Investigation of peatland restoration (grip blocking) techniques to achieve best outcomes for methane and greenhouse gas emissions/balance.

Field Trials and Process Experiments Final Report

Defra Project SP1202

Status: final version

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Key point summary

The overall aim of project SP1202 is to provide information which can be used to identify blanket peatland restoration or re-wetting methods yielding the lowest global warming potential (GWP). Of particular interest is whether increased methane (CH_4) emissions from restored blanket peatland offset reductions in net carbon dioxide loss when drained peatlands are re-wetted.

SP1202 was divided into four parts and the main results from each part are summarised below.

1. Update to the literature review on Defra SP0574.

The purpose of this additional literature review was to update the review undertaken for Defra SP0574. The main findings of the additional review were:

- Re-profiling or **partial infilling of ditches**, in particular with peat scraped from the peatland surface adjacent to the ditch, **may prove increasingly popular as a blanket peatland restoration method**. We also found that heather bales are used for ditch infilling as well as for dams.
- Additional studies confirm that **sedges are associated with higher CH_4 emissions from peatlands than areas dominated by *Sphagnum* mosses**. However, it is not clear whether *Sphagnum* will always increase in cover with time after restoration.
- The evidence-base regarding increases in CH_4 emissions after restoration of peatlands is still limited. It is sometimes assumed that the post-restoration increase in CH_4 emissions, if one occurs, will be short-lived (five-10 years), especially in bogs, as *Sphagnum* recolonises a site. However, the only study we could find of an old, well-established restored site suggests that **CH_4 emissions can remain high and that a restored peatland with close to natural plant assemblages may not be a strong C sink**.

2. Laboratory mesocosm experiments were undertaken to investigate (a) how different methods of blocking drainage ditches (grips) affect greenhouse gas fluxes to and from the grip, and (b) how different plant functional types (heather, *Sphagnum* moss, cotton grass (a type of sedge)) affect the carbon budget of re-wetted peat. These experiments were carried out at the Open University between 2010 and 2011 and the results reported to Defra in 2011[1] . This experimental work was also published in the journal *Wetlands Ecology and Management* in 2014[2]. The work found that:

- **Methane (CH_4) emissions and global warming potential (GWP) were affected by ditch blocking method.** Ditches with no infill or which had been colonised by a mat of *Sphagnum* mosses had a lower GWP than ditches that had been partially infilled and dammed and ditches blocked with heather bales. Heather bale dams may be susceptible to rapid decomposition and may be prone to failure.
- **In areas of re-wetted peatland between blocked drainage ditches, plant functional type affected CH_4 emissions but not GWP;** this is because differences in CO_2 exchanges between the plant types offset differences in CH_4 emissions. When considering radiative forcing, this finding suggests that it does not matter which plant type dominates a re-wetted area.

3. A fully replicated, long-term field trial was conducted on a blanket peatland in a catchment of the Upper Conwy in North Wales. Twelve ditches were investigated. After an initial period of monitoring, four of these ditches were left open, four were dammed with peat (no infilling) and four were partially infilled with peat and dammed (called re-profiling). The results from the field trials are the subject of the current report. The key findings are:

- **Substantial changes in hydrological conditions occurred after ditch blocking.** Post-blocking there have been significant changes to the size and shape of the catchments of the experimental ditches and a substantial reduction (five fold) in flow down blocked ditches. The effect of ditch blocking has been to divert flow to areas between ditches where it flows downhill as surface (overland) flow and as shallow subsurface flow. In the blocked ditches there has been an increase in baseflow over time that has not been

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[1] See: http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=16991

[2] See Green *et al*. (2014).

seen in the open (unblocked) ditches. The cause of this increase is unclear but it may be related to the dams in blocked ditches developing leaks over time.

• **Ditch blocking had a modest effect on blanket peatland water tables at the study site.** Water tables on the site are shallow, and any effect of ditch blocking on local water tables has been generally small (on average less than 2 cm over distances of 1-3 m from the drainage ditch) although spatially highly variable. When a strict statistical test is applied to post-blocking water-table data, there is no significant difference in water tables between open and blocked ditches.

• **CH_4 fluxes and GWP showed no evidence of varying systematically between the drained and re-wetted blanket peatland or between the different types of re-wetted peatland in the four-year period after management interventions.** This finding applies to both ditch channels (whether open, dammed, or re-profiled) and the areas between the ditches at the study site.

• **There was no unequivocal evidence that CH_4 fluxes or GWP changed systematically over time in any of the management interventions (open ditches, dammed ditches, re-profiled ditches) at the study site.**

• **Overall, GWP was positive for the first three years of the study; the study peatland, even in restored areas, was radiatively forcing. During the fourth year GWP became negative (radiative cooling) which is likely to be a consequence of the differences in meteorological conditions between the years of study.**

• **There has been no obvious short-term (four year) GWP benefit from re-wetting of the study site**.

