} h^{-1} towards the end of the snow free measurement period in 2004. Compared to 2004, emissions in 2005 were low. Seasonal peak emissions of 125 mg m^{-2} h^{-1} occurred in mid May. Subsequently, emissions varied with a low of 56 mg m^{-2} h^{-1} in mid June, another peak of 91 mg m^{-2} h^{-1} in mid July and finally decreased to 28 mg m^{-2} h^{-1} in mid November (Fig. 5).

We examined the relationship between bare soil respiration and temperature (no other supporting measurements were available for the peat extraction site). Segregating the data according to rainy and rain-free periods did not help improve the temperature relationships. An exponential fit of the respiration data against soil surface temperature yielded R^2 values of 0.80 ($p = 0.00$) and 0.47 ($p = 0.002$) for the 2004 and 2005 seasons, respectively. While the temperature was a reliable predictor of soil respiration during the wet 2004 season, the temperature relationship during the drier 2005 season, although significant, was weaker. Similar observations on temperature and soil respiration during dry conditions have been reported in previous studies (e.g. Yuste et al., 2003).

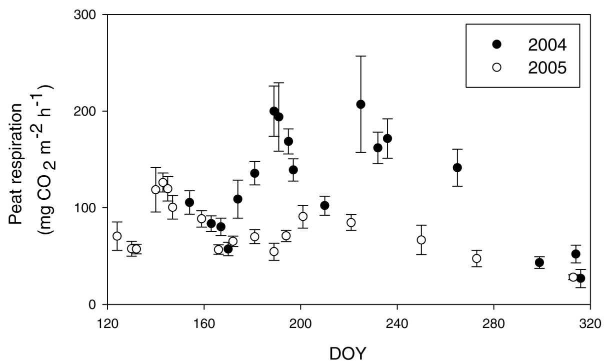

Fig. 5. Seasonal distributions of bare soil respiration during 2004 and 2005 from the Linnansuo peat extraction site in eastern Finland.

3.5. Winter CO_2 emissions – RCG and peat extraction sites

CO_2 emissions were measured several times during the early part of 2004 using the snow gradient method in the RCG and peat extraction sites. This method has been successfully used to monitor greenhouse gas emissions from organic soils in Finland and elsewhere (Dunfield et al., 1995; Alm et al., 1999; Maljanen et al., 2003). Winter emissions ranged from 4.7 to 23.9 mg m^{-2} h^{-1} at the RCG site and from 6.6 to 14.9 mg m^{-2} h^{-1} at the peat extraction site. Based on these values, we estimated a mean emission value of 16.6 mg m^{-2} h^{-1} for the RCG site ($SE =$ 5.0 mg m^{-2} h^{-1}) and 8.2 mg m^{-2} h^{-1} ($SE = 2.5$ mg m^{-2} h^{-1}) for the peat extraction site. We have used these average values to construct the winter contribution to the annual ecosystem respiration from the two study sites in 2004 and 2005.

3.6. Annual carbon losses

Annually estimated ecosystem respiration values from RCG and peat extraction sites are shown in Table 4 along with the contributions from the snow free period and winter emissions to the annual totals during 2004 and 2005. Annually, the RCG site released 1465 and 1968 g CO_2 m^{-2} in 2004 and 2005, respectively. Winter emissions accounted for nearly 4.5% in 2004 and 3.6% of the total annual respiration in 2005. Major contributions to the annual values came from the emissions during the snow free period. Owing to lower emissions from the peat extraction site during the snow free period, the winter contributions from this site were higher, 6.5% and 17% to the annual emissions of 498 and 264 g CO_2 m^{-2} in 2004 and 2005, respectively. The annual ER from RCG cultivation were nearly 3 and 7.5 times higher respectively in 2004 and 2005 in comparison with those from the peat extraction site. Silvola et al. (1996) observed that the snow-free season C budgets constructed by interpolating directly from measurements made during the daytime were on an average 23% higher compared to budgets estimated from regression transfer functions. As described in Section 2.6, we estimated our snow-free budgets from regression functions involving hourly measured temperature data and therefore, we believe that the seasonal budgets reported here are not constrained by the time of the day when gas fluxes were measured.

