Derivation of Greenhouse Gas emission factors for peatlands managed for extraction in the Republic of Ireland and the United Kingdom

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Abstract

Drained peatlands are significant hotspots of carbon dioxide (CO_2) emissions and may also be more vulnerable to fire with its associated gaseous emissions. Under the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol, greenhouse gas (GHG) emissions from peatlands managed for extraction are reported on an annual basis. However, the Tier 1 (default) emission factors (EFs) provided in the IPCC 2013 Wetlands Supplement for this land use category may not be representative in all cases and countries are encouraged to move to higher Tier reporting levels with reduced uncertainty levels based on country or regional specific data. In this study, we quantified (1) CO_2-C emissions from 9 peat extraction sites in the Republic of Ireland and the United Kingdom, which were initially disaggregated by land use type (industrial versus domestic peat extraction), and (2) a range of GHGs that are released to the atmosphere with the burning of peat. Drainage related methane (CH_4) and nitrous oxide (N_2O) emissions, as well as CO_2-C emissions associated with the off-site decomposition of horticultural peat were not included here. Our results show that net CO_2-C emissions were strongly controlled by soil temperature at the industrial sites (bare peat), and by soil temperature and leaf area index at the vegetated domestic sites. Our derived EFs of 1.70 (±0.47) and 1.64 (±0.44) t CO_2-C ha^{-1} yr^{-1} for the industrial and domestic sites respectively, are considerably lower than the Tier 1 EF (2.8±1.7 t CO_2-C ha^{-1} yr^{-1}) provided in the Wetlands Supplement. We propose that the difference between our derived values and the Wetlands Supplement value is due to differences in peat quality and, consequently, decomposition rates. Emissions from burning of the peat (g kg^{-1} dry fuel burned) were estimated to be approximately 1346 (CO_2), 8.35 (methane, CH_4), 218 (carbon monoxide, CO), 1.53 (ethane,C_2H_6)), 1.74 (ethylene,C_2H_4)), 0.60 (methanol,CH_3OH)), 2.21 (hydrogen cyanide, HCN) and 0.73 (ammonia, (NH_3) and emphasises the importance of understanding the full suite of trace gas emissions from biomass burning. Our results highlight the importance of generating reliable Tier 2 values for different regions and land-use categories. Furthermore, given that the IPCC Tier 1 EF was only based on 20 sites (all from Canada/Fenno-Scandia) we suggest that data from another 9 sites significantly expands the global dataset, as well as adding a new region.

1 Introduction

Greenhouse gas (GHG) emissions to the atmosphere have increased significantly since pre-industrial times as a direct result of human activities, such as fossil fuel burning, cement production and land use changes (IPCC, 2013). The Intergovernmental Panel on Climate Change (IPCC) have estimated in their Fifth Assessment Report (AR5) that around one third of all anthropogenic emissions of carbon dioxide (CO_2) for the period 1750-2011, were caused by land use changes (IPCC, 2013). From 2000-2009, the Agriculture, Forestry and Other Land-Use (AFOLU) sector accounted for 24% of all global GHG emissions (around 10 Gt CO_2-eq yr^{-1}), with emissions from peatland drainage and burning alone estimated at around 0.9 Gt CO_2-eq yr^{-1}.

Natural (i.e. undrained) peatlands function as long term carbon (C) stores as the sequestration of CO_2 over time is greater than the amount of C that is emitted from the peatland as methane (CH_4) and leached in waterborne exports (Roulet et al., 2007; Nilsson et al., 2008; Koehler et al., 2011; Gažovič et al., 2013). Key to this role is the position of the water table, which largely dictates the rate of decomposition within the peatland. When the water table is positioned close to the peat surface, the breakdown and degradation of organic matter typically proceeds very slowly in the absence of oxygen. As a consequence, there is an accumulation of peat (and C within) (Dise, 2009).

In the Republic of Ireland (ROI) and the United Kingdom (UK), peat has been extracted for energy use for many centuries (Chapman et al., 2003; Renou et al., 2006). Traditionally, this involved the manual removal of the peat i.e. hand cutting, however this has been largely superseded by highly mechanised methods to extract the peat for both energy and horticulture requirements. In the ROI, over 4 million tonnes of peat per annum are industrially extracted from approximately 50,000 ha to provide ca. 5.5% of primary energy requirements (Howley et al., 2012) and for use in horticulture. A further 0.4 million tonnes per year is likely burned for domestic heating (Duffy et al., 2014) and may impact as much as 600,000 ha of peatlands (Wilson et al., 2013b). Although peat extraction areas in the UK have generally declined over the last few decades, approximately 0.8 million tonnes of peat is still extracted each year in England and Scotland (Webb et al., 2014), although it is UK Government policy to phase out peat extraction in England by 2030 (Department of Environment Food and Rural Affairs, 2011). Peat extraction areas in Wales are small (482 ha) and have remained unchanged in the 1991-2010 period (Webb et al., 2014). In Northern Ireland, the area of peatland utilised for fuel (mechanical and hand cutting) has declined considerably in the 1990-2008 period,

1 although a slight increase in the areas used for horticulture have been recorded (Tomlinson,
2 2010).

3 In industrial peatlands, the extraction of peat is facilitated by the installation of drainage
4 ditches at regular (typically 15-30m) intervals across the peatland. For peat used for
5 horticultural purposes, the more fibrous upper layers (e.g. *Sphagnum* peat) are extracted and
6 utilised. If the peat is to be used for energy production the more highly decomposed peat is
7 milled, dried in the production fields and removed for immediate use or stockpiled for later
8 requirements. Peat extraction ceases for energy production when either the sub-peat mineral
9 soil is reached, large quantities of fossilised timber are encountered or drainage is no longer
10 practical (Farrell and Doyle, 2003). For peatlands used for the provision of domestic heating,
11 the peat is either removed by a digger from the margins of peatlands, placed in a tractor
12 mounted hopper and extruded onto the surface of the peatland, or the peat is extruded onto
13 the surface of the peatland from openings made in the peat by a chain cutter. Over a period of
14 weeks the peat is dried *in situ* and removed from the site. The effect of peat extraction on the
15 hydrological functioning is marked by a large fall in the water level either throughout the
16 peatland (industrial) or at the margins of the peatland (domestic). In the latter, significant
17 water level drawdown is also experienced further inward towards the centre of the peatland
18 (Schouten, 2002).

19 The impact of drainage on C cycling in peatlands has been widely documented. In general, a
20 lowering of the water table leads to increased CO_2 emissions (Silvola et al., 1996; Salm et al.,
21 2012; Haddaway et al., 2014) as the aerobic layer is deepened and mineralisation rates are
22 accentuated. Concurrently, CH_4 emissions (with the exception of ditches) may decrease or
23 cease (Salm et al., 2012; Turetsky et al., 2014), waterborne C exports may increase (Strack et
24 al., 2008; Evans et al., 2015) and there may be a heightened risk of C loss through fire
25 (Turetsky et al., 2015). In the case of peat extraction, C cycling may be further altered by the
26 removal of vegetation (Waddington and Price, 2000), and losses of windblown particulate
27 organic carbon (POC) may be exacerbated from the bare peat surfaces (Lindsay, 2010).

28 Under the United Nations Framework Convention on Climate Change (UNFCCC) and the
29 Kyoto Protocol, "Annex 1" countries (i.e. countries that have committed to targets that limit
30 or reduce emissions) are obligated to prepare annual National Inventory Reports (NIR) and
31 up-to-date annual inventories, detailing GHG emissions and removals from six different
32 sectors. Emissions associated with off-site peat combustion are reported under the Energy

sector and are not considered further here. The recent IPCC Wetlands Supplement (IPCC, 2014) to the 2006 Good Practice Guidance (GPG) (IPCC, 2006) derived new Tier 1 emission factors (EFs) for drained organic soils that differentiated between on-site emissions (e.g. CO_2-$C_{on\text{-}site}$, fire) and off-site losses (e.g. leaching of waterborne C). In the case of peatlands managed for extraction in the temperate climate zone, the CO_2-$C_{on\text{-}site}$ values have increased from 0.2 (nutrient poor/bogs) and 1.1 (nutrient rich/fens) t CO_2-C ha^{-1} yr^{-1} in the 2006 GPG to a single higher EF of 2.8 t CO_2-C ha^{-1} yr^{-1} (covering the entire boreal and temperate regions) in the Wetlands Supplement. On-site burning directly consumes aboveground C stocks (prescribed and wildfire burning) and the underlying peat C store (wildfire burning), and rapidly releases both gases (e.g. CO_2, CH_4) and particulates (e.g. black carbon) to the atmosphere. In the Wetlands Supplement, an EF for GHG emissions from prescribed fire on drained peatlands is not provided due to a paucity of published data at present. However, emissions from wildfires are addressed and EFs of 362, 9 and 207 g kg^{-1} dry fuel burned is provided for CO_2-C, CH_4 and CO respectively with a proviso that they were derived from a very small dataset.

Given the relatively large areas under peat extraction in both the ROI and the UK, a move from Tier 1 to higher reporting levels is desirable, particularly as (a) a wide range in uncertainty is associated with the IPCC Tier 1 values (1.1 - 4.2 t CO_2-C ha^{-1} yr^{-1}), which reflects the disparity in emissions from drained peatlands from different climate zones and nutrient composition, (b) the most recently published annual CO_2 flux estimates (not included in the derivation of IPCC Tier 1 values) also display a very wide amplitude (cf. Järveoja et al., 2012; Mander et al., 2012; Salm et al., 2012; Strack et al., 2014), (c) no data from ROI or UK peatlands were included in the IPCC derivation, which might mean that the Tier 1 value may not be appropriate for these countries, and (d) no distinction is made between industrial or domestic extraction sites, despite large differences in their drainage, vegetation cover and management characteristics. In addition, previous studies of peatland fire EFs have focused on the boreal peatlands of Alaska (Yokelson et al., 1997) and Canada (Stockwell et al., 2014); and the temperate peatlands of Minnesota (Yokelson et al., 1997) and North Carolina (Stockwell et al., 2014). These studies found that the smouldering combustion of peats associated with low combustion efficiency leads to relatively lower CO_2 emissions (compared with other ecosystems), and much higher carbon monoxide (CO), CH_4, and other non- CH_4 hydrocarbon emissions. Therefore, it is important to quantify emissions of these

gases as they include strong GHGs (e.g. CH_4) and reactive gases responsible for tropospheric ozone formation and poor air quality (e.g. CO, ammonia (NH_3), hydrogen cyanide (HCN)).