• **Post blocking, waterborne carbon fluxes from the site differed in terms of the pathway taken but not in terms of overall carbon load.** In drained areas most carbon leaves the site via ditch flow. Where ditches are blocked, more waterborne carbon leaves the site via surface (overland) flow and shallow subsurface flow. This implies that, at the catchment scale, any changes in waterborne carbon concentrations and fluxes in the period following blanket bog re-wetting may be minor.

• **Currently, there is no evidence that drain blocking has had an effect on the vegetation at the site.** The abundance of sedges (mostly cotton grasses) is high in the areas adjacent to ditches across all treatments (open ditches, dammed ditches, re-profiled ditches). There has been significant variability in sedge and *Sphagnum* moss abundance over time, but this variability is not systematic and may be related to variations in meteorological conditions.

4. Laboratory and in-field process studies have been used to elucidate how CH_4 production and oxidation are affected by re-wetting. The main finding of this work is that:

• **Microbial CH_4 production potential and CH_4 oxidation have not been not been significantly influenced by short term changes in ditch management conditions.**

1. Aim, objectives, and background

1.1 Project aim and objectives

The overall aim of project SP1202 is to **review restoration methods used in blanket peatlands and to identify, using laboratory and field experiments, those methods which produce the best outcomes in terms of reducing peatland methane (CH_4) emissions and global warming potential (GWP).** Overall, the project has four main objectives:

(a) To undertake a literature review of the materials and methods for ditch (grip) blocking and peatland restoration currently in use in the UK and the impacts of the techniques on greenhouse gas (GHG) emissions.

(b) To undertake controlled, small-scale laboratory experiments to examine how different ditch (grip) blocking techniques might affect GHG emissions from restored blanket peatland.

(c) To conduct larger-scale field trials of different ditch blocking methods to see how these affect GHG emissions from restored blanket peatland.

(d) To report the results of (a) to (c) in a format that can be easily understood by site managers and also in the international scientific literature.

The field trials (c) were complemented with some detailed process studies. These were carried out both in the lab. (with samples of peat taken from the field trials area) and in the field.

1.2 Previous reports and papers

The literature review (a) was completed in April 2010 and is reproduced as Appendix A. Papers being prepared from the project (see section 1.3 below) also contain more recent updates to the literature. A systematic literature review was undertaken in July 2014 to place the site used for the field experiments into the wider context of UK blanket peatlands. The systematic review is available as Appendix B (an Excel file) and is discussed briefly in section 2.1. The search terms and search engines used for the review are provided at the end of Appendix A.

The controlled laboratory experiments (b) were completed in 2011 and are presented in a separate report (**Green *et al.*, 2011**) available online from Defra[3]. The laboratory experiments have also been published in **Green *et al.* (2014)**. The main findings from this laboratory study are given in the keypoint summary at the beginning of this report and also in section 3.2.

1.3 The field trials

The most substantial part of the project has been field trials looking at how ditch (grip) blocking affects the carbon balance of blanket peatland. Many areas of blanket peatland have been drained using shallow ditches or grips, and there is interest in blocking these ditches on a large scale because of the perceived benefits that such blocking brings including hydrological (reduction of flood risk), ecological (return of wetland plants, invertebrates and birds), and carbon storage (return of carbon-sink function or reduction in carbon losses). The trials took place in a blanket peatland in a sub-catchment of the Upper Conwy in North Wales.

Although the focus of the study was methane (CH_4), peatland-atmosphere exchanges of carbon dioxide (CO_2) were also measured. Nitrous oxide (N_2O) fluxes were initially measured but were negligible, so measurements were discontinued. The net exchange of CO_2 between an ecosystem such as a peatland and the atmosphere is called net ecosystem exchange or NEE. Our measurements of NEE and CH_4 exchanges allowed us to estimate the global warming potential (GWP) of the peatland which is a measure of how net

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[3] See: http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=16991

GHG exchanges between an ecosystem and the atmosphere affect climate (see **Baird *et al.*, 2009** (Defra SP0574) for details). As well as GHG fluxes, waterborne fluxes of carbon from the study site – dissolved organic carbon (DOC), particulate organic carbon (POC) and dissolved inorganic carbon (DIC) – were measured. DOC and POC may later be mineralised and released as CH_4 and CO_2 from water bodies; hence, they can be regarded as a peatland-atmosphere exchange and should be accounted for when considering the carbon balance and GWP of a peatland (**Baird *et al.*, 2009**).

To provide data with which to calculate the waterborne fluxes and understand the controls on the gaseous C fluxes, we measured flow of water in both ditch channels and the areas between the ditches; we also measured water tables across the experimental site.