3.7. Comparison with other studies

The instantaneous measured rates of respiration reported in this study from the Linnansuo peat extraction area are comparable with the rates measured from other peat extraction areas in Finland (Ahlholm and Silvola, 1990; Nykänen et al., 1995; Tuittila et al., 1999) and Sweden (Sundh et al., 2000). Ahlholm and Silvola (1990) measured CO_2 emissions from peat extraction areas in the vicinity of our site in the Ilomantsi region in eastern Finland. They reported hourly rates ranging from 25 mg m^{-2} h^{-1} in November to 250 mg m^{-2} h^{-1} in September. They concluded that peat extraction sites in this region would emit about 870 g CO_2 m^{-2} annually. Nykänen et al. (1996) reported an annual emission rate of 880 g CO_2 m^{-2} a^{-1} and Tuittila et al. (1999) estimated a seasonal efflux of 191–403 g CO_2 m^{-2} a^{-1} from bare peat surfaces on a cutaway peatland in central Finland. Sundh et al. (2000) measured hourly rates of respiration from several peat extraction areas in the southern and northern boreal regions in Sweden ranging from 61 to 228 mg m^{-2} h^{-1}. Their estimated growing season emissions varied from 230 to 1000 g of CO_2 m^{-2} a^{-1}. The wide variability in their estimations suggests that the CO_2 emissions from these ecosystems are extremely sensitive to prevailing climatic conditions and specific site types. Also, the depth of the leftover peat after extraction may be an important indicator of the emission levels. The peat from the peat extraction site under study is being extracted to the extent that in some parts of the site, the underlying mineral soil is visible. This suggests that there is little carbon left to decompose and hence the emissions reported in this paper are on the lower side

To the best of our knowledge, this is the first study that aims to report CO_2 emissions from reed canary grass cultivation on a cutover peatland and there are no other studies to compare the emissions reported in this paper. Nevertheless, we can try to better understand these emissions in light of the emissions from, for example, grasslands on cultivated organic soils and forestry drained peatlands purely from the viewpoint of assessing how this ecosystem fares in comparison with others. Forestry has been considered as the main after use option for cutaway peatlands (Selin, 1999). Aero et al. (2006) measured soil greenhouse gas emissions from forested cutaway peatlands in central Finland and reported annual soil respiration rates ranging from 275 to 479 g CO_2-C m^{-2} a^{-1}. It is worth noting here that the respiration measurements of Aero et al. (2006) represent C losses from the

Table 4. Annual estimates (in g CO_2 m^{-2} a^{-1}) of reed canary grass ecosystem respiration and peat extraction site respiration during 2004 and 2005 with contributions (percentages in parenthesis) from the winter season.

Year	Reed canary grass site			Peat extraction site		
	Snow free period	Winter	Annual	Snow free period	Winter	Annual
2004	1400	66 (4.5%)	1465	466	32 (6.5%)	498
2005	1897	71 (3.6%)	1968	219	45 (17.0%)	264

soil and do not include aboveground tree respiration. Nykänen et al. (1995) measured greenhouse gas emissions from pristine and drained peatlands in eastern Finland during 1991 and 1992. Their annual estimates for CO_2 losses from the bare organic soil during the 2 yr ranged from 1437 to 1470 g CO_2 m^{-2} and those from a grassland on an organic soil ranged from 1774 to 2566 g CO_2 m^{-2}. Maljanen et al. (2002) and Maljanen et al. (2004) measured ecosystem respiration from cultivated organic agricultural soils and reported mean growing season values that are clearly higher than even the peak RCG emissions reported in this study. Higher emissions from organic soils in these previous studies could be accounted for by the greater depth of peat, relatively higher rates of fertilization and most importantly by the tilling of the soils in the beginning of the growing season in the agricultural organic soils. West and Post (2002) analysed global databases from several long-term experiments on various cropping systems. They observed that in comparison to the conventional tillage, the no tillage option aids in the sequestration of significant amounts of carbon into the soil. Except tillage during the initial land preparation phase of the RCG cultivation, the RCG site was not tilled at all.

4. Conclusions

Climatic conditions during the two measurement years were contrasting—2004 was wet and 2005 was drier. Heterotrophic respiration measurements made during the 2005 season indicated that heterotrophic respiration accounts for about 45% of ER and autotrophic respiration is the dominant component of ER in this ecosystem. Further studies are needed to enhance our understanding of the C loss patterns and their controlling mechanisms in these sites through ecosystem respiration partitioning by means of more continuous measurements and isotopic analyses. Compared to respiratory carbon losses from afforested and cultivated organic soils reported in previous studies, losses from the reed canary grass site were lower suggesting based on this comparison alone that the cultivation of reed canary grass for bioenergy may be a recommendable option for the after-use of cutover peatlands. The overall assessment of the importance of bioenergy crops in the carbon balance of managed peatlands, however, should include the determination of the net ecosystem CO_2 exchange to account for the plant carbon uptake and carbon leaching losses (Freeman et al., 2004). In the assessment of total radiative forcing due to GHG emissions from these sites, fluxes of N_2O and CH_4 may also become relevant.

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