The objectives of the study are (1) to provide estimates of the annual CO_2-C exchange (i.e. CO_2-$C_{on\text{-}site}$) for 9 peat extraction sites in the ROI and the UK, (2) to derive regional specific CO_2-C EFs for drained peat extraction areas that would permit ROI and the UK to progress to the Tier 2 reporting level, (3) analyse the factors that influence CO_2-C dynamics in this region (i.e. land use, climate etc.), and (4) to report GHG emissions associated with the burning of Irish *Sphagnum* moss peat in the first laboratory study to investigate fire emissions from European temperate peats.

2 Materials and Methods

2.1 Study sites

The study sites were located at 9 peat extraction areas in the ROI and the UK with a history of either industrial peat (IP) or domestic peat (DP) extraction (Table 1). Boora (IP1), Blackwater (IP2), Bellacorick (IP3), Turraun (IP4), Middlemuir Moss (IP5) and Little Woolden Hall Moss (IP6) are industrial cutaway peatlands where significant areas of bare peat (i.e. unvegetated microsites) have remained following the cessation of milled peat extraction. At IP6, milled peat is currently extracted from areas close (<150m) to the study site. The IP sites are former raised bogs with the exception of IP3, which is a former Atlantic blanket bog. At all sites, the drainage ditches have remained functional. Here we define "drained" as a mean annual water table position deeper than -20cm (Couwenberg and Fritze, 2012; Strack et al., 2014). Physico-chemical characteristics of all the sites are detailed in Table 1.

At Clara (DP1), Glenlahan (DP2) and Moyarwood (DP3) the peat has been extracted from the margins of the sites for use in domestic heating. In the case of Clara, peat extraction was an ongoing activity at the time of our study despite the designation of the site as a Special Area of Conservation (SAC). DP1 and DP3 are raised bogs and DP2 is a mountain blanket bog. The vegetation component at all the sites is species poor and is composed mainly of ling heather (*Calluna vulgaris*), cross leaved heather (*Erica tetralix*) and lichens (*Cladonia* spp.) A continuous water table level was not observed at DP2, as the relatively shallow peat

deposit (~40cm) over bedrock at that site was prone to drying out at various times throughout the study.

2.2 Climatic conditions

All the sites are located within the temperate zone as defined by IPCC (2006), and are characterised by an oceanic climate with prevailing south-west winds, mild mean annual air temperatures (8 to 10.3°C) and moderate to high annual rainfall (804 to 1245 mm) (Table 1).

2.3 Environmental monitoring

At each site, 3-9 aluminium square collars (60 x 60 cm) were inserted to a depth of 30cm into the peat. At IP6, smaller circular plastic collars were used (15cm diameter) to facilitate the use of the CPY-4 chamber (PP Systems, UK) at that site. Soil loggers (µ logger; Zeta-tec, UK, Hobo External Data Loggers; Onset Computer Corporation, MA, USA or Comark N2012 Diligence Loggers, Norwich, UK) were established in all the IP sites and recorded soil temperatures (°C) at hourly intervals. Weather stations were installed at all the DP sites and recorded photosynthetic photon flux density (PPFD; µmol m^{-2} s^{-1}) and soil temperatures (5 and 10cm depths) at 10 minute intervals. At DP3, soil volumetric moisture content (VMC, %) was also recorded (at 10 min intervals) by the weather station at that site. At sites IP5 and IP6, soil temperature was only measured manually during CO_2 flux measurements. In order to estimate soil temperature at times where data was lacking at these two sites, a regression based approach between manually recorded T_{5cm} and air temperature recorded at 15 min intervals by a logger on the site was used to gap fill the data (r^2 = 88.7 %). Water table level (WT) was manually measured from dipwells (internal diameter 2 cm) inserted adjacent to each collar. Wooden boardwalks were established at each site (exception IP6).

2.4 Leaf area index (LAI)

At the IP sites, the vegetation had been removed prior to the commencement of peat extraction and virtually no natural recolonization has taken place following cessation of peat extraction. However, at the DP sites a vegetation component was present and in order to incorporate the seasonal dynamics of the plants into CO_2-C exchange models, the leaf area index (LAI) was estimated for each of the collars. This involved accounting for the green photosynthetic area of all vascular plants (leaves and stems) within the collar at monthly intervals. In short, the number of leaves and stems were counted from five subplots (8 x 8cm)

within each collar. The size (length, width) of the leaves was measured from sample plants outside the collars. The LAI was then calculated by multiplying the estimated number of leaves by an area estimate of the leaf. Moss and lichen % cover was estimated at the same time. Species-specific model curves were applied to describe the phenological dynamics of the vegetation of each collar, and the models (vascular plants and moss) were summed to produce a plot-specific LAI. For a detailed description of the method see Wilson et al. (2007). At site DP1 only, the vegetation was removed by regular clipping from one third of the collars, in order to provide an estimate of the heterotrophic contribution (R_H) to ecosystem respiration (R_{eco}).

2.5 On site carbon dioxide flux estimation

2.5.1 Field measurements

At sites IP1-5 and DP1-3, R_{eco} was measured with a static polycarbonate chamber (60 x 60 x 33 cm) equipped with two internal fans to ensure mixing of the air within the chamber, and a cooling system (submerged ice packs, and pumped water to a radiator located within the chamber) to maintain the temperature within the chamber close to the ambient air temperature (for a more detailed description see Alm et al., 2007b). At IP6, R_{eco} was measured with a CPY-4 (PP Systems, UK) clear acrylic chamber (14.6 cm diameter, 14.5 cm height). The CPY-4 chamber was equipped with an internal fan, PPFD sensor and thermistor. Sampling was carried out at fortnightly or monthly (winter) intervals (2-4 measurements per collar per measurement day). For each R_{eco} flux measurement, the chamber was placed in a water-filled channel at the top of the collar or connected with a rubber gasket (IP5), covered with an opaque cover and the CO_2 concentration (ppmv) in the chamber headspace was measured at 15-second (5-second at IP6) intervals over a period of 60-180 seconds using a portable CO_2 analyser (EGM-4; PP Systems, UK). Concurrently, air temperature (°C) within the chamber and soil temperatures at 5, 10 and 20 cm depths were recorded at each collar (soil temperature probe; ELE International, UK). The WT position relative to the soil surface was manually measured with a water level probe (Eijkelkamp Agrisearch Equipment, The Netherlands). At the DP sites, net ecosystem exchange (NEE) was measured with the same polycarbonate chambers described above under a range of ambient light levels (PPFD; µmol m^{-2} s^{-1}) prior to R_{eco} measurements. NEE measurements were carried out between 8 am and 6pm in the summer and between 9am and 3pm in the winter (3 to 8 measurements per collar per measurement day) to ensure that the maximum PPFD was reached at each measurement

date. Artificial shading was used in the early morning to obtain low PPFD levels (<100 µmol m^{-2} s^{-1}). PPFD was recorded from a sensor (PAR-1. PP Systems) located within the chamber. The portable CO_2 analysers were regularly calibrated with a CO_2 standard gas.

2.5.2 Flux calculations

Flux rates (mg CO_2-C m^{-2} h^{-1}) were calculated as the linear slope of the CO_2 concentration in the chamber headspace over time, with respect to the chamber volume, collar area and air 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 zero (mainly in winter time where soil processes are typically slower) and the r^2 is always low (Alm et al., 2007b). In these cases the flux data were examined graphically and fluxes with obvious non-linearity (due to chamber leakage, fan malfunction etc.) were discarded. The remainder were accepted provided that some of the environmental variables measured at the same time (e.g. soil temperature) were sufficiently low to account for the low flux values (Wilson et al., 2013a). In this study, we followed the sign convention whereby positive values indicated a CO_2-C flux from the peatland to the atmosphere (source) and negative values indicated a flux from the atmosphere to the peatland (sink). Gross primary production (GPP) was calculated as NEE minus R_{eco} (Alm et al., 2007b), and the closest R_{eco} flux value in time to a NEE flux value was used.

2.5.3 Modelling

Statistical and physiological response models (Alm et al., 2007b) were constructed and parameterised for each study site. Model evaluation was based on the following criteria; (a) statistically significant model parameters ($p<0.05$), (b) lowest possible standard error of the model parameters and (c) highest possible coefficient of determination (adjusted r^2) (see Laine et al., 2009). The basic R_{eco} models, based upon the Arrhenius equation (Lloyd and Taylor, 1994), are non-linear models related to soil temperature. GPP was related to PPFD using the Michaelis–Menten type relationship that describes the saturating response of photosynthesis to light (Tuittila et al., 1999). GPP model coefficients and associated standard errors were estimated using the Levenberg-Marquardt multiple non-linear regression technique (IBM SPSS Statistics for Windows, Version 21.0. Armonk, NY, USA). During model construction, the relationship between R_{eco} or GPP and a range of independent environmental variables (recorded in conjunction with flux measurements) was tested. Only

variables that increased the explanatory power of the model (i.e. improved r^2 values) were included. The models were accepted if the residuals were evenly scattered around zero.

2.5.4 Annual CO_2 –C balance

The response functions estimated for R_{eco} and GPP were used for the reconstruction of the annual CO_2 -C balance. R_{eco} fluxes were reconstructed for each collar in combination with an hourly time series of (1) T_{5cm}, (2) VMC (at DP3) recorded by the data loggers or (3) WT depths linearly interpolated from weekly measurements. The annual CO_2-C balance (g C m^{-2} yr^{-1}) was calculated for each sample plot by integrating the hourly R_{eco} values over each 12-month period. (Note: integration periods vary between study sites; see Table 1). At the DP sites, GPP was reconstructed in combination with (1) PPFD values recorded by the weather station, (2) plot specific modelled LAI and (3) an hourly time series of T_{5cm} (DP1only). At the DP sites, annual NEE was calculated as annual GPP + annual R_{eco}.