Finally, to help understand how ecological conditions at the site changed in response to re-wetting and to help with the modelling of CH_4 and CO_2 fluxes, we undertook two types of vegetation survey. The abundance, and in some cases the vigour (the robustness or size), of the different plant species found at the site were monitored once every year between August and October (inclusive) using a series of permanent 1 m × 1 m quadrats. Additionally, multiple digital photographs were taken each year of small plots (enclosed by collars) used for monitoring GHG fluxes; two of these photographs from each year of the study were used to estimate the abundance of key plant species in each plot.

1.4 The process studies

To complement the field experimental work, we undertook process studies to investigate whether microbial activity in the peat varied between the blocking treatments (see section 2.2), and with the plant types growing in the peat. Laboratory experiments were conducted on peat samples taken from the site to assay how CH_4 production potential and CH_4 oxidation vary between blocking treatment and plant type. A separate set of peat samples was used to characterise more directly the structure of the microbial communities in the soil. Finally, in-field tracer tests were used to measure (a) differences in rates of CH_4 oxidation between the blocking treatments and (b) CH_4 oxidation in peatland with intact carpets of *Sphagnum* moss, and with the carpets removed.

1.5 Layout of this report

In agreement with Defra, the principal outcomes of this project are being prepared as papers for submission to peer-reviewed, international journals as follows. The detailed analyses that will be reported in the papers are given in the appendices as follows:
(a) Appendix C: hydrological 'behaviour' of the different field trial treatments.
(b) Appendix D: fluxes of CH_4 and CO_2 from the different treatments and any differences between the treatments in terms of these fluxes.
(c) Appendix E: waterborne carbon fluxes from the different treatments.
(d) Appendix F: processes controlling the production and consumption of CH_4 in restored blanket peatland.
(e) Appendix G: the effect of ditch blocking or re-wetting on blanket peatland vegetation.

In section 3 the main findings of each block of work reported in the appendices are presented in simple, non-technical language and in a little more detail than in the key point summary which precedes section 1. Section 3 also contains the main findings of the literature review and the mesocosm study. Section 2 provides background information on the site used for the field experiments and on the measurements that were made.

2. Field site description and data collection programme

2.1 Field site

The study was carried out on part of the Migneint blanket bog in the upper Conwy catchment in North Wales (latitude 52.97°N, longitude 3.84°W). The primary focus of the study was an area of hillslope located at approximately 500 m above sea level, with a total drainage area of ~ 2 ha, drained by a set of 12 parallel ditches running approximately downslope (see Figure 2.1). The ditches had a mean spacing of 16 m (range 11 to 26 m), mean slope of 4.5° (range 3.9 to 5.1°), and a mean length of 99 m (range 84 to 107 m). The ditches were mostly shallow and in some cases overgrown by vegetation, although all were hydrologically functional at the start of the experiment. Measured peat depth in the study area ranged from around 0.5 to 2.5 m, and vegetation comprised a typical blanket mire assemblage including *Calluna vulgaris* (Common Heather), *Eriophorum vaginatum* (Hare's Tail Cotton Grass) and various species of *Sphagnum* (Bog Mosses). The peat in this area overlies Cambrian mudstones and siltstones (**Lynas, 1973**) which appear to be largely hydrologically isolated from the overlying peat.

An important consideration was the wider representativeness of the site; in other words, how well results from the field site could be applied to other UK blanket peatlands. In order to put the site into such a context we characterised the physical and chemical properties of the peat in the experimental area and undertook a systematic review of the academic, professional and grey literature to collate information on other UK blanket peatlands. For the physical and chemical survey, 12 square-sectioned (5 cm × 5 cm) cores of peat 40-50 cm in length were extracted from the field site in October 2013. Core sets (comprising three cores associated with a single ditch) were extracted 3-4 m from the edges of four ditches that were left unblocked (open) throughout the experiment. One core from each ditch set was analysed in detail at 5-cm intervals (0-5 cm, 5-10 cm, 10-15 cm and so forth). The remaining two cores had sub-samples analysed from the top (0-10 cm), middle (15-25 cm) and bottom (30-40 cm) of the profile. Cores were assessed for their degree of humification (von Post scale), bulk density, volumetric water content, organic matter content (loss on ignition – LOI), carbon to nitrogen ratio (C:N), pH (H_2O and $CaCl_2$) and electrical conductivity. Table 2.1 provides a summary of these properties disaggregated by depth.

There is a limited literature on the soil physical and chemical properties of UK blanket peats, with few studies providing a comprehensive assessment. Our systematic review of the literature contains further details and is available as Appendix B (Excel file) (for search terms and search engines see section 6 of Appendix A). From what has been published, our study site is similar to other UK blanket peatlands. The bulk density of the peat at the site is within the published range (mostly 0.02 - 0.3 g cm^{-3}) (**Coggins *et al.*, 2006**; **Finnegan *et al.*, 2014**; **Holden *et al.*, 2011**), as is pH (H_2O), with other UK sites ranging between pH 3.6 and pH 4.3 (e.g., **Adamson *et al.* (2001)**, and **Clark *et al.* (2005)**), and C:N (26.7 to 46.8 – **Clark *et al.* (2005)**). Finally, LOI at the study site is within the range reported within the literature although somewhat to the upper part of this range (**Adamson *et al.* (2001)** 90-94 %; **Clark *et al.* (2005)** 92.5%; **Crowe *et al.* (2008)** 90-98%; **Finnegan *et al.* (2014)** 98-100%). LOI varies according to measurement method (temperature of ignition in particular) and position in peatland (in some blanket peatlands mineral 'wash-in' across a peatland surface may occur where natural peat pipes discharge at the surface). This mineral mater can be incorporated into the growing peat and will give a lower LOI value. Dust deposition from surrounding agricultural land can also affect LOI.

Table 2.1. *Soil physical and chemical parameters (*n *= 12). Parentheses contain standard deviation.*

Depth (cm)	Bulk density (g cm^{-3})	Volumetric water content (cm cm^{-3})	Loss on ignition (%)	pH (H_2O)	pH ($CaCl_2$)	Conductivity (H_2O μS cm^{-1})	C:N
0 - 10	0.08 (0.02)	0.77 (0.18)	98.8 (2.74)	3.80 (0.15)	2.98 (0.05)	61.6 (18.8)	36.6 (10.9)
15 - 25	0.10 (0.03)	0.96 (0.12)	99.6 (0.32)	3.62 (0.11)	2.97 (0.05)	81.2 (13.6)	30.0 (5.33)
30 - 40	0.11 (0.03)	0.91 (0.12)	99.7 (0.10)	3.63 (0.18)	2.95 (0.05)	79.2 (16.5)	34.8 (7.54)

Hydrological and GHG measurements and water sampling at the site took place between July 2010 and February 2015, although much of this report considers the period from 1st March 2011 after which the experiment was formally started (see section 2.2). For reporting purposes we have divided the experimental period into project years as follows: March 2011 – February 2012 (2011/12, Year 1), March 2012 – February 2013 (2012/13, Year 2), March 2013 – February 2014 (2013/14, Year 3) and March 2014 – February 2015 (2014/15, Year 4).

Meteorological conditions were highly variable over the 48 months from March 2011 and are summarised in Figure 2.2. The study site had an annual mean air temperature of 7.8 °C (March 2011 - March 2012 – Year 1), 6.5 °C (2012/13 – Year 2), 6.9°C (2013/14 – Year 3) and 7.6°C (2014/15 – Year 4). In the same period, the rainfall for each project year was 2255, 2409, 1786 and 1936 mm, respectively. Year 3 had a substantially drier summer (Jun, Jul, Aug) than the previous two years. The cold winter of 2012-2013 and very cold early spring of 2013 stand out, as does the late winter and early spring drought and high temperatures of February-March 2012 (Figure 2.2).

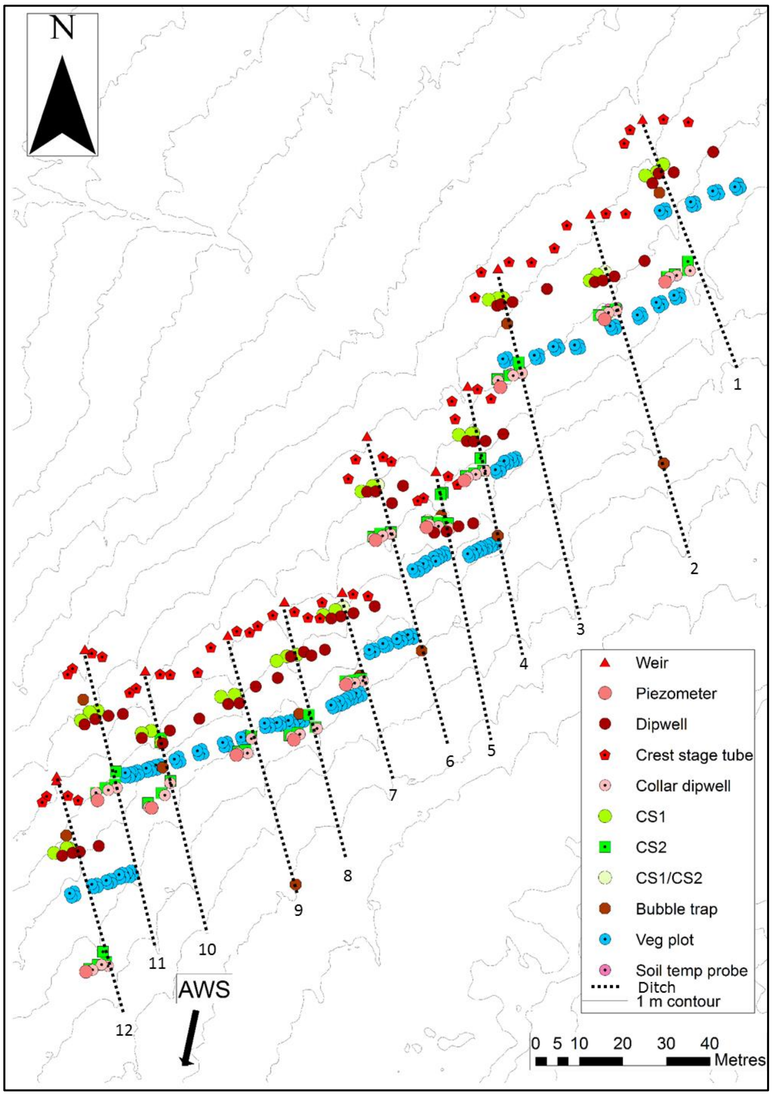

Figure 2.1. *Schematic of the experimental area. The number of each ditch is shown as well as the approximate location of the weirs at the downslope end of each ditch (red filled triangle). Meteorological data were collected using an on-site automatic weather station (AWS), the location of which is also indicated. 'CS' denotes collars used for measurement of methane and carbon dioxide fluxes.*

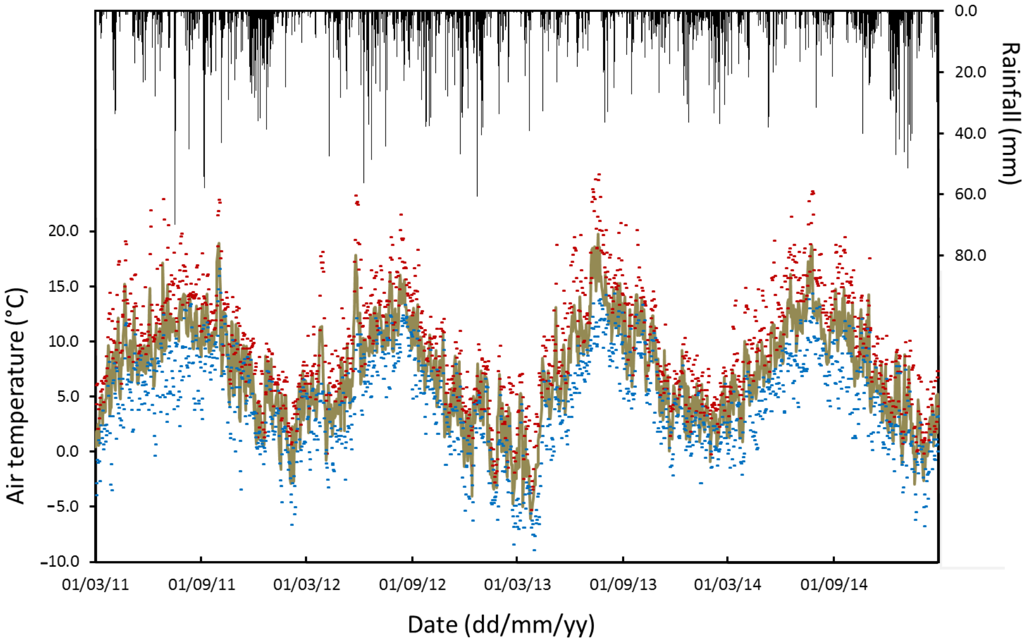

Figure 2.2. *Meteorological conditions at the experimental site between 1st March 2011 and 28th February 2015. The black bars indicate daily rainfall. Average daily air temperature is denoted by the green-brown line, daily high temperature by the red dashes and daily low by the blue dashes.*

2.2 Experimental design and measurement summary

In February 2011, eight of the 12 study ditches were blocked using two different methods, and four open ditches were retained as controls. The assignment of the ditches to different treatments took account of their measured pre-blocking discharge rate and position on the hillslope and was undertaken by David Cooper, a statistician at CEH Bangor. The two ditch-blocking methods used were damming and re-profiling+damming (henceforth just called re-profiling). For the dammed treatment, peat dams were constructed at regular intervals along the ditch using peat extracted from 'borrow pits' adjacent to the ditch, creating a sequence of pools behind the dams. For ditches in the re-profiling treatment, ditch vegetation was removed, the peat base of the ditch compressed to destroy any natural pipes that may be present, the ditch partially infilled with peat scraped from inter-ditch areas, and the vegetation replaced. This treatment also involved the construction of peat dams, but pools tended to be shallower or absent due to the partial infilling of the ditch. Above all dams, small channels were created with the intention of channelling water back onto the bog surface in the inter-ditch area rather than it following the original drainage line. Table 2.2 indicates the grips, by number, in each treatment (see also Figure 2.1).

Table 2.2. *The identity of the grips assigned to each treatment (see also Figure 2.1.).*

Replicate #:	Control	Dammed	Re-profiled
a	6	12	3
b	2	4	1
c	7	5	8
d	9	10	11

A summary of the measurements made at the field trials is given in section 1.3; details of measurement locations and measurement methods can be found in Appendices C to G (see also Figure 2.1).

Excluding meteorological conditions, the hydrological functioning of the site was monitored as follows:

- Water discharge down open and dammed ditches: v-notch weirs logged every 15 minutes.
- Overland flow: v-notch weir boxes logged every 15 minutes.
- Water tables (automatic): 24 dipwells logged every 2 hours.

- Water tables (manual): 59 wells logged every 3-6 weeks.

Greenhouse gas fluxes at the site were measured using a total of 2818 dark chamber tests and 1426 light chamber tests for CH_4 fluxes and 1654 dark and 1654 light chamber tests for CO_2. Two sets of collars, to which flux chambers were fitted during tests, were used: 36 in set 1 and 48 in set 2 (see Appendix D). Readings in set 1 were taken mostly seasonally, while in set 2 they were taken every three to six weeks, with the higher frequency in the summer months. A total of 660 samples of water from the weirs were analysed for their chemical properties, while 1106 overland flow water and 540 soil water samples were also analysed. To our knowledge this represents the most detailed dataset ever collected for characterising the hydrological behaviour and C balance of a blanket peatland.

As noted in section 1.3 we undertook surveys of the vegetation at the site. Vegetation in the permanent quadrats was measured at the end of the growing season in each of 2010-2014, so included the pre-blocking condition. The collars used for flux chamber tests were photographed every time a test was done. A selection of these photographs was later analysed to determine the abundance of the plant species within them; the data from these were used for modelling CH_4 and CO_2 fluxes as is explained in Appendix D. The vegetation data from the quadrats and associated analyses are detailed in Appendix G.

2.3 Routine and campaign monitoring and quality control

Base-line data collection at the site started in July and August 2010, after all the field equipment had been installed. All equipment was removed on the 2nd February 2011, prior to the blocking of eight of the experimental grips by Dinsdale Moorland Services Ltd (Skipton, North Yorkshire, UK). Re-installation of the equipment was completed by 23rd February 2011, after which monitoring resumed until the end of August 2014.

Peat sampling for the laboratory-based work in the process study (section 1.4; Appendix F) took place in May 2012 (108 samples for the CH_4 production and oxidation assays) and November 2013 (36 samples to examine differences in peat bacterial and fungal community structure). The in-field experimental work to look at CH_4 oxidation took place in June 2014.

2.4 Data collation and project data sets

All project data have been collected and analysed using strict protocols that conform to Defra's and NERC's JCoP (Joint Code of Practice) standards. The protocols have been written as methods sheets and can be made available alongside the data files, although many of the latter contain quality assurance information within them anyway. Project data are stored at Leeds, and we are investigating using one of NERC's data repositories as an additional store.

3. Summary results

In this section, the main outcomes of each part of the project are provided in a little more detail than in the key point summary at the beginning of this report.

3.1 Supplement to the literature review on Defra SP0574

A detailed literature review on CH_4 emissions from peatlands, including damaged and re-wetted peatlands, was prepared for Defra in 2009 under contract SP0574[4]. For the current project (SP1202) an update to the SP0574 review was required, the main aim being to provide (a) the latest information on ditch (grip) blocking techniques used in UK blanket peatlands, and (b) the latest information on what is known about methane (CH_4) emissions from restored peatlands, especially blanket peatlands. The review was completed

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[4] See: http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=15992

in April 2010 and is reproduced in Appendix A. Over 20 reports and papers not included in the original review were consulted.

In preparing the review we gathered the latest information on grip blocking techniques used in the UK and this showed that re-profiling or partial infilling of ditches, in particular with peat scraped from the peatland surface adjacent to the ditch, may prove increasingly popular. It was also clear that heather bales are used for ditch infilling as well as for dams or 'filters'.

The updated review confirms that sedges are associated with higher CH_4 emissions than peatland areas dominated by *Sphagnum* mosses. In the update we caution against over-interpreting a single study by **Frenzel and Karofeld (2000)**. The study is given particular prominence in an extensive review by **Lindsay (2010)**, and suggests that *Sphagnum*, through its hosting of methanotrophs (methane-consuming bacteria), may remove almost all of the CH_4 that is produced in the peat profile. However, other studies have shown that CH_4 emissions can still be quite high from *Sphagnum*-dominated areas. In addition, it is not clear whether *Sphagnum* will always increase in cover with time after restoration (see below).

The evidence-base regarding changes in CH_4 emissions after the re-wetting of peatlands is still limited. For example, only five studies were found by **Bussell *et al.* (2010)** who undertook a systematic review and meta-analysis of papers and reports published up to the beginning of September 2008. It is sometimes assumed that the post-restoration increase in CH_4 emissions will be short-lived, especially in bogs, as *Sphagnum* recolonises a site (**Lindsay, 2010**). However, the only study we could find of an old, well-established restored site (**Yli-Petäys *et al.*, 2007**) – a boreal peatland in Finland – suggests that CH_4 emissions can remain high even 50 years after restoration and that a restored peatland with close to natural plant assemblages may not be a strong C sink.

3.2 Mesocosm experiments

The mesocosm experiments were carried out at the Open University in 2010 and 2011. They were undertaken to establish (a) how different methods of blocking drainage ditches (grips) affect greenhouse gas fluxes to and from the ditch, and (b) how different plant functional types (PFT) (heather, *Sphagnum* moss, cotton grass (a type of sedge)) affect the carbon budget of re-wetted peat. The results are reported in a paper published in the journal *Wetlands Ecology and Management* (**Green *et al.*, 2014**). They may also be found in a detailed report to Defra from 2011[5].

The experiments were conducted on cores of peat removed from an area of blanket bog close to where the field trials took place (see sections 2.1 and 3.3-3.5). Cores were taken from within ditch (grip) channels and from the area between ditches. In the latter case, the cores included the surface vegetation.

Experiment 1 of the mesocosm study focused on greenhouse gas exchanges from blocked ditches (grips) and evaluated the effects of restoration method, water-level dynamics and climate on CH_4 emissions and global warming potential (GWP). Four types of restoration method were considered: peat dams with pools between them ('no infill'), peat dams but where the pools had colonised with *Sphagnum* ('*Sphagnum* mat'), ditches blocked with cut heather ('heather bale'), and ditches blocked with peat ('re-profiled'). Experiment 2 assessed the role of PFT on CH_4 emissions from restored peat outside of the ditch (i.e., from areas of peatland between parallel ditches). The peat cores or mesocosms were housed in environmental cabinets and were subjected to a nine month meteorological simulation (representing conditions at the study site between April and December).

In Experiment 1, we found that CH_4 emissions and GWP were affected by ditch blocking method. Re-profiling, heather bale, and *Sphagnum* mat had significantly higher CH_4 emissions than the no-infill mesocosms, with the latter showing no net release of CH_4 or even a slight uptake. No infill and *Sphagnum*

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[5] See: http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=16991

mat had a lower GWP than re-profiled and heather bale. Heather bale GWP was also significantly higher than re-profiled. Heather bale had a high (positive) net ecosystem exchange (NEE) (net loss of CO_2) which suggests that intense decomposition of the heather was occurring within the cores. Our data suggest that heather bales may not be a suitable material for ditch blocking because they may decompose and break up over relatively short timescales (5-10 years).

In Experiment 2, we found that, in areas of re-wetted peatland between blocked drainage ditches, plant functional type affected CH_4 emissions but not GWP. CH_4 emissions were substantially greater for the sedge PFT than for the *Sphagnum* PFT. However, differences in CO_2 exchanges (NEE) between the plant types offset the differences in CH_4 emissions, so that GWP did not vary significantly between plant types. When considering radiative forcing, this finding suggests that it does not matter which plant type dominates a re-wetted area.

Both experiments were short-lived and involved small sample sizes (numbers of cores), and the findings should be viewed in this context. Although they provide a useful insight into carbon cycling within restored ditches and areas between ditches, more reliable results are likely to be obtained from long-term field studies.

3.3 Hydrological conditions

Details of the hydrological work may be found in Appendix C. An initial five-fold reduction in discharge occurred in ditches that had been blocked with dams or partly infilled and blocked with dams. However, there was evidence of a slow change over time in ditch flow at the site in subsequent years, with the overall volume of water leaving the blocked ditch weirs increasing per unit of rainfall. There was, therefore, clear evidence of the benefits of long-term monitoring because hydrological findings in the initial year after ditch blocking were rather different from those in later years. The additional water that flowed in later periods of the study from the blocked ditch weirs occurred in the form of a more continuously flowing baseflow with fewer dry periods. The cause of this increase is unclear but it may be related to changes in subsurface flow pathways in the peat at the site in response to re-wetting or possibly to the dams in the blocked grips becoming more leaky over time.

Overland flow and subsurface throughflow in the upper 3 cm of the peat was an important component of flow at the study site, even in areas of the peatland that flowed into open ditches.

Water-table depths on the site were relatively shallow (mostly within the upper 10-15 cm of the peat profile) and the effect of ditch blocking on local water tables was small overall (on average, water tables in the ditch-blocked areas moved ~ 0.5-2 cm nearer the ground surface) although spatially highly variable. When strict statistical tests were applied to post blocking water-table data, there was no significant differences between the open and blocked ditches.

The study also provided evidence that the catchment areas for peatland ditches may, in some instances, be very different from those expressed by surface topography alone. This evidence is twofold. First, the discharge of water from some weirs on unblocked or control ditches increased substantially after the blocking of adjacent ditches, and this is consistent with surface and shallow subsurface water tracking obliquely across the neighbouring blocked ditch to be intercepted by the control ditch. Prior to blocking, this water would have been intercepted by the neighbouring ditch, so the catchment at that time would have been much smaller. Secondly, using high-resolution topographic data we were able to calculate the topographic areas (topographic catchments) that feed into each weir using a geographical information system (GIS). We could do this by assuming ditches were left open or by assuming they were blocked/infilled. This GIS analysis shows some catchments changing substantially after ditch infilling. Therefore, peatland studies that have estimated aerially-weighted water or carbon fluxes from one or two open or blocked ditches and where the data have also been used in upscaling estimates need to be treated with caution. There are major benefits of sampling a relatively large number of ditches over long periods as was the case in this study.

3.4 Greenhouse gas fluxes

Details of the GHG flux work may be found in Appendix D. CH_4 fluxes and GWP over a 100-year time frame in the experimental area show no evidence of varying systematically between drained and re-wetted blanket peatland or between different types of re-wetted peatland (dammed and re-profiled). This finding applies to both the ditch channels (whether open or partially infilled) and the areas between the ditches. In addition, there was no evidence that CH_4 fluxes (NEE) or the GWP of the peatland change systematically over time. GWP was positive for the first three years of the study; the study peatland, even in restored areas, was radiatively forcing. During the fourth year GWP became negative (radiative cooling) which is likely to be a consequence of the differences in meteorological conditions between the years of study. Therefore, the results suggest that there is no obvious short-term (four year) GWP benefit from restoring drained blanket peatland. This conclusion applies to peatlands like the study site that have shallow drainage ditches that are not actively eroding. An alternative, 'no-regrets', interpretation is that ditch blocking does not have any obvious negative effects from a carbon-balance perspective.

The only other study that we have found where a full C budget based on measurements was calculated for a blanket peatland – Auchencorth Moss in central Scotland – suggests that such peatlands can have strongly negative GWP values indicating a radiatively cooling effect. Notably, however, Auchencorth is a partly drained and relatively dry peatland with very low CH_4 fluxes. If it were to be re-wetted (and we understand that partial re-wetting of the site has been approved and will happen) it is possible that CH_4 fluxes would increase and not be offset by changes in NEE so that GWP would also increase. Therefore, the evidence from the two studies (ours and that at Auchencorth Moss) is that the case for restoring modestly drained blanket peatlands for benefits to C storage and GWP is, at best, unproven. Where peatland ditches are clearly eroding and exporting POC, a much stronger case for restoration can be made. This may also be true where ditches are deeper (exposing a greater depth of peat to aerobic decomposition), although more data would be needed to confirm this. However, for stable, shallow ditches in which little or no erosion occurs, restoration may not yield any C storage or GWP benefits. Restoration is carried out for a range of reasons and restoration of a site may be justified on grounds other than C storage and GWP.

3.5 Water chemistry and waterborne C fluxes

The water chemistry and waterborne C flux data and analysis may be found in Appendix E. The results of the experiment have not demonstrated a clear beneficial impact of re-wetting on waterborne C loss. We found no evidence that ditch-blocking changed the concentrations of DOC, POC, CO_2 or CH_4 in water sampled from the ditch network, or of any change in DOC concentration due to ditch-blocking in peat porewaters or overland flow. On the other hand, ditch-blocking (using both damming and re-profiling methods) was very effective at reducing water flow down the ditch network, and as a result the fluxes (i.e., the total amounts) of all forms of carbon transported down the ditches were reduced by around 75%. However, it is highly unlikely that this result indicates a genuine decline in waterborne C export, because any water not transported down the (blocked) ditch network must instead have left the site via different hydrological pathways. These may include greater overland or shallow subsurface flow (implying that the ditch-blocking achieved its objectives in terms of returning the peatland to a more natural hydrological behaviour) but it is also possible that some of the water bypassing blocked ditches is now being transported down the remaining open ditches. Because DOC concentrations in overland flow and porewater samples had similar or higher concentrations than DOC collected from the ditches, it seems unlikely that changes in hydrological pathway have resulted in an overall reduction in DOC export from the peat. This conclusion is supported by CEH catchment-scale monitoring data showing little difference in DOC concentrations between the stream draining the ditch-blocked area (as part of the larger area restored by the National Trust) and a nearby stream draining a similar, largely unrