RESEARCH ARTICLE

Rewetting of Cutaway Peatlands: Are We Re-Creating Hot Spots of Methane Emissions?

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Abstract

Hot spots of CH_4 emissions are a typical feature of pristine peatlands at the microsite and landscape scale. To determine whether rewetting and lake construction in a cutaway peatland would result in the re-creation of hot spots, we first measured CH_4 fluxes over a 2-year period with static chambers and estimated annual emissions. Second, to assess whether rewetting and lake creation would produce hot spots at the landscape level, we hypothesized a number of alternative land use scenarios for the peatland following the cessation of peat extraction. Using the results from this study and other studies from literature, we calculated the global warming potential (GWP) of each scenario and the respective contribution of CH_4.

The results showed that hot spots of CH_4 fluxes were observed as a consequence of microsite-specific differences in water table (WT) position and plant productivity. CH_4 fluxes were closely related to peat temperature at 10 cm depth and WT position. Annual emissions ranged from 4.3 to 38.8 g $CH_4\,m^{-2}\,yr^{-1}$ in 2002 and 3.2 to 28.8 g $CH_4\,m^{-2}\,yr^{-1}$ in 2003. The scenario results suggest that lake creation is likely to result in the re-creation of a hot spot at the landscape level. However, the transition from cutaway to wetland ecosystem may lead to a reduction in the GWP of the peatland.

Key words: afforestation, global warming potential, grassland, rewetting, spatial variation, water table.

Introduction

Following the cessation of industrial peat extraction, there is an opportunity to create new land use options that may exhibit some of the aesthetic, hydrological, and ecological functions of the pre-industrial ecosystem. For example, pristine peatlands are known to be a significant source of atmospheric methane (CH_4) (Nykänen et al. 1998), and the occurrence of CH_4 "hot spots," that is, patches that show higher emissions relative to the surrounding area (McClain et al. 2003), is typical at both the microsite (Alm et al. 1999) and the landscape scale (Bubier et al. 2005). In rewetting a cutaway peatland, conditions for CH_4 production (increased anoxia within the peat profile coupled with the reestablishment of vegetation communities) are likely to more resemble a wetland in terms of functioning and may result in a resumption of CH_4 emissions and the creation of a hot spot at the landscape scale. Whether hot spots of CH_4 production occur *within* the rewetted peatland are likely to be determined by the result of complex relationships between a range of interconnecting biological, chemical, and physical factors.

Studies in a range of peatland types have demonstrated that CH_4 production is closely related to net primary production (Ström et al. 2003), substrate quality (Wachinger et al. 2000), water table (WT) position (Bubier et al. 1993), soil temperature (Crill et al. 1988), bulk density (Nykänen et al. 1998), pH (Duval & Goodwin 2000), nutrient status (Dise & Verry 2001), and competitive inhibition by alternative electron acceptors (Nedwell & Watson 1995). The role of vascular vegetation in the production of CH_4 is of major importance because a high proportion of the CH_4 produced is a result of the breakdown of recently sequestered C in root exudates and plant litter (Saarnio et al. 2004). The substrate is used as an energy source by a range of microbial groups culminating in the production of CH_4 by the methanogenic Archaea within the anoxic zone (Galand 2004). Furthermore, aerenchymatic vascular vegetation also provides a conduit for CH_4 movement from the saturated peat to the atmosphere (Sebacher et al. 1985) bypassing the oxic zone at the surface where CH_4 is oxidized to CO_2 by methanotrophic bacteria (Svensson & Sundh 1993).

Rewetting may enhance recolonization of the cutaway by plant species that may differ widely in terms of primary productivity, organic matter supply, and CH_4 transport characteristics. For example, construction of artificial lakes may lead to extensive littoral zones where higher CH_4 emissions than the surrounding areas may be expected (Juutinen et al. 2003). These intrinsic differences

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may produce hot spots of CH_4 emissions. To date, there have been few CH_4 flux studies in rewetted cutaways, and these have been located predominantly in Finland (Komulainen et al. 1998; Tuittila et al. 2000) or Canada (Marinier et al. 2004). Climatic conditions in Ireland are strongly influenced by the proximity of the North Atlantic Ocean, which produces highly humid conditions, mild winters, and cool summers (Keane & Sheridan 2004). Our knowledge of CH_4 dynamics in rewetted cutaways under these climatic conditions remains limited.

Furthermore, up to 80,000 ha of peatlands are likely to come out of industrial production in Ireland over the next couple of decades. Of this total, 30,000 ha are deemed suitable for wetland creation (McNally 1997) and could potentially be a significant source of CH_4. In this study, our aims were (1) to measure CH_4 fluxes over a 2-year period in a range of microsite types representative of the natural regeneration processes that have occurred following wetland creation; (2) to determine whether hot spots are present within this new ecosystem and what factors either enhance or constrain CH_4 dynamics; and (3) from the results of this study and relevant studies in literature, to evaluate the role of CH_4 emissions from rewetted cutaways in relation to global warming potential (GWP) from other land use options.

Methods

Study Site

The study was carried out at a cutaway peatland at Turraun, Co. Offaly, Ireland (lat 53°14′ to 53°19′N, long 7°42′ to 7°48′W). Industrial milled peat extraction ceased in the early 1970s, and the cutaway was allowed to revegetate naturally. Twenty years later, the cutaway was rewetted by blocking of drainage ditches and construction of a peat/mineral soil bund. A 60-ha lake was created to enhance the wildlife and amenity potential of the cutaway. Since that time, a wide range of minerotrophic vegetation communities have become established in the littoral zone of the lake and within the cutaway in general.

The residual peat deposit (0–1.8 m depth) is mainly *Phragmites australis* or fen-type peat overlying undulating calcareous marl, clay subsoils, or limestone bedrock (Rowlands & Feehan 2000). The pH of the residual peat in the study area ranged from 5.8 to 6.3 (Rowlands 2001). Bulk density values were 180 ± 48 kg/m^3 (0–15 cm peat depth), 120 ± 7 kg/m^3 (15–30 cm), and 120 ± 11 kg/m^3 (30–45 cm). The mean monthly temperature ranges from 4.8°C (January) to 14.9°C (July). Mean annual rainfall is 80.4 cm (Met Éireann—Birr Station, 1961–1990). Annual rainfall at the site was 102 and 77 cm in 2002 and 2003, respectively.

Vegetation

At the start of the study, a visual survey was undertaken to determine the dominant microsites in the littoral zone.

Four microsites were subsequently selected to reflect the transition in plant communities from shallow water to drier terrestrial areas. Within each microsite, two to four sample plots were established to capture spatial variation in CH_4 fluxes: *Typha latifolia* L. (T1 and T2), *Phalaris arundinacea* L. (P1 and P2), *Eriophorum angustifolium* Honck./*Carex rostrata* Stokes (EC1–EC4), and areas of bare (unvegetated) peat (BP1–BP4). Each sample plot consisted of a stainless steel collar (60 × 60 cm) that was inserted 30 cm into the peat prior to the start of the study. Each collar was topped by a 4-cm-wide and 3-cm-deep channel, which was filled with water to provide an airtight seal during gas measurements. Wooden walkways were constructed around each of the collars to prevent compression of the peat during gas sampling.

Environmental Variables

A time series of soil temperatures at 2, 5, 10, and 20 cm depths were recorded from 1 January 2002 until 31 December 2003 by an environmental monitoring station (ELE International, Bedfordshire, United Kingdom) and by data loggers (MM900; ELE International) located within each of the microsites. The loggers were pre-programed to record average hourly temperatures (6 readings/hour). Cumulative rainfall was recorded with a tipping gauge (ELE International) at hourly intervals by the station. WT position relative to the soil surface was manually measured with a water-level probe (Eijkelkamp Agrisearch Equipment, Giesbeek, The Netherlands) in perforated polyvinyl chloride pipes. An hourly time series of WT was calculated for each sample plot by linear interpolation between measured values (Laine et al. 2006).

Vascular Green Area

In order to incorporate the phenological changes that occur in the vegetation into CH_4 models, a vascular green area index (VGA) was developed. At monthly intervals throughout the study period, the green area of leaves and stems of all species within each sample plot was measured. Species-specific model curves were applied to describe phenological dynamics in vegetation. The models were summed to produce a VGA for each community. For a more detailed description of the method, see Wilson et al. (2007a).

CH_4 Measurements

We measured CH_4 fluxes with a static chamber technique (Crill 1991) at weekly to biweekly intervals from July 2002 to December 2003. Each chamber (60 × 60 × 25 cm) was equipped with a battery-operated fan, which mixed the air within the chamber headspace. Extension chambers (20–150 cm tall) were used to facilitate sampling within the taller plant communities. Four 40 mL samples were withdrawn into 60-mL polypropylene syringes from the

chamber headspace at 5-minute intervals over a 20-minute period. At the same time, air temperature inside the chamber, soil temperatures, and WT outside the chamber were recorded. Gas samples were analyzed for CH_4 concentration within 24 hours of collection with a gas chromatograph (Shimadzu GC-14-B) using a flame ionization detector. Column and detector temperatures were 40 and 330°C, respectively. Nitrogen was used as the carrier gas. CH_4 standards (1.7, 4, and 10 ppm; BOC Gases Ireland Ltd., Dublin, Ireland) were used. The detection limit was estimated at 0.04 mg $CH_4 \, m^{-2} \, hr^{-1}$. In order to remove moisture, samples and standards were injected through a 12-cm Tygon tubing (6 mm diameter) filled with drierite (10/20 mesh) prior to entering the 2-mL sample loop. CH_4 fluxes (mg m^{-2} hr^{-1}) were calculated from the linear change in CH_4 concentration as a function of time, chamber volume, and temperature. A flux was accepted if the coefficient of determination (r^2) was at least 0.90. An exception was made in cases where the flux was close to 0, and the r^2 is always low (Alm et al. 2007). Negative flux values indicate biospheric CH_4 uptake, and positive flux values indicate CH_4 emissions to the atmosphere.

Modeling CH$_4$ Fluxes

Because the data were not normally distributed (Kolmogorov–Smirnov test, $p < 0.05$), the nonparametric repeated measures Friedman test (SPSS, Chicago, IL, U.S.A.) was used to test for differences in measured CH_4 fluxes between and within microsites. The models were parameterized for each microsite using the nonlinear Levenberg–Marquardt technique. The models (equations (1), (2), and/or (3)) and the hourly time series of peat temperature ($T_{10 \, cm}$), WT, and VGA were used to calculate CH_4 fluxes for each of the sample plots. The hourly values were then integrated to provide an estimate of the annual CH_4 balance (g $CH_4 \, m^{-2} \, yr^{-1}$) for each of the sample plots. As nighttime CH_4 fluxes were not quantified in this study, a correction figure of 0.68 (Juutinen et al. 2004) was applied to integrated daily fluxes in the *Typha* sample plots during the growing season to avoid possible overestimation of CH_4 due to diurnal variation in CH_4 fluxes in that species (e.g., Käki et al. 2001).