2.5.5 Statistical analysis

The CO_2-C flux data (R_{eco} for the IP sites, and R_{eco} and GPP for the DP sites) had a non-normal distribution, so the non-parametric Kruskal-Wallis ($p=0.05$) and Mann-Whitney tests were used to test for differences between sites. Uncertainty in reconstructed annual R_{eco} and GPP was calculated by summing up the maximum and minimum standard errors associated with each of the model parameters (e.g. Drösler, 2005; Elsgaard et al., 2012; Renou-Wilson et al., 2014). Uncertainty in the annual R_{eco} or NEE estimate was calculated following the law of error propagation as the square root of the sum of the squared standard errors of GPP and R_{eco} (IPCC, 2006).

2.6 Peat fire emissions

Around 5 kg (dry mass) of loose Irish *Sphagnum* moss peat (H2-H3 on the von post decomposition scale) was used for measuring fire EFs. Subsamples of the peat were taken and placed into a 22 x 12 x 10 cm open-topped insulated chamber. The chamber was constructed from lightweight Celcon insulation blocks and was used to replicate natural surface combustion conditions, leaving only one surface of the peat exposed to open air thereby reducing heat loss and oxygen exchange from the other surfaces, in accordance with the suggested peat combustion methodology of Rein et al. (2009). Each sample was dried in an oven overnight at 60°C. In order to produce comparable replicates, the samples for the burning experiment had to be dried to an absolute dry base to increase ignition probability

(Frandsen, 1997) and encourage pyrolysis (Rein et al., 2009). Following drying, the chamber and sample were placed in a fume cupboard under controlled air flow conditions and the peat was ignited using a coiled nichrome wire heated to ~600°C and placed in contact with the surface of the peat. This also best represents natural ignition conditions (e.g. from a surface shrub fire), also in accordance with the methodology of Rein et al. (2009). Once ignited, each 1 kg sample proceeded to burn for ~90 minutes. The resulting smoke was continuously sampled using a pump and a 90 cm sample line with a funnel held ~12 cm above the smouldering peat. The smoke was sampled into an 8.5 litre infrared White (multipass) cell (Infrared Analysis, Inc.) where infrared spectra were collected using a Fourier Transform Infrared (FTIR) spectrometer. Analysis of the FTIR spectra was performed using the Multi Atmospheric Layer Transmission (MALT) software (Griffith, 1996), yielding trace gas mole fractions inside the White cell, from which emissions factors may be calculated. A full description of how EFs may be calculated from FTIR measurements of gas mole fractions is given in Paton-Walsh et al. (2014) and Smith et al. (2014). Here we use the C mass balance approach to calculate EFs for CO_2 and CO (Eq. 1 in Paton-Walsh et al., 2014). The C content of the peat (required for calculating EFs via the C mass balance approach) is assumed to be 53.3%, as measured in Scottish sphagnum moss peat (Cancellieri et al., 2012). For all other gas species considered in the study; CH_4, ethylene (C_2H_4), ethane (C_2H_6), methanol (CH_3OH), HCN, NH_3), we use their respective emission ratios to CO and the EF for CO to calculate EFs (via Eq. 5 in Paton-Walsh et al., 2014).

Combustion efficiency is a measure of the amount of fuel carbon released as CO_2, and may be approximated using the Modified Combustion Efficiency (MCE) formula, which requires only a measurement of CO and CO_2 rather than all the C containing gases (Yokelson et al., 2008):

$$MCE = \frac{\Delta CO_2}{\Delta CO_2 + \Delta CO} \quad (1)$$

where ΔCO_2 and ΔCO represent the elevated mixing ratios of these gases (the difference between mixing ratios measured in biomass burn emissions and those in the ambient air). MCE is often expressed as a percentage. Generally, an MCE lower than 0.9 (90%) is considered a low combustion efficiency burn (Lobert et al., 1991; Yokelson et al., 1996).

3 Results

3.1 Environmental variables

Annual rainfall varied between sites and between years (Fig. 1). The wettest site was DP3 (1390 mm), and the driest was IP6 (746 mm) in the first year of measurements at that site. All multi-year sites displayed inter-annual variation in rainfall with the largest differences observed in IP4 (210 mm difference in annual rainfall between years). Annual rainfall at IP2, IP5, DP1, DP2 and DP3 was above the long-term average in all years. IP1 and IP4 were wetter than the long-term average in one of the years and drier in the other. IP3 and IP6 were drier than the long-term average. The mean annual water table was below -20cm at all sites in all years (Fig. 1). The deepest mean annual values were at IP1 (-60cm) and the shallowest at IP3, 4 and 5 (-25cm). Mean water table position tracked annual rainfall (i.e. higher rainfall resulted in higher water table positions) in all multi-year sites with the exception of IP1.

The highest mean annual soil temperature (T_{5cm}) value (12.7°C) was recorded at IP4 and the lowest at IP5 (6.7°C) and inter-annual variation was evident in the multi-year sites (Fig. 1). The lowest hourly T_{5cm} value (-12.9°C) was recorded at IP5 and the highest (28.4°C) at IP4 (Fig. 2). The proportion of hourly T_{5cm} values less than 0°C ranged from 0% (IP3) to 13.8% (IP5), and the proportion of values greater than 20°C ranged from 0.2% (IP5) to 5.3% (IP2) (Fig.2).

3.2 On-site carbon dioxide fluxes

At the IP sites, R_{eco} fluxes ranged from 0 to 133 mg CO_2-C m^{-2} hr^{-1} and differed significantly between sites (Fig. 3a Kruskal-Wallis, H=98.59). Site IP4 had significantly higher R_{eco} flux values than all the other IP sites (Mann Whitney $p<0.001$) and IP5 had significantly lower flux values than IP2, IP4 and IP6 (Mann Whitney $p<0.001$) but not IP1 and IP3 (Mann Whitney p=0.31). At the DP sites, R_{eco} fluxes ranged from 12 to 200 mg CO_2-C m^{-2} hr^{-1} and there was a significant difference in R_{eco} fluxes between the DP sites (Fig. 3b Kruskal-Wallis, H=37.52) but no significant difference between DP1 and DP2 (Mann Whitney p=0.075). R_{eco} values differed significantly between the IP and DP sites (Kruskal-Wallis, H=395.22). Measured NEE (at PPFD>1000 µmol m^{-2} s^{-1}) ranged from 60 to -325 mg CO_2-C m^{-2} hr^{-1} at the DP sites and values differed significantly between sites (Fig. 3c Kruskal-Wallis, H=90.82).

3.2.1 Modelling

At sites IP6 and DP2, T_{5cm} was the sole explanatory variable in the R_{eco} models (Eq.2) and explained 32% and 42% respectively of the variability in fluxes. The addition of water table to the R_{eco} model (Eq.3) slightly improved the explanatory power and the model explained between 55% and 85% of the variability at IP1-4 and 69% at DP1. No relationship between R_{eco} and WT was observed at DP3, but the addition of VMC (Eq. 4) also slightly improved the explanatory power of the model (78%). At IP5, the data were too limited (n=22) to construct a reliable model that satisfied the criteria outlined in section 2.5.3. Instead, we calculated monthly mean values and integrated these values over the 12 month study period.

$$R_{eco} = \mathrm{a} * \exp * \left[b \left(\frac{1}{T_{REF} - T_0} - \frac{1}{T - T_0}\right)\right] \quad (2)$$

$$R_{eco} = \mathrm{a} * \exp * \left[b \left(\frac{1}{T_{REF} - T_0} - \frac{1}{T - T_0}\right)\right] * WT \quad (3)$$

$$R_{eco} = \mathrm{a} * \exp * \left[b \left(\frac{1}{T_{REF} - T_0} - \frac{1}{T - T_0}\right)\right] * VMC \quad (4)$$

where R_{eco} is ecosystem respiration, T_{REF} is reference temperature set at 283.15 K, T_0 is the (minimum) temperature at which respiration reaches zero and is set here at 227.13 K, T is the soil temperature at 5 cm depth, WT is water table depth, VMC is volumetric moisture content, a and b are fitted model parameters.

A strong relationship was observed between GPP and PPFD at the DP sites. It was the sole explaining variable at DP2 (Eq. 5) where it accounted for 70% of the variation. The addition of LAI (Eq. 6) increased the explanatory power of the GPP model at DP3 (59%) and the addition of LAI and T_{5cm} resulted in 62% of the variation explained at DP1.

$$GPP = P_{max} \left(\frac{PPFD}{PPFD + k_{PPFD}}\right) \quad (5)$$

$$GPP = P_{max} \left(\frac{PPFD}{PPFD + k_{PPFD}}\right) * LAI \quad (6)$$

$$GPP = P_{max} \left(\frac{PPFD}{PPFD + k_{PPFD}}\right) * LAI * T5cm \quad (7)$$

where GPP is gross primary productivity, P_{max} is maximum photosynthesis, PPFD is photosynthetic photon flux density, k_{PPFD} is the PPFD value at which GPP reaches half its maximum, LAI is leaf area index, T_{5cm} is soil temperature at depth of 5 cm.

3.2.2 Annual CO_2-C balance

The annual CO_2-C balance varied both spatially (between sites) and temporally (multi-year sites) (Figs. 4 and 5). In the IP sites, emissions ranged from 93 g CO_2-C m^{-2} yr^{-1} (IP5) to 304 g CO_2-C m^{-2} yr^{-1} (IP4). Annual emissions varied considerably within the multi-year sites, where coefficient of variation values ranged from 4% (IP1) to 20% (IP2). As would be expected given the close relationship observed between soil temperature and CO_2-C fluxes, a noticeable increase in modelled CO_2-C emissions was observed during the summer months at all sites (Fig. 4), although the rate of the increase varied somewhat in strength between years in the multi-year sites as a function of measured T_{5cm} and WT (where applicable). In the DP sites (Fig. 5), annual GPP and R_{eco} were highest in DP1 (-526 and 702 g CO_2-C m^{-2} yr^{-1} respectively), intermediate in DP2 (-484 and 687 g CO_2-C m^{-2} yr^{-1} respectively) and lowest in DP3 (-319 and 434 g CO_2-C m^{-2} yr^{-1} respectively). The DP sites were a net annual CO_2-C source with the highest emissions observed at DP2 (203 g CO_2-C m^{-2} yr^{-1}), intermediate at DP1 (176 g CO_2-C m^{-2} yr^{-1}) and lowest at DP3 (114 g CO_2-C m^{-2} yr^{-1}). Estimated emissions from heterotrophic respiration (R_H) at DP1 were 344 g CO_2-C m^{-2} yr^{-1}, which equates to 49% of R_{eco} at that site. Applying this proportional value to the other DP sites, we estimate that R_H emissions to be 337 and 213 g CO_2-C m^{-2} yr^{-1} at DP2 and DP3 respectively.

3.3 Drivers of annual CO_2-$C_{on\ site}$

No relationships were observed between annual CO_2-C balances (NEE) and nutrient concentrations, water table levels (average, maximum or minimum) or the von Post scale at either the IP or DP ($p>0.05$) sites. A strong relationship ($r^2=0.63$) between average soil temperature at 5cm depth and R_{eco} was very evident across the IP sites (Fig. 6); the highest annual emissions and highest average soil temperatures were associated with IP4 and the lowest at IP5. The variation in NEE between the DP sites appeared to be related to differences in LAI (Fig. 6), however the number of sites was very small (n=3) and some caution must be used in this regard.

3.4 Emission factors

Using a single mean value for each multi-year site and for its associated uncertainty (IPCC, 2014), an EF was calculated for each land use category. The derived EFs for the IP and DP sites were 1.70 (±0.47) and 1.64 (±0.44) t CO_2-C ha^{-1} yr^{-1} respectively (Table 2). The 95% confidence intervals associated with the derived EFs were ±28% and ±26% for the IP and the

DP sites respectively. There was no significant difference in the EF values between the IP and DP sites ($p=0.90$).

3.5 Peat fire emission factors

Mean modified combustion efficiency (MCE) and EFs with their standard deviations for eight trace gas species were calculated from measurements of five Irish sphagnum moss peat samples (Table 3). The peat burned with a mean MCE of 0.837 (±0.019) typical of smouldering combustion (e.g. Yokelson et al., 1996; Bertschi et al., 2003). Emissions of CO_2 amounted to 1,346 (±31) g CO_2 kg^{-1} of dry fuel burned or 342 (±8) g CO_2-C. Other carbonaceous emissions amounted to 218 g CO kg^{-1}; 8.35 g CH_4 kg^{-1}; 1.74 g C_2H_4 kg^{-1}; 1.53 g C_2H_6 kg^{-1}; and 0.60 g CH_3OH kg^{-1} of dry fuel burned. Emissions of the nitrogenous compounds amounted to 2.21 g HCN kg^{-1}; and 0.73 g NH_3 kg^{-1}.

4 Discussion

There is a very wide range in reported CO_2 emissions from both active and abandoned peat extraction areas in the literature (Figure 7). Much of this variation can be attributed to differences in climate, drainage level, peat type, peat extraction methods and the end use of the peat and, as such, provides a useful framework to examine the variations in this study.

4.1 Effects of climate

While the study sites in this paper are all located within the temperate zone, considerable variation in CO_2-C emissions was evident. Given that all the sites are drained to a similar depth (Fig. 1), it is not surprising that the variation in emissions appeared to be controlled largely by differences in soil temperatures between the sites (Fig. 6). The coldest site in terms of mean soil temperatures and lowest in terms of annual emissions was Muirhead Moss (IP5) in North-Eastern Scotland. Although rainfall and site water table levels were similar to the other sites, soil temperatures at this site remained below 0°C for a high proportion (~14%) of the year, and are likely to have resulted in a slowdown of extracellular enzymatic diffusion (Davidson and Janssens, 2006), reduced microbial activity (Fenner et al., 2005) and consequently lower rates of CO_2 production (Basiliko et al., 2007). Indeed, it is likely that our value of 0.93 t CO_2-C ha^{-1} yr^{-1} at this site may be an overestimation given that it was calculated from monthly mean values that were measured during day time hours (highest

daily temperatures). As much of the peatlands in Scotland fall within the same temperature regime (Chapman and Thurlow, 1998), CO_2-C emissions data from a wider range of peat extraction sites in this region might significantly refine our EF derivation.

At the other end of the spectrum, the highest emissions and soil temperatures were observed at Turraun (IP4) in the Irish Midlands. Data from this site had been previously reported by Wilson et al. (2007). In this study, we only utilised CO_2-C flux data from plots where the mean annual water table position was deeper than -20cm. This resulted in a higher mean value (taken over two years) in this current study. Three of IP sites in the ROI are located in the Midlands where more "extremes" in climate are generally experienced (lower winter temperatures, higher summer temperatures) than along the Western coast (IP3). However, during this study, winter temperatures at all the ROI sites seldom decreased below 0°C (Fig. 3) and the proportion of hourly temperatures higher than 20°C were somewhat similar between the sites. Although, Little Woolden Moss (IP6) received the lowest annual rainfall of all sites in year 1 of the study at that site (Fig.1), mean annual soil temperatures were in the mid-range of the 9 study sites, hourly T_{5cm} values were normally distributed (Fig.3) and CO_2-$C_{on\ site}$ emissions were close to the derived EF value of 1.70 t CO_2-C ha^{-1} yr^{-1} (Table 2).

The DP sites are all located in the ROI and within a 35km radius, but considerable variation in annual rainfall was apparent during this study (Fig. 1), with DP3 (the furthest west) receiving the highest rainfall of all sites in the study (on average 34% more rainfall than the other DP sites). The east-west rainfall gradient in the ROI is well documented and coincides with a change in peatland types (i.e. raised bogs to Atlantic blanket bogs). This climatic variation is reflected in the annual R_{eco} values, which were similar between DP1 and DP2 but much lower in DP3 (Fig. 5). There is an established relationship between rainfall amount and the moisture content of peat (Price and Schlotzhauer, 1999; Strack and Price, 2009). For the sites located in high rainfall areas, such as DP3, there may be a suppression of aerobic microbial activity within the peat matrix, and as a consequence R_{eco} values may be lower than would be expected for a drained peat soil. Indeed, at some of these sites, occult precipitation (e.g. dew and fog droplets) may also contribute significantly to higher levels of soil moisture (Lindsay et al., 2014). During the growing season, the transpiration process is also likely to play a role in determining the moisture content of the peat within the rooting zone (~20cm depth) at these vegetated sites. Moisture losses are likely to be accentuated on sunny days when air and soil temperatures are high, when LAI values are highest (mid-summer) and when vapour pressure deficit is not a limiting factor. As CO_2 emissions were closely

correlated to soil temperature at 5 cm depth, reduced moisture content in this zone is likely to stimulate aerobic microbial activity. Annual GPP showed a similar trend to annual R_{eco} in these vegetated DP sites. GPP is strongly controlled by the amount of light received by the plants (i.e. PPFD levels and LAI) and the efficiency with which the plants use it. PPFD values (data not shown) and the vegetation composition were broadly similar during the sampling periods, which would seem to indicate that LAI is the driver of both productivity and therefore NEE at these sites (Fig. 6). However, variations in LAI are likely to be the result of subtle differences in a number of other variables (e.g. nutrient status, site management) that were not captured in our measurements.

4.2 Effects of drainage level

While a close relationship between WT position and CO_2-C emissions has been established in some peatland studies (Silvola et al., 1996; Blodau and Moore, 2003; Blodau et al., 2004), soil temperature proved to be the strongest determinant of CO_2-$C_{on\text{-}site}$ emissions at our sites and this relationship has also been observed by other studies in peat extraction areas (e.g. Shurpali et al., 2008; Mander et al., 2012; Salm et al., 2012)**.** While the addition of WT or VMC improved the performance of the R_{eco} models at some of the sites, the improvement was only slight and this is likely due to the fairly narrow range of WT/VMC values recorded over the course of the 12 month study (e.g. the range in VMC values at DP3 only ranged between 56-64%). Therefore, optimum WT /VMC levels for respiration may not have been encountered. The R_{eco} models used here are only valid for the data that was measured over the course of the study at each site and cannot be readily extrapolated beyond the range of that data. For those sites where water table did not appear to influence R_{eco} dynamics it may be that fluctuations in WT level were missed with the interpolation approach and CO_2-C flux measurement regimes that we employed here, although these methodologies have been widely used elsewhere (Riutta et al., 2007; Soini et al., 2010; Renou-Wilson et al., 2014). Instead, it is probable that our results reflect the complexity of the relationship between R_{eco} and WT in very dry soils as outlined by Lafleur et al.(2005), where factors such as a stable, low surface soil moisture content, and decreased porosity (i.e. limited oxygen availability) at the depths that the WT is mainly located, ensure that when CO_2-C fluxes are measured, the WT is deeper than the zone where it has a discernible impact on R_{eco} (Juszczak et al., 2013). As such, the soil temperature regime in these sites may act as a "proxy" for drainage level

(i.e. higher soil temperatures are likely to occur in conjunction with deeper water table levels and vice versa) (Mäkiranta et al., 2009).

4.3 Peat characteristics

Industrial peat extraction involves the removal of surface vegetation and results in the exposure of decomposed peat at the surface. The level of decomposition in the peat is related to depth and as extraction proceeds, the more highly decomposed peat is exposed. The peat in industrial extraction sites tends to have a lower aerobic CO_2 production potential than natural sites for example, due to differences in substrate and nutrient availability, a more extreme physical environment (Glatzel et al., 2004) and reduced labile organic matter supply in the absence of plant communities (i.e. priming). In our study, the C content (with the exception of DP2) was similar across all sites (Table 1). Although, Glatzel et al. (2004) noted that CO_2 production was negatively correlated with the von Post scale of decomposition, no correlation with annual CO_2-C emissions was evident in our study ($p>0.05$). Similarly, despite obvious difference in nitrogen content and pH values between IP sites, no relationships with CO_2 fluxes were discerned. However, the residual peat at IP4 is strongly influenced by the close proximity of limestone parent material, as evidenced by high pH values and the lowest C:N ratio (Table 1), and is highly minerotrophic. Given the high CO_2-C emissions associated with this site, consideration should be given to disaggregation by nutrient type should more data become available in the future.

Organic matter quality has been closely linked to the soil respiration rate, with lower emission rates associated with the poorer quality organic matter found at depth in drained peatlands (Leifeld et al., 2012). The lowest emissions at our sites occurred where the residual peat was either of Cyperaceous (IP3) or *Sphagnum* / Cyperaceous (IP5) origin. However, while the slow decomposition rate of *Sphagnum* litter in comparison to other plant litter has been well documented (Verhoeven and Toth, 1995; Bragazza et al., 2007), there is insufficient data from our study sites to determine whether the limited relationship observed here between peat type and CO_2-C emissions in our study sites is coincidental rather than causal.

4.4 Effects of peat extraction methods and peat end use

For peat utilised for horticulture, the more fibrous peat layers nearer the surface are extracted. This may result in the oxidation of more labile organic matter and may account for the very

high emissions associated with Canadian peatlands for example (Fig. 7) in comparison to countries where the deeper peat layers are extracted (Mander et al., 2012). However, the IP sites in this study are highly decomposed peat and have been abandoned for 30 years or more in some cases (e.g. IP4) and have remained unvegetated. It is possible that CO_2-C emissions from active extraction areas may be higher than those derived in this study given that over the summer period the surface of the peat is regularly scarified and aerated. However, Salm et al. (2012) reported higher emissions from abandoned areas in comparison to active areas, although colonisation by vegetation in the former may have accentuated respiration losses. High annual CO_2-C emissions following abandonment and recolonization have also been reported by Strack and Zuback (2013) and are in close agreement with the R_{eco} values reported here for the DP sites (Fig. 5).

We have estimated the contribution of heterotrophic respiration (R_H) to R_{eco} at 49%. Although, this is based on measurements at a single site (DP1), it is within the range reported by other studies (Frolking et al., 2002; Moore et al., 2002; Shurpali et al., 2008). The R_H values measured at DP1 (Fig.5) and estimated at DP2 are higher than the R_{eco} values at the IP sites, which would indicate that decomposition of the belowground biomass (following clipping) and subsequent "priming" effects may contribute significantly to CO_2-C dynamics at vegetated extraction sites. Furthermore, the methods employed to extract the peat at some of the DP sites (the peat is extruded onto the surface of the peatland from narrow openings made in the peat by a chain cutter) has led to the formation of deep fissures (ca. 4 cm wide and > 2m deep) within the peat that may enhance oxidation throughout the peat profile. Nonetheless, fissures (ca. 10 cm wide and > 1m deep) formed in the peat during climatically dry years and that were partially filled in during wetter/windier years were also observed at IP5 where the lowest annual emissions were observed.

4.5 Fire emission factors

The mean MCE reported here (0.837) is typical of smouldering combustion (e.g. Yokelson et al., 1996; Bertschi et al., 2003) and comparable with the reported range of MCE in other studies of high latitude peats (Yokelson et al., 1997; Stockwell et al., 2014). Emission factors for CO_2 and CO are also typical of smouldering combustion and similar to those from other peat studies, particularly Yokelson et al. (1997). As found in other studies of peat fire emissions, our measurements confirm that the CH_4 EF for Irish peat is particularly high (8.35 g kg^{-1} dry fuel burned) when compared with other forms of biomass burning. Given the high

Global Warming Potential, where each gram of emitted CH_4 is equivalent to 34 g of CO_2 (100 year time horizon, IPCC, 2013), the CH_4 emissions from Irish peat fires may account for over 12% of the CO_2-equivalent emissions. This result emphasises the importance of understanding the full suite of trace gas emissions from biomass burning, rather than focussing solely on CO_2 and CH_4 emissions. In general, the other EFs reported here lie within the range of variability observed by other peat burning studies, with the exception of NH_3, which is particularly low, possibly as a result of the nitrogen-poor soils that are typical of Irish and UK blanket bogs. Here, we also report the first C_2H_6 EF for peat (1.53 ± 0.17 g kg^{-1} dry fuel burned), similar in magnitude to C_2H_6 emissions from boreal forests (1.77 g kg^{-1} dry fuel burned) according to Akagi et al. (2011). However, the use of prescribed fire in the UK to burn off old heather growth to encourage new growth (e.g. the muirburn practice) may not impact the underlying peat to any great extent, given that the practice is restricted to the October-April period when soil moisture conditions are highest. Emissions result from the burning of the woody aboveground biomass, and the underlying peat is generally unaffected. In contrast, wildfires typically occur during the summer months when temperatures are highest and moisture levels are low, resulting in burning of both the vegetation and the peat itself. Indeed, recent work by Kettridge et al. (2015) has highlighted the vulnerability of drained peatlands, even at high latitudes, to increased risk of wildfire and subsequent vegetation changes.

4.6 Implications for National Inventory reporting

The ROI currently employs the 2006 GPG default value of 0.2 t CO_2-C ha^{-1} (nutrient poor) in reporting of all peat extraction areas, and estimated emissions for 2012 (the most recent assessment year) were 9,312 t CO_2-C yr^{-1} (Table 4). In contrast, the approach in the UK has been to differentiate between peat extracted for fuel and horticulture and then applying the default EFs for nutrient rich (1.1 t CO_2-C ha^{-1}) and nutrient poor peat (0.2 t CO_2-C ha^{-1}) respectively. For 2012, CO_2-C emissions from UK extraction peatlands were estimated at 2,118 t CO_2-C yr^{-1} (Table 4).

Reported annual emissions are likely to increase considerably if the Tier 1 values in the IPCC Wetlands Supplement are adopted by inventory compilers. We estimate that emissions from peatlands managed for extraction will be approximately 16 and 10 times higher for the ROI and UK respectively (Table 4). The EFs derived in this study for CO_2-$C_{on\ site}$ for both industrial and domestic peatlands (Table 2) are considerably lower than the Tier 1 value of

2.8 tonnes CO_2-C ha^{-1} yr^{-1} provided in the IPCC Wetlands Supplement (2014). Although the EFs derived in this study fall within the lower confidence margin of the Tier 1 range, our new EFs have a marked reduction in associated uncertainty. As the Tier 1 is a generic value based on published literature rather than a targeted measurement programme, it is naturally subject to a certain level of bias, which result when the underlying studies are not representative of management practices, climatic zones, or soil types in a particular region (Ogle et al., 2004), and may lead to either an over- or underestimation of CO_2-C emissions. Given that no significant difference exists between the EFs derived for the IP and DP sites in this study, we propose a single EF for CO_2-$C_{on\text{-}site}$ of 1.68 t CO_2-C ha^{-1} yr^{-1} to be applied to peatlands managed for extraction in the ROI and UK regardless of peat type. This EF value could be further disaggregated by regional climate, domestic peat extraction intensity (based on extraction rates) or by end use of the peat (horticulture or energy) if more data becomes available. For the latter, it would be highly useful to determine quantitatively whether CO_2-$C_{on\text{-}site}$ emissions vary between the less decomposed residual peat utilised for horticulture and the more decomposed residual peat used for energy production. As the EFs derived in this study have come from sites located within the same "climatic" region, we feel that they are more appropriate for the ROI and the UK inventory purposes than either the 2006 GPG or the 2013 Wetlands Supplement. If the CO_2-$C_{on\ site}$ EFs derived from this study are used in annual NIRs, we estimate that annual emissions would be 9.5 and 6 times higher for the ROI and UK respectively, in comparison to the emissions calculated with the 2006 GPG Tier 1 value, and 40% lower than emissions calculated with the Wetlands Supplement EF.

As reported CO_2-$C_{on\text{-}site}$ emissions are henceforth likely to be much higher for any country that moves from the 2006 GPG to the 2013 Wetlands Supplement, some consideration of potential mitigation measures is required. Wetland Drainage and Rewetting is a new elective activity under Article 3.4 of the Kyoto Protocol (second commitment period) and applies to all lands that have been drained since 1990 and to all lands that have been rewetted since 1990. Countries that elect to report under this activity will also be able to claim C benefits from the rewetting of drained peatlands. In theory, this should provide an impetus for the rewetting of high emitting land use categories such as peatlands managed for extraction, particularly as these areas will remain persistent long term emission hotspots in the absence of rewetting actions (Waddington et al., 2002).

4.7 Information gaps

Greenhouse gas emissions from peatlands used for extraction are composed of (a) on-site emissions (i.e. from peat extraction areas, ditches and stockpiles) and (b) off-site emissions associated with water borne losses and the use of the peat for energy or horticulture. In this paper, we have focused solely on the on-site CO_2-C emissions from the peat extraction areas, and GHG emissions from fire. However, C losses from other pathways may also be substantial. Research has shown that GHG emissions from on-site peat stockpiles and ditches are considerable (Alm et al., 2007a and references therein). Currently, emissions data from stockpiles in the temperate zone are not available and the IPCC Wetlands Supplement does not provide a Tier 1 value, and instead encourages countries to move to higher Tiers in terms of reporting (IPCC, 2014). However, countries such as Finland have developed a Tier 2 approach in which EFs (incl. CH_4 and N_2O) depend on regional weather and in which emissions from ditches and stockpiles are taken into account (Alm et al., 2007a; Lapveteläinen et al., 2007). The IPCC Wetlands Supplement provides Tier 1 EFs for CH_4 emissions from both peat extraction areas and from ditches. The value for the latter is particularly high (542 kg CH_4 ha^{-1} yr^{-1}, expressed per unit area of ditch surface) and indicates the importance of this pathway in the full GHG balance (Evans et al., 2015). Similarly, N_2O emissions have been shown to be significant from drained peatlands (Regina et al., 1996) yet despite this, there are only a small number of published studies and more research is critical in order to provide regional specific EFs. While CH_4 and N_2O fluxes have been quantified at some of the sites, the data is currently being processed with a view to publication in the future. In terms of the fire study, N_2O is a difficult gas to measure using the FTIR setup employed in this study, as it can only be determined from spectra with very large enhancements of trace gases. This is because the N_2O absorption occurs in a similar wave number region to both the CO_2 and CO absorption bands (Paton-Walsh et al., 2014). Paton-Walsh et al. (2014) could only determine N_2O from two of their five open fires, whilst Smith et al. (2014), who used a similar setup, failed to determine N_2O from any of their 21 fires studied. In our study, we found that excess mole fractions of N_2O could not be correlated to either CO_2 or CO for the determination of emission ratios, precluding the calculation of EFs. One explanation for this is that N_2O is predominantly a product of flaming combustion and is strongly correlated to CO_2 (Paton-Walsh et al., 2014). The lack of flaming combustion in our peat burns probably explains our inability to detect significant excess N_2O mole fractions.

Other pathways may be of equal importance. For example, the loss of POC from bare peat surfaces may be considerable where the surface is exposed and subject to wind or water

erosion (Evans et al., 2006; Lindsay, 2010). While some of the windborne POC is likely to be deposited within the extraction field itself, a proportion undoubtedly leaves the peatland, although there are currently few data available to quantify losses from either wind or water erosion, or the extent to which POC is converted to CO_2 (IPCC, 2014). In addition, high losses of DOC from drained peatlands have been reported (Evans et al., 2015 and references therein). Although a Tier 1 EF value for DOC is provided in the IPCC Wetlands Supplement, disaggregated by climate zone, with the assumption that 90% of the exported DOC is converted to CO_2, there is an obvious need to quantify these losses on a regional basis given the high precipitation loads experienced by the ROI and the UK, and associated differences in peat type (Evans et al., 2015). Emissions from burning are not currently reported in either the ROI or UK inventory reports. The EF provided in the IPCC Wetlands Supplement for CO_2 emissions associated with wildfire burning is similar to our value here (Table 3). Furthermore, given the high CH_4 emissions associated with the burning of the peat that we have reported here (Table 3), and taking cognisance of the strong GWP of CH_4, more research is urgently required to quantify this emission pathway, particularly under field conditions.

The provision of activity data for inventory reporting varies between the ROI and the UK, with the peat extraction industry the source of data in the former (Duffy et al., 2014), and a multi-source approach (Directory of Mines and Quarries point locations with Google Earth imagery, scientific reports/papers) used in the latter (Webb et al., 2014). However, CO_2 emissions from domestic peat extraction in the ROI are not currently reported due to a lack of activity data and could potentially be very high (Wilson et al., 2013b). In the UK, areas under domestic extraction are included in the Grassland category but may be moved as the UK considers changes post-Wetlands Supplement. Determining to what degree that peatlands have been affected by domestic peat extraction and how far those impacts extend into the main peatland area are obvious challenges facing future research. The use of remote sensing platforms could provide high resolution data that will be able to differentiate between domestic peat extraction and other types of disturbed peatlands. In particular, the use of Unmanned Aerial Vehicles (i.e. drones), which have been used to map individual peatlands at a very high resolution (e.g. Knoth et al., 2013) offer considerable potential for more detailed mapping of domestic peatlands at the national scale.

5 Conclusion

Peatlands managed for extraction are a substantial CO_2-C emissions hotspot at the landscape scale and further contribute to climate change through significant GHG emissions when the peat is burned or utilised in horticulture. This study, which measured and modelled emissions from a range of sites across the ROI and the UK, has highlighted the importance of generating robust Tier 2 values for different regions and land-use categories. Given that the IPCC Tier 1 EF was only based on 20 sites (all from Canada/Fenno-Scandia) we suggest that data from another 9 sites significantly expands the global dataset, as well as adding a new region.

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Table 1. Site characteristics. Mean annual air temperature (°C) and mean annual rainfall (mm yr^{-1}) are long-term values (1981-2010; Met Éireann http://www.met.ie/ and Met Office UK; http://www.metoffice.gov.uk). *Time between cessation of peat extraction and the study period.

Site name	Boora	Blackwater	Bellacorick	Turraun	Middlemuir Moss	Little Woolden	Clara	Glenlahan	Moyarwood
Site code	IP1	IP2	IP3	IP4	IP5	IP6	DP1	DP2	DP3
Time since last extraction*	>20 years	>25 years	>10 years	>30 years	>10 years	ca. 1	0	>20 years	>20 years
Study period	1/9/2007: 30/8/2009	1/5/2011: 30/4/2014	1/1/2012: 31/12/2013	1/1/2002: 31/12/2003	1/11/2003: 31/10/2004	1/1/2013: 31/12/2014	1/4/2006: 31/3/2007	1/4/2006: 31/3/2007	1/4/2013: 31/3/2014
Latitude	53.203	53.297	54.128	53.260	57.60	53.451	53.316	53.103	53.346
Longitude	-7.726	-7.965	-9.556	-7.720	-2.15	-2.468	-7.647	-7.538	-8.514
Sub-region	Irish Midlands	Irish Midlands	North-West Ireland	Irish Midlands	North-East Scotland	Northern England	Irish Midlands	Irish Midlands	Western Ireland
Mean annual air temperature (°C)	9.3	9.8	10.3	9.3	8.0	10.2	9.3	9.3	10.0
Mean annual rainfall (mm yr^{-1})	970	907	1245	807	851	867	970	804	1193
Vegetation							*Calluna vulgaris*, *Erica. tetralix*, *Cladonia* sp.		
Peat type	Phragmites	Phragmites	Cyperaceous	Phragmites	Sphagnum/ Cyperaceous	Sphagnum/ Cyperaceous	Sphagnum	Ericaceous	Sphagnum
von Post scale	H7	H7	H5 to 6	H7	H8	H6 to 7	H6	H6	H6
Parent material	Limestone	Limestone	Shale	Limestone	Granite drifts and rocks	Triassic Sandstone	Limestone	Old Red Sandstone	Limestone
Peat depth (m)	1.0	1.5	0.5	0.5-1.8	0.7-3.1	0.5-1.75	4	0.4	4.4
pH	4.3	4.9	3.8	6.3	3.6-4.1	2.9	4.0	3.8	4.4
C (%)	50	52.4	56	52	52	49.1	49.8	29.1	51.5
N (%)	1.09	2.14	0.97	2.1	1.4	1.34	1.46	0.69	1.32
C:N	45.9	24.5	57.7	24.8	37	36.6	34.1	42.2	39

Table 2. Emission factors (tonnes CO_2-C ha^{-1} yr^{-1}) for sites IP1-6 and DP1-3.

Uncertainties are 95% confidence intervals.

Site	CO_2-C (t ha^{-1} yr^{-1})	95% confidence interval (t ha^{-1} yr^{-1})	
IP1	1.82	1.75	1.89
IP2	1.53	1.37	1.60
IP3	1.38	1.25	1.52
IP4	2.86	2.65	3.06
IP5	0.93	0.59	1.27
IP6	1.70	1.43	1.98
Emission factor	**1.70**	**1.23**	**2.17**
DP1	1.76	1.59	1.99
DP2	2.03	1.73	2.30
DP3	1.14	0.85	1.41
Emission factor	**1.64**	**1.22**	**2.06**

Table 3. Mean modified combustion efficiency (MCE) and emission factors (g kg^{-1} dry fuel burned) reported by this study and those for the same trace gases reported by previous studies of temperate or boreal peat (Yokelson et al. 1997; Stockwell et al. 2014). The mean and standard deviation of the emission factor is calculated from individual sample burns. *nr*=not reported.

	Emission Factor (g kg^{-1} dry fuel burned)			
Trace Gas	Irish sphagnum moss peat (this study)	Canadian boreal peat (Stockwell et al. 2014)	North Carolina temperate peat (Stockwell et al. 2014)	Alaska/Minnesota peat (Yokelson et al. 1997)
MCE	0.837 ± 0.019	0.805 ± 0.009	0.726 ± 0.009	0.809 ± 0.033
CO_2	1346 ± 31	1274 ± 19	1066 ± 287	1395 ± 52
CO	218 ± 22	197 ± 9	276 ± 139	209 ± 68
CH_4	8.35 ± 1.3	6.25 ± 2.17	10.9 ± 5.3	6.85 ± 5.66
C_2H_4	1.74 ± 0.23	0.81 ± 0.29	1.27 ± 0.51	1.37 ± 0.51
C_2H_6	1.53 ± 0.17	*nr*	*nr*	*nr*
CH_3OH	0.60 ± 0.87	0.75 ± 0.35	2.83 ±2.87	4.04 ± 3.43
HCN	2.21 ± 0.35	1.77 ± 0.55	4.45 ± 3.02	5.09 ± 5.64
NH_3	0.73 ± 0.50	2.21 ± 0.24	1.87 ± 0.37	8.76 ± 13.76

Table 4. Annual CO_2-C emissions (tonnes CO_2-C yr^{-1}) from peatlands managed for extraction in the ROI and UK calculated using the IPCC 2006 Good Practice Guidance (Tier 1 value: 0.2 and 1.1 t CO_2-C ha^{-1} $yr^{-1}$for nutrient poor and nutrient rich peatlands respectively), the IPCC 2013 Wetlands Supplement (Tier 1 value: 2.8 t CO_2-C ha^{-1} yr^{-1}) and the Emission Factors derived in this study (Table 2). Areas (ha) and CO_2-C emissions using the IPCC 2006 Good Practice Guidance values are taken from the 2014 National Inventory Reports (NIR) for the ROI (Duffy et al., 2014) and the UK (Webb et al., 2014).

Country	Area (ha)	Emissions (tonnes CO_2-C yr^{-1})		
		IPCC 2006	IPCC 2013	This study
ROI	52,422	9,312	146,782	88,069
England	4,790	960	13,412	8,047
Scotland	1,610	545	4,508	2,705
Wales	482	95	1,350	810
N. Ireland	1,030	518	2,884	1,730
UK	7,912	2,118	22,154	13,292

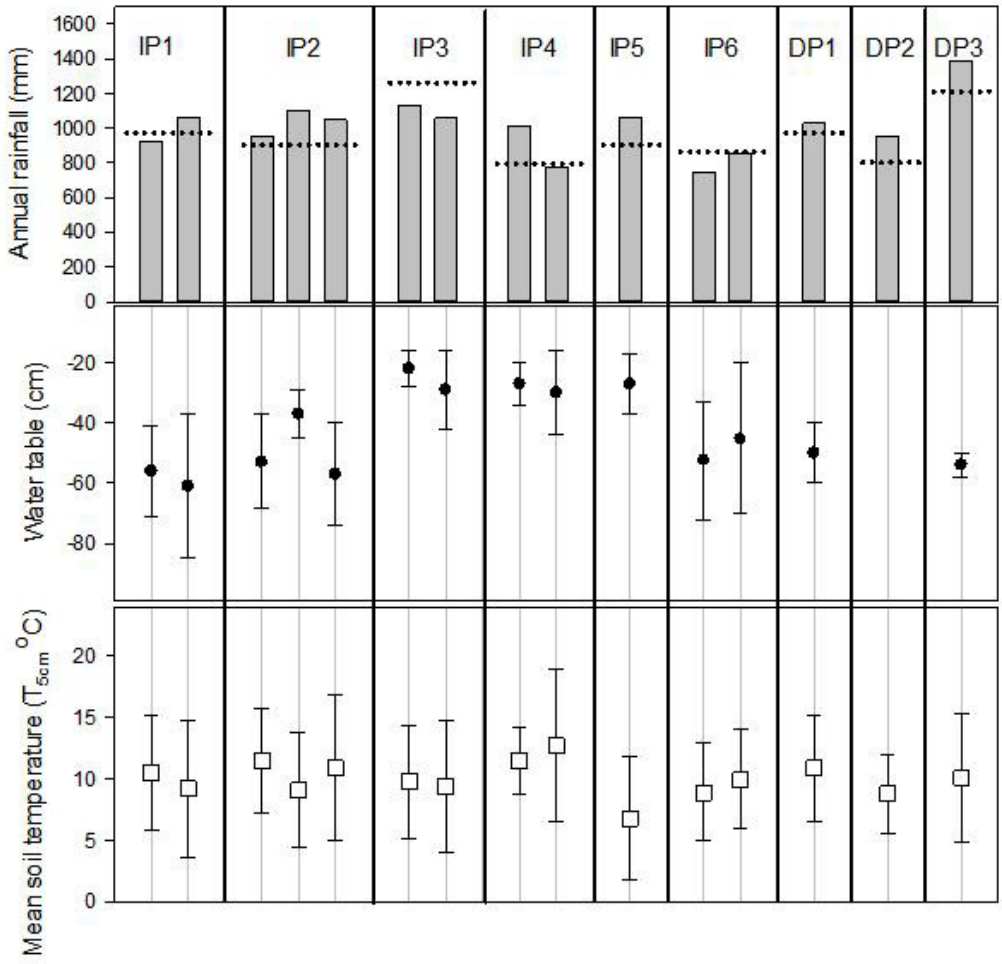

Figure 1. Annual rainfall (mm), mean annual water tables (cm), mean annual temperature (°C) at 5 cm depths (T_{5cm}) at sites IP1 (two years), IP2 (three years), IP3 (two years), IP4 (two years), IP5 (one year), IP6 (two years), DP1 (one year), DP2 (one year) and DP3 (one year). Dotted horizontal line indicates 30 year mean rainfall at each site (1981-2010; Met Éireann http://www.met.ie/ and Met Office UK; http://www.metoffice.gov.uk). Error bars are standard deviations. Negative water table values indicate water level below the soil surface.

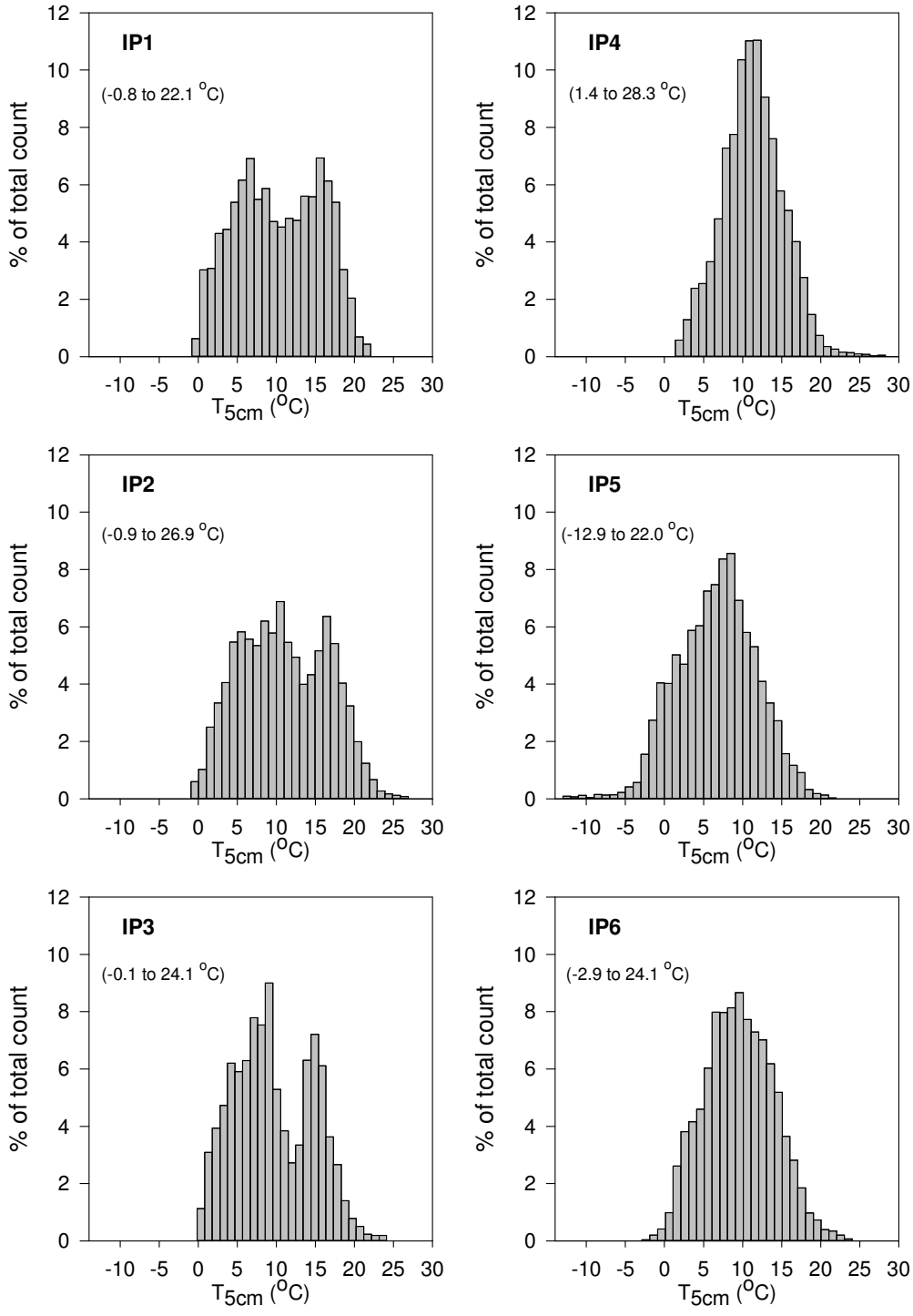

Figure 2. Frequency distribution of soil temperature at 5cm depth (T_{5cm}) at sites IP1-6 shown as a percentage (%) of total count. Measured temperature range (°C) at each site shown in parenthesis.

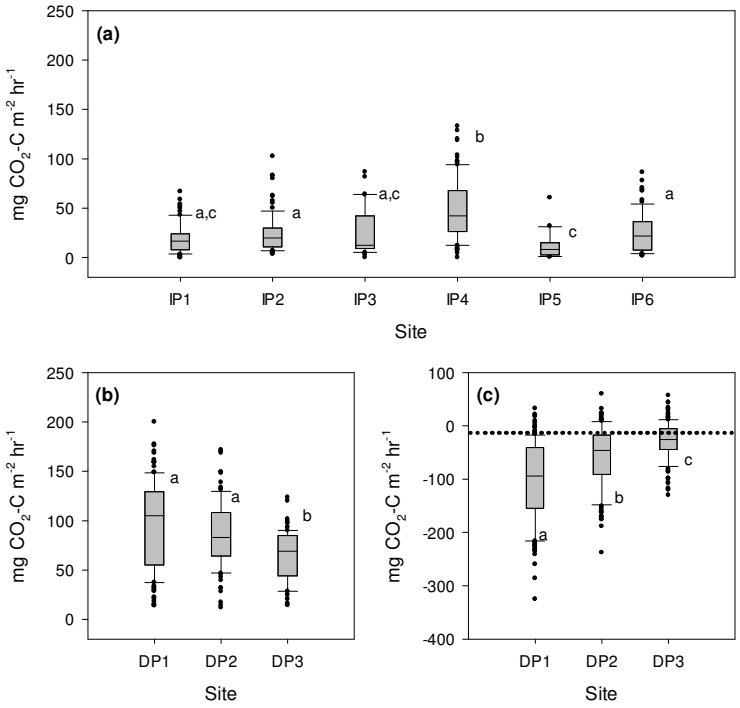

Figure 3. (a) Ecosystem respiration (R_{eco}; mg CO_2-C m^{-2} hr^{-1}) at sites IP1-6, (b) R_{eco} (mg CO_2-C m^{-2} hr^{-1}) at sites DP1-3 and (c) net ecosystem exchange (NEE; mg CO_2-C m^{-2} hr^{-1}) when PPFD>1000 µmol m^{-2} s^{-1} at sites DP1-3. Positive values indicate CO_2-C flux from the peatland to the atmosphere (source) and negative values indicate CO_2-C flux from the atmosphere to the peatland (sink). The 10th and 90th percentile are indicated by the bars, the 25th and 75th percentiles with the top and bottom of the box and the median value by the centre line. Different letters indicate significant differences in the *post-hoc* test for multiple comparisons.

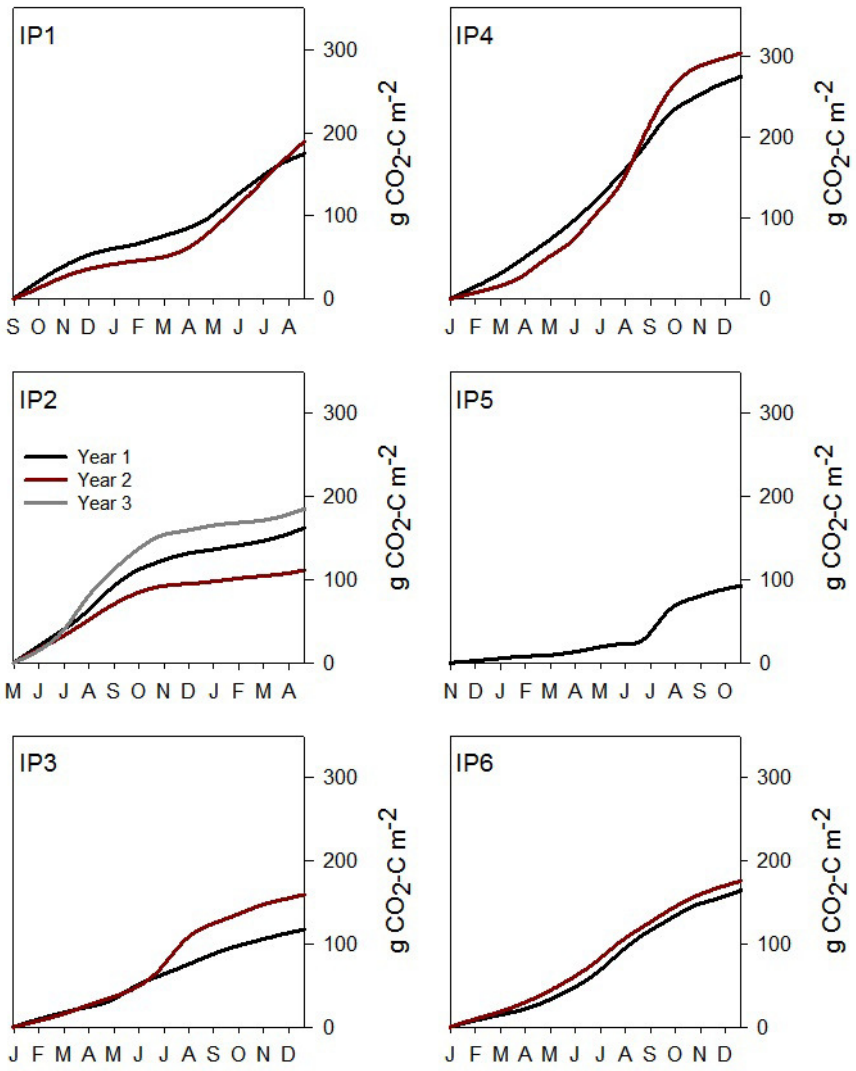

Figure 4. Annual cumulative ecosystem respiration (R_{eco}: g CO_2-C m^{-2}) at sites IP1-6. Positive values indicate CO_2-C flux from the peatland to the atmosphere (source). Value at end of the curve indicates the total annual R_{eco} value. Brown line indicates year 1, black line year 2 and grey line year 3 of the study at the individual sites. Note the differences in integration period between sites (x axis).

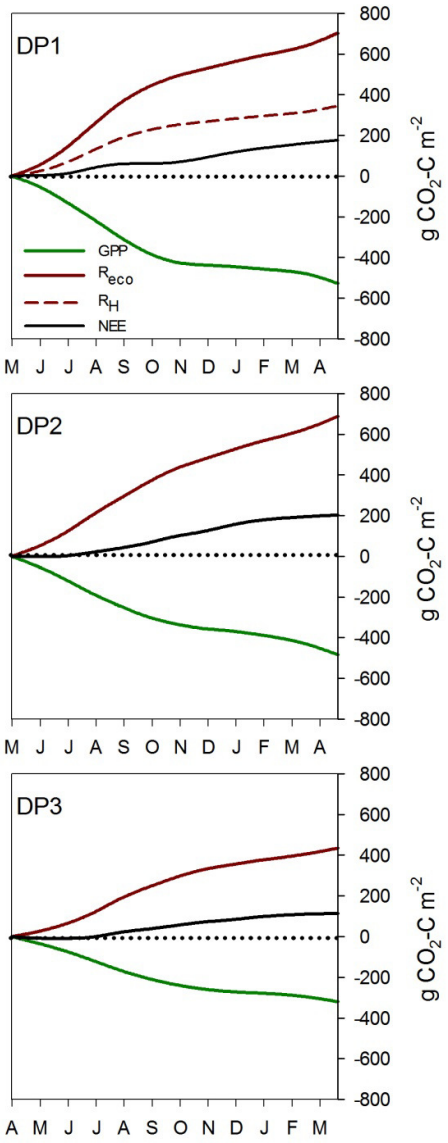

Figure 5. Annual cumulative gross primary productivity (GPP: g CO_2-C m^{-2}), ecosystem respiration (R_{eco}: g CO_2-C m^{-2}), heterotrophic respiration (R_H: Site DP1 only) and net ecosystem exchange (NEE: g CO_2-C m^{-2}) at sites DP1-3. Positive values indicate CO_2-C flux from the peatland to the atmosphere (source) and negative values indicate CO_2-C flux from the atmosphere to the peatland (sink). Value at end of the curve indicates the total annual value for each component. Note the differences in integration period between sites (x axis).

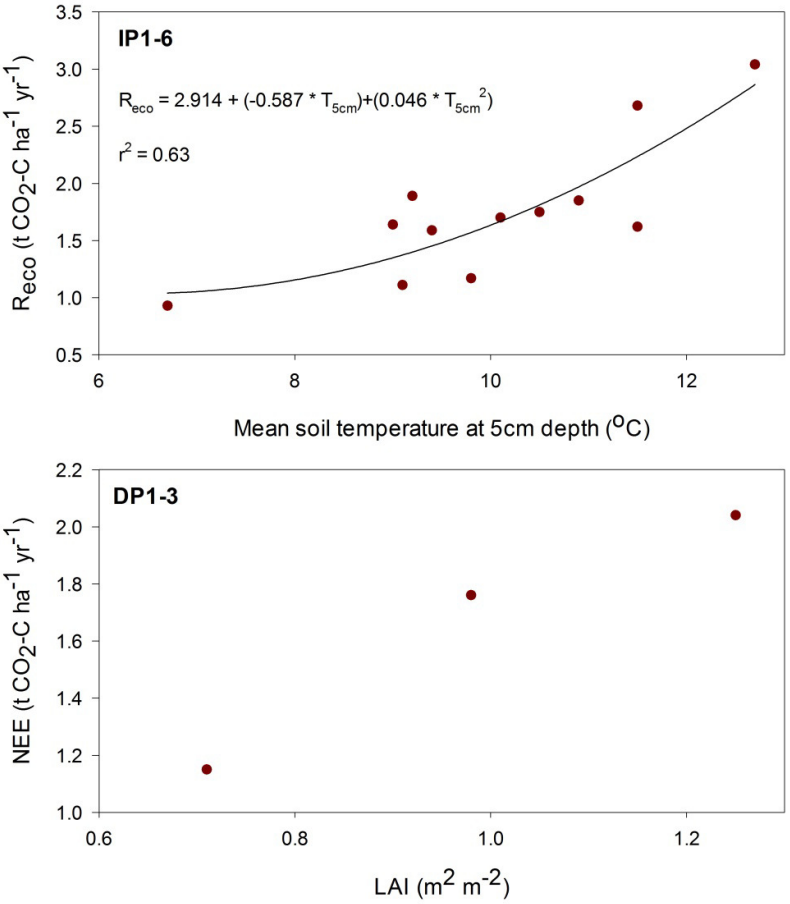

Figure 6. Relationship between (a) ecosystem respiration (R_{eco}: t CO_2-C ha^{-1} yr^{-1}) and mean soil temperature (°C) at 5 cm depth at the IP sites and (b) net ecosystem exchange (NEE: t CO_2-C ha^{-1} yr^{-1}) and leaf area index (LAI: m^2 m^{-2}). Circles indicate an annual value.

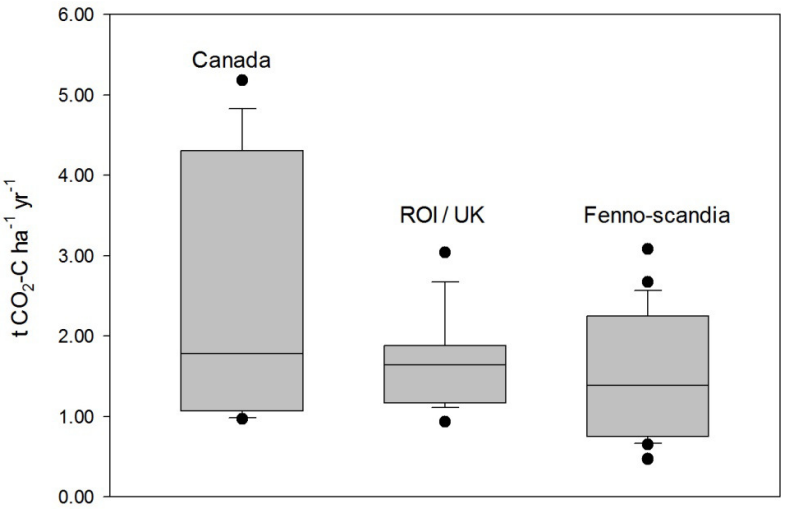

Figure 7. Carbon dioxide emissions (t CO_2-C ha^{-1} yr^{-1}) from peatlands managed for extraction in Canada, ROI/UK (this study) and Fenno-scandinavia. The 10th and 90th percentile are indicated by the bars, the 25th and 75th percentiles with the top and bottom of the box and the median value by the centre line.

(Data for Canada and Fenno-Scandia taken from the following studies; Tuittila and Komulainen, 1995; Sundh et al., 2000; Waddington et al., 2002; Glatzel et al., 2003; McNeil and Waddington, 2003; Tuittila et al., 2004; Cleary et al., 2005; Alm et al., 2007a; Shurpali et al., 2008; Waddington et al., 2010; Järveoja et al., 2012; Mander et al., 2012; Salm et al., 2012; Strack et al., 2014). Where studies reported seasonal fluxes (typically May to October), these were converted to annual fluxes by assuming that 15% of the flux occurs in the non-growing season (Saarnio et al., 2007).