Wetlands as Greenhouse Gas Hot Spots

The contribution of CH_4 emissions in relation to the GWP (tonnes CO_2 equivalents) from this and other land use options was evaluated. GWP was calculated for five potential land use scenarios on the basis of the results from this study and other relevant literature studies. CH_4 and N_2O emissions were converted into CO_2 equivalents by assuming a GWP of 23 and 296 over a 100-year horizon, respectively (IPCC 2001). Each scenario is located within a hypothetical 100-ha peatland that had undergone decades of peat extraction. The scenarios were as follows:

(1) Cutaway: The peatland landscape is composed of 15-m-wide-peat extraction strips devoid of vegetation. In between the strips, drainage ditches (1 m wide) are still functioning. Due to regular maintenance, the ditches contain minimal vegetation.

(2) Wetland creation: An artificial lake is created surrounded by a littoral zone dominated by reed species such as *Typha*. A pronounced WT gradient within the peatland results in large areas dominated by "drier" species such as *Eriophorum* spp. Some areas of bare peat remain.

(3) Afforestation: The peatland is afforested with a coniferous species such as Norway spruce (*Picea abies*) or Sitka spruce (*Pi. sitchensis*). The drainage ditches are reasonably maintained. Phosphatic fertilizer is applied.

(4) Deciduous woodland: The peatland is allowed to regenerate spontaneously, and an extensive *Betula/Salix* woodland develops.

(5) Grassland: The peatland is cultivated (deep plowing to mix the mineral soil and peat, harrowing, etc.) and developed as grassland. Nitrogen fertilizer is routinely applied. Cattle graze for approximately 9 months/year at a stocking rate of 0.9 livestock units (LU)/ha.

Results

Environmental Variation

The soil temperature at 10 cm depth showed strong seasonality within the microsites (Fig. 1a). The lowest values (approximately 1°C) occurred in the winter months and increased to a maximum of approximately 18°C in midsummer in both years. The mean annual WT position varied both between and within microsites in 2002 and 2003. For most of 2002, the WT remained close to or above the soil surface in the *Typha latifolia* and *Eriophorum angustifolium/Carex rostrata* microsites (Fig. 1b). In contrast, at the *Phalaris arundinacea* site, it fell below the soil surface from early summer and reached its lower position of approximately −10 cm in late summer. The WT in the bare peat microsites remained deep within the peat profile for the whole year. In 2003, it followed a similar trend until midsummer when it dropped considerably in all microsites and remained relatively low for the remainder of the year.

Variation in Measured CH$_4$ Fluxes

Observed CH_4 fluxes showed a distinct temporal variation in all sample plots (Fig. 2). CH_4 fluxes followed the trend *Typha* > *Phalaris* > *Eriophorum/Carex* > bare peat in both years of the study. Maximum flux values generally occurred in midsummer. The highest values of 8.9 and 16 mg $CH_4 \, m^{-2} \, hr^{-1}$ were observed in the T1 sample
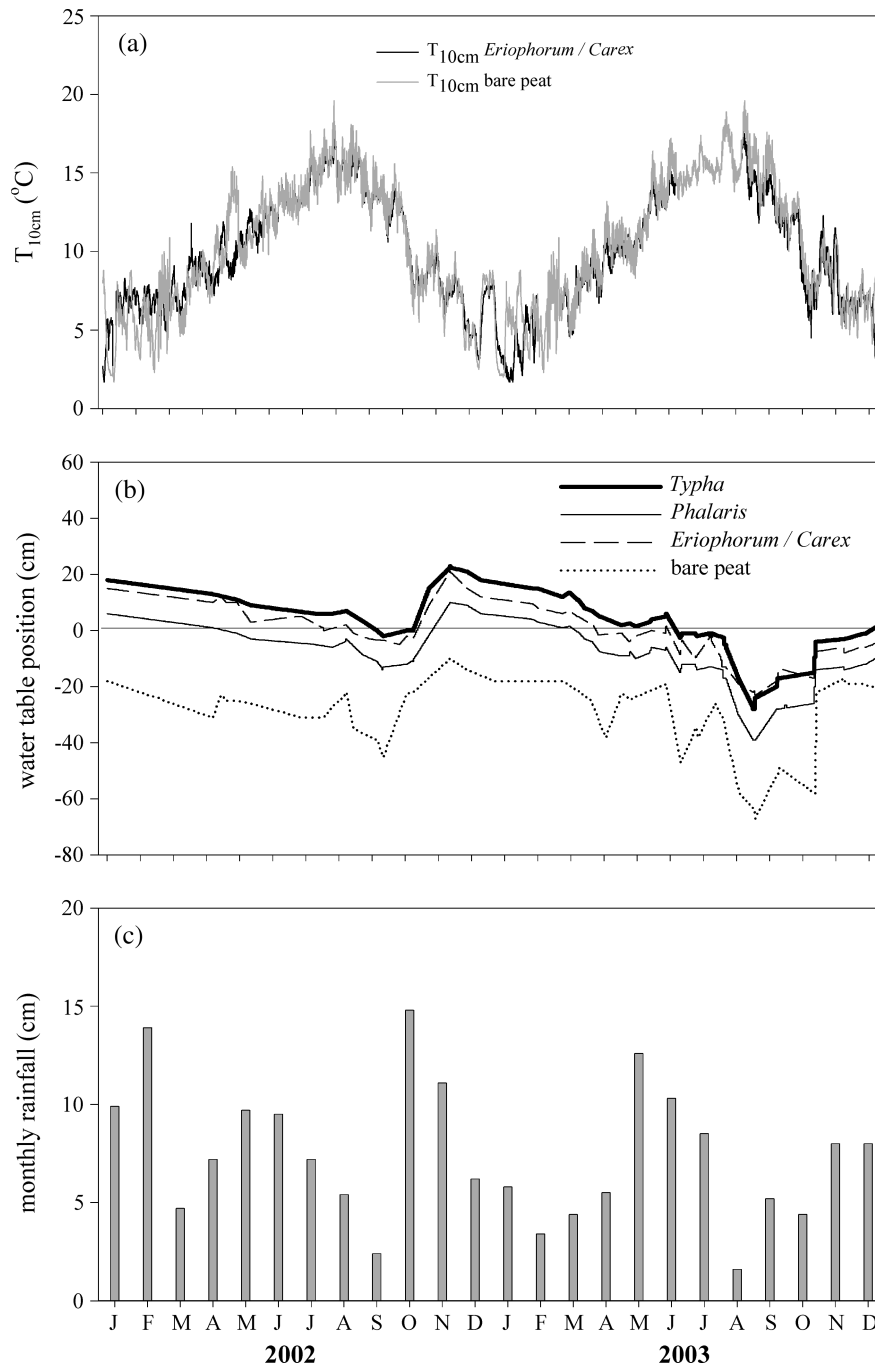
Figure 1. (a) Peat temperature (°C) at 10 cm depth ($T_{10\,cm}$) in the *Eriophorum/Carex* and bare peat microsites. $T_{10\,cm}$ for the *Typha* and *Phalaris* microsites was similar to *Eriophorum/Carex*. (b) WT position (cm) at *Typha latifolia* (sample plot T2), *Phalaris arundinacea* (P2), *Eriophorum angustifolium/Carex rostrata* (EC1), and bare peat microsites (BP1). Positive values indicate WT position above the peat surface. WT was calculated for each sample plot by linear interpolation between measured values. (c) Monthly rainfall (cm) in 2002 and 2003 at Turraun, Co. Offaly.

plot in 2002 and 2003, respectively. A small uptake of CH_4 between 0.07 and 0.12 mg m^{-2} hr^{-1} was observed in late summer/early autumn of 2003 in the *Phalaris* plots in conjunction with a low WT of around −38 cm (Fig. 1). In the *Eriophorum/Carex* sample plots, the highest values (1.8 mg CH_4 m^{-2} hr^{-1}) were observed in midsummer

in 2002. Observed fluxes in the bare peat sample plots were very small and alternated between small losses and small uptake (Fig. 2d). Relatively high values of CH_4 were observed in autumn, winter, and early spring in the vegetated plots as a result of considerable litter input following senescence of the plant stand. In particular,
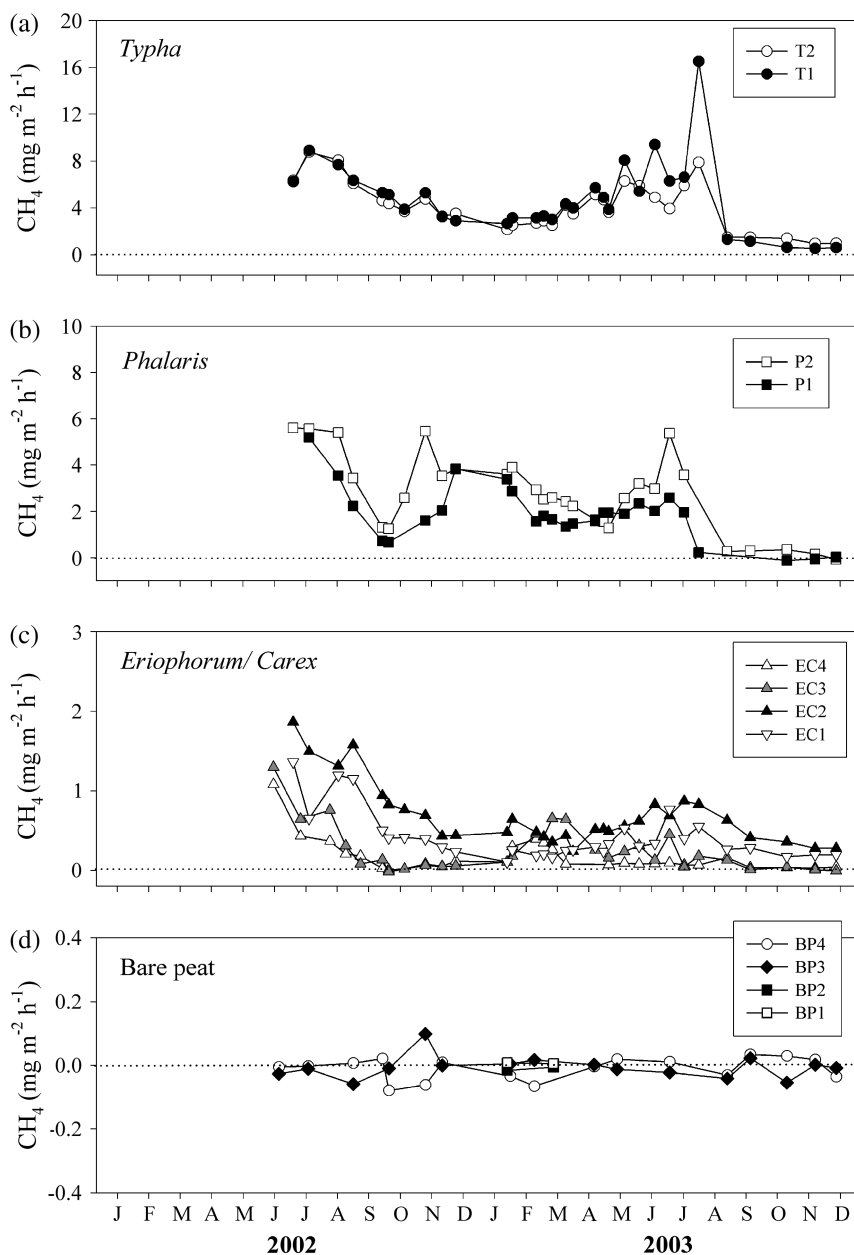
Figure 2. Measured CH_4 fluxes (mg CH_4 m^{-2} hr^{-1}) in (a) *Typha latifolia* (T1 and T2), (b) *Phalaris arundinacea* (P1 and P2), (c) *Eriophorum angustifolium/Carex rostrata* (EC1–EC4), and (d) bare peat microsites (BP1–BP4) from July 2002 to December 2003 at Turraun, Co. Offaly. Positive values indicate emission of CH_4 to the atmosphere. Negative values indicate an uptake of CH_4. Note differences in scale on *y*-axis.

relatively high rates of CH_4 emissions (approximately 5 mg CH_4 m^{-2} hr^{-1}) were observed in the *Typha* and *Phalaris* sample plots over the 2002–2003 winter period. Spatial variation was observed in CH_4 fluxes, and the coefficient of variation for all microsites ($n = 12$) was 136%. There was a significant difference in CH_4 fluxes between all microsites ($p < 0.001$) and within the *Eriophorum/Carex* and *Phalaris* microsites ($p < 0.001$), although there was no significant difference in observed CH_4 fluxes within the *Typha* microsite ($p = 0.068$).

Modeling CH_4 Fluxes

CH_4 fluxes from all microsites were closely related to the peat temperature at $T_{10\ cm}$ and the WT position, but the strength and form of the relationship varied between microsites (Table 1). Therefore, in order to more accurately reconstruct CH_4 fluxes, we used several nonlinear multiple regression models. In *Phalaris*, CH_4 fluxes showed a strong exponential relationship to T_{10cm} and a linear relationship to WT and VGA, and we used the model form:

Table 1. Parameter estimates for CH$_4$ models.

Community	b_0	b_1	b_2	b_3	b_4	r^2
Phalaris[a]	1.27 (0.11)	0.11 (0.08)	0.15 (0.01)	−0.16 (0.07)	—	0.83
Typha[b]	1.76 (0.29)	0.11 (0.01)	18.4 (6.17)	11.36 (1.78)	—	0.67
Eriophorum/*Carex*[c]	0.41 (0.06)	2.30 (0.72)	4.26 (0.83)	0.005 (0.004)	0.261 (0.033)	0.58

Standard error of estimates is in parentheses. Coefficient of determination (r^2) values are shown.
[a] Equation (1).
[b] Equation (2).
[c] Equation (3).

$$CH_4 = b_0 \times e(b_1 \times T_{10\,cm}) + (b_2 \times WT) + (b_3 \times VGA) \tag{1}$$

where b_0 is the basal CH$_4$ flux, b_1, b_2, and b_3 are coefficients.

In *Typha*, CH$_4$ fluxes had a similarly strong exponential relationship to $T_{10\,cm}$ but a Gaussian form of relationship to WT:

$$CH_4 = b_0 \times e(b_1 \times T_{10\,cm}) + \left(-0.5 \times \left(\frac{WT - b_2}{b_3}\right)^2\right) \tag{2}$$

In the model, b_0 is the basal CH$_4$ flux, b_1 is the coefficient for $T_{10\,cm}$, b_2 is the position of the WT corresponding to maximum water level–dependent CH$_4$ flux, and b_3 is the tolerance of WT. For *Eriophorum*/*Carex*, a model with a Gaussian relationship between CH$_4$ fluxes and WT and a linear relationship to $T_{10\,cm}$ and VGA was used:

$$CH_4 = b_0 \times e\left(-0.5 \times \left(\frac{WT - b_1}{b_2}\right)^2\right) + (b_3 \times T_{10\,cm}) + (b_4 \times VGA) \tag{3}$$

In the model, b_0 is the maximum water level–dependent CH$_4$ flux, b_1 is the position of the WT corresponding to maximum CH$_4$ flux, b_2 is the tolerance of WT, and b_3 and b_4 are coefficients for $T_{10\,cm}$.

In general, the relationship between observed and predicted CH$_4$ fluxes was reasonably good (Fig. 3) and explained between 58 and 83% of the variation in CH$_4$ fluxes (Table 1). However, in the *Eriophorum*/*Carex* communities, the models tended to underestimate CH$_4$ fluxes at the higher values.

Annual CH$_4$ Balance

Considerable spatial variation in the mean annual CH$_4$ balance (g CH$_4$ m^{-2} yr^{-1}) was observed between communities in both years of the study. In 2002, mean annual CH$_4$ emissions were 38.8, 31.1, and 4.3 g CH$_4$ m^{-2} yr^{-1} in *Typha* ($n = 2$), *Phalaris* ($n = 2$), and *Eriophorum*/*Carex*, respectively ($n = 4$) (Table 2). Emissions from all micro-

sites were lower in 2003, but the spatial pattern did not change. Mean annual emissions were 28.8, 18.4, and 3.2 g CH$_4$ m^{-2} yr^{-1} in *Typha*, *Phalaris*, and *Eriophorum*/*Carex*, respectively. No discernible relationship could be detected between CH$_4$ fluxes and WT and peat temperature in the bare peat plots (data not shown). The annual CH$_4$ balance was therefore calculated by integrating the mean monthly fluxes and resulted in a small uptake by the bare peat plots of 0.07 g CH$_4$ m^{-2} yr^{-1}.

Gross photosynthesis (P$_G$) values from Wilson et al. (2007*b*) were used to investigate the relationship between plant productivity and annual CH$_4$ emissions. P$_G$ was calculated from chamber measurements of net ecosystem exchange and ecosystem respiration (R$_{TOT}$) and modeled using the observed relationships between P$_G$ and photosynthetically active radiation (PAR) and VGA. In general, the highest annual CH$_4$ emissions were associated with high WT positions and high primary productivity (P$_G$) (Table 2). The proportion of annual gross photosynthesis (P$_G$) that is released as CH$_4$ varied between years
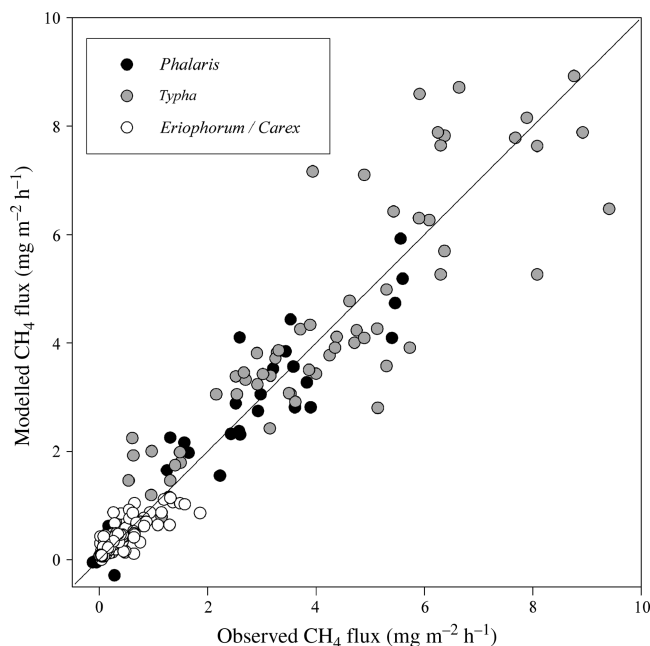

Figure 3. Relationship between observed and modeled CH$_4$ fluxes (mg CH$_4$ m^{-2} hr^{-1}) in *Phalaris arundinacea* ($n = 60$), *Typha latifolia* ($n = 62$), and *Eriophorum angustifolium*/*Carex rostrata* ($n = 110$) communities at Turraun, Co. Offaly.

Table 2. Mean annual WT position (cm), annual gross photosynthesis (P_G) (g CO_2 m^{-2} yr^{-1}), and annual CH_4 balance (g CH_4 m^{-2} yr^{-1}) for *Phalaris arundinacea, Typha latifolia, Eriophorum angustifolium/Carex rostrata*, and bare peat microsites at Turraun, Co. Offaly in 2002 and 2003.

	2002			*2003*		
	WT	P_G	CH_4	*WT*	P_G	CH_4
Phalaris	3.0 (1.4)	3,425 (147)	31.1 (11.1)	−11.2 (0.9)	4,099 (180)	18.4 (4.4)
Typha	7.0 (1.4)	3,274 (146)	38.8 (3.9)	0.3 (1.1)	4,360 (136)	28.8 (2.9)
Eriophorum/Carex	5.0 (2.6)	2,643 (950)	4.3 (1.9)	−6.3 (1.9)	2,662 (950)	3.2 (1.9)
Bare peat	−24.0 (5.2)	—	−0.07	−27.0 (6.2)	—	−0.07

Positive WT values indicate water position above the peat surface. Positive CH_4 values indicate emission to the atmosphere, and negative values indicate an uptake of CH_4. Standard deviations are in parentheses. P_G values adapted from Wilson et al. (2007*b*).

and microsites (Fig. 4). A greater proportion of the carbon sequestered by P_G was emitted as CH_4 from all communities in 2002 than in 2003 primarily as a result of higher CH_4 emissions rather than lower P_G. The difference was enhanced by greater oxidation rates brought about by lower WTs in 2003. The *Typha* and *Phalaris* communities emitted between 1.8 and 3.5% of gross carbon production as CH_4 in 2002 and 1.1 and 2.1% in 2003. The values were considerably lower in the *Eriophorum*/*Carex* sample plots and ranged from 0.3 to 0.6% in 2002 and 0.2 to 0.4% in 2003.

CH_4 Hot Spots at the Landscape Scale

Wetland creation is likely to result in a hot spot of CH_4 emissions at the landscape level (Table 3). Our scenario suggests that if 100 ha of wetlands were to be created, this would result in CH_4 emissions of around 105 tonnes CO_2 equivalents per year, somewhat higher than that released from the cutaway scenario. The largest CH_4 hot spot is the grassland option (207 tonnes CO_2 equivalents per year), and the lowest is the naturally regenerated deciduous woodland scenario (25 tonnes CO_2 equivalents per year). The GWP of each scenario was dominated by the CO_2

component with only afforestation showing a net uptake of CO_2 and cooling effect. The contribution of N_2O to the overall GWP was lowest (9 tonnes CO_2 equivalents per year) in the wetland and highest in the grassland scenario (228 tonnes CO_2 equivalents per year).

Discussion

Re-Creation of CH_4 Emissions Hot Spots

The results from this study have shown that rewetting, lake construction, and recolonization of the cutaway peatland at Turraun have resulted in the re-creation of hot spots of CH_4 fluxes. The CH_4 fluxes observed in this study are at the lower range of those reported elsewhere for littoral *Phragmites australis*/*Typha latifolia* stands (Kankaala et al. 2004) and *Eriophorum* spp. and *Carex* spp. microsites in boreal fens (Alm et al. 1997). Our results are in agreement with studies elsewhere that have reported lower CH_4 fluxes initially following rewetting and recolonization in comparison to nearby undamaged sites (Komulainen et al. 1998; Tuittila et al. 2000). However, Yli-Petäys et al. (2007) found relatively high CH_4 emissions (6.5–38.4 g CH_4 m^{-2} yr^{-1}) in association with a rapid accumulation of fresh peat in a naturally regenerated block-cutting trench five decades after the abandonment. In a wide-ranging study of CH_4 fluxes, Nykänen et al. (1998) observed a linkage between the low fluxes and the relatively high bulk density values in drained peatland sites and suggested that compression of the peat induced by drainage may affect the diffusion of CH_4 through the peat profile. The relatively high bulk density values at Turraun, undoubtedly a consequence of its previous land use, are in agreement with values for drained peatlands recorded elsewhere (Tuittila et al. 1999). Notwithstanding lower fluxes, hot spot occurrence was evident within the peatland, driven by both abiotic and biotic factors.

Figure 4. Annual CH_4 emissions as a proportion of annual gross photosynthesis (P_G) for *Typha latifolia*, *Phalaris arundinacea*, and *Eriophorum angustifolium*/*Carex rostrata* communities at Turraun, Co. Offaly in 2002 and 2003.

Biotic Factors and Spatial Variation in CH_4 Fluxes

The littoral zones of lakes can be highly productive ecosystems (Larmola et al. 2004), and recent studies have shown that they can significantly contribute to CH_4 emissions (Juutinen et al. 2003). Similarly, the observed
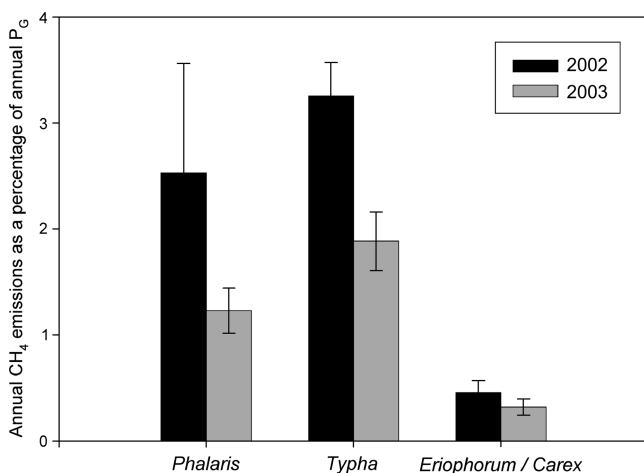
Table 3. GWP (tonnes CO_2 equivalents) for five future land use scenarios.

	Cutaway	Wetland	Afforestation	Deciduous	Grassland	References
Land use cover (ha)						
Bare surface	95	5	—	5	—	
Ditches	5	—	5	—	—	
Open water	—	60	—	—	—	
Littoral	—	10	—	—	—	
Terrestrial	—	25	—	30	—	
Grass	—	—	—	—	100	
Trees	—	—	95	65	—	
Total	100	100	100	100	100	
GHG (tonnes CO_2 equivalents)						
CO_2	979 (887–1,072)	585 (359 848)	−427 (−444 to −433)	1,641 (1,400–1,825)	1,497 (292–2,891)	Sundh et al. (2000), Huttunen et al. (2003*a*), Maljanen et al. (2007), Wilson et al. (2007*b*), Byrne et al. (2007*a*, 2007*b*, 2007*c*)
CH_4	87 (7–187)	105 (65–154)	87 (7–188)	25 (21–29)	207 (206–208)	This study, Huttunen et al. (2003*a*), Minkkinen and Laine (2006), Maljanen et al. (2007), Mäkiranta et al. (2007)
N_2O	28 (22–42)	9 (8–10)	70 (28–110)	18 (8–23)	228 (118–452)	Toda et al. (1994), Huttunen et al. (2003*a*, 2003*b*), Nilsson and Nilsson (2004), Byrne et al. (2007*a*), Maljanen et al. (2007), Mäkiranta et al. (2007)
GWP	1,094 (916–1,301)	699 (433–1,011)	−269 (−409 to −125)	1,685 (1,429–1,878)	1,932 (617–3,551)	

Minimum and maximum values in parentheses. Each scenario is a hypothetical 100-ha peatland. CH_4 and N_2O emissions were converted into CO_2 equivalents by assuming a GWP of 23 and 296 over a 100-year horizon, respectively (IPCC 2001).

differences in fluxes between the unvegetated bare peat and the vegetated microsites of the littoral zone confirm the importance of vegetation in regulating CH_4 emissions and indicate a link between hot spot occurrence and vegetation composition. As such, the spatial differences in CH_4 emissions observed can to a certain extent be attributed to the primary productivity of the microsites. The close relationship between plant productivity and CH_4 emissions has been observed elsewhere (Strack et al. 2004). Plants provide the labile C required for methanogenesis through litter input (Saarnio et al. 2004), and therefore, an increase in P_G is likely to lead to a corresponding increase in CH_4 emissions through greater quantities of substrate input.

The highest CH_4 emissions could be expected to occur with the most productive communities within peatland (Strack et al. 2004), but this was not always the case in our study. Although productivity was reasonably similar between *Eriophorum angustifolium*/*Carex rostrata* and *T. latifolia* and *Phalaris arundinacea*, CH_4 emissions are much lower in the former. Furthermore, the proportion of P_G that is emitted as CH_4 is much lower in *Eriophorum*/*Carex* when compared to *Typha* and *Phalaris*, which suggests differences between species in the quality of substrate for the methanogenic populations and/or in the transport of CH_4. Similar spatial variation related to differences between plant species has been noted by others (Saarnio et al. 1997). Specifically, other studies have suggested that variation in fluxes between species may occur due to differences in the ratio of stable and labile components in plant material (Hartman 1999) as well as the close relationship between the size of the methanogen community and the input of fresh organic matter (Wachinger et al. 2000).

Abiotic Factors and Spatial Variation in CH_4 Emissions

Our results suggest that WT position has a major influence on CH_4 fluxes. This is supported by similar findings in other restored ecosystems, such as riparian zones (Altor & Mitsch 2006) and forested wetlands (Li et al. 2004), where CH_4 fluxes have been shown to be highly sensitive to fluctuations in the WT. The position of the WT can be seen as a fundamental controller because it establishes the extent of the oxic zone where CH_4 can be consumed by methanotrophic bacteria. Perhaps more importantly, a deep WT will result in a reduction in substrate supply to the methanogenic bacteria because a considerable proportion of the plant litter is initially degraded by aerobic bacteria and released as CO_2 (Svensson & Sundh 1993). This is supported by the findings that CH_4 oxidation occurs mainly just below the WT (Saarnio et al. 1997) where both the substrate (CH_4) and the oxygen are in maximum supply (Kettunen et al. 1999). At our study site, lower WT positions in late summer and autumn in 2003 resulted in high emissions of CO_2 as plant litter was broken down (Wilson et al. 2007b), and subsequently, lower wintertime CH_4 fluxes were observed. The highest CH_4 emissions were

from the sample plots with a mean annual WT close to or above the soil surface. Rainfall was 25 cm lower in 2003, which resulted in deeper WT positions (between 3 and 14 cm) and lower annual CH_4 emissions at all microsites. Although there was a strong relationship between $T_{10 cm}$ and observed fluxes in each microsite, there was little difference in the hourly temperature time series between microsites suggesting that temperature had little influence on the observed spatial variation in CH_4 fluxes as also reported by Fiedler and Sommer (2000).

Greenhouse Gas Hot Spots at the Landscape Scale

The results of the scenarios presented here have major implications for land managers and planners working in the new post-industrial environment. In order to decide how best to maximize the potential of these new ecosystems, the effect on the global climate must form an integral part of the decision-making process. Clearly, the large emissions of CO_2 and CH_4 associated with the cutaway scenario are not sustainable in the long term, and a transition to a new land use with a lower GWP is desirable. The results from this study suggest that wetland creation is a relatively attractive option in this regard. Wetland creation is likely to result in a hot spot of CH_4 emissions at the landscape level, primarily driven by the large emissions associated with the littoral zones. Undoubtedly, the extent of how a land use option will act as a hot spot at the landscape scale is closely coupled to the distribution of hot spots within the peatland. In our scenario, we have suggested that the littoral zone could account for around 10% of the wetland. Of course, any change in this proportion will have a considerable effect on the overall GWP. The lowest CH_4 fluxes were estimated to occur in the naturally regenerated deciduous woodland scenario, where CH_4 uptake by methanotrophic soil communities within the tree stand (Mäkiranta et al. 2007) offset the relatively small emissions associated with terrestrial plants such as *Eriophorum*. However, large losses of CO_2 have also been reported for these ecosystems (Byrne et al. 2007b). Similarly, the afforested peatland is also likely to be a small CH_4 sink, but drainage ditches may be a significant CH_4 source (Minkkinen & Laine 2006). Of the scenarios hypothesized, however, it is the only one that is potentially a net CO_2 sink, although due to high soil CO_2 emissions, the stand is probably a net C source in its early years. The largest CH_4 hot spot is the grassland option, primarily as a consequence of high CH_4 emissions associated with grazing cattle, animal manure, and so forth (e.g., Byrne et al. 2007c). However, this value is likely to be highly dependent on the type of agricultural management system in operation. We have suggested a relatively low stocking rate of 0.9 LU/ha for the scenario. Therefore, an increase in the carrying capacity of the grassland, such as in intensive dairy farming, will have a corresponding impact on the hot spot potential of this scenario. Similarly, as a consequence of routine nitrogen fertilizer applications, the highest N_2O emissions were also associated with the

grassland scenario. Some caution should be expressed, however, when interpreting the scenario results. First, due to the limited number of C gas studies in Ireland, it was necessary to employ values from studies where the climate and methodology may differ considerably from this study. Second, GHG fluxes in general are subject to large spatial variations, and this is reflected in the large range of GWP values for each scenario. Third, the GWP approach is used here as a tool for evaluating the possible changes in all three GHGs simultaneously. Although GWP is not an ideal measure for GHG balance change over time, it is widely used and facilitates the relative comparison of the impacts by different land use scenarios.

Conclusions

In seeking to determine the optimum land use following the cessation of peat extraction, planners are faced with a number of choices. If the goal is to increase the cooling impact on the global climate, then the afforestation of the peatland is likely to be an attractive scenario. Alternatively, from an ecological point of view, the restoration of ecosystem functioning as found in the pre-industrial state is a desirable goal. It is expected that over the next few decades, considerable areas of cutaway peatlands in Ireland will come out of industrial peat production and be suitable for wetland creation. If the bare peat microsites can be assumed to be representative of conditions that prevail at the end of peat extraction, then rewetting and recolonization of the cutaway have resulted in the return of the CH_4 source function and the re-creation of hot spot production at both the microsite and the landscape level albeit at lower levels than would be expected in comparable pristine ecosystems. However, in ecological terms, the rewetted cutaway in this study is a relatively young ecosystem, and dynamic succession processes within the cutaway are likely to result in considerable changes in both vegetation composition and CH_4 dynamics in the years ahead.

Implications for Practice

- Lake creation and rewetting of an industrial cutaway peatland result in resumption in CH_4 emissions.
- Spatial variation or hotspots of CH_4 emissions are linked to vegetation communities and underlying hydrological conditions.
- The GWP of these new ecosystems may be lower than if the peatland was left bare, naturally regenerated, or converted to grassland but higher than if it was afforested.

Acknowledgments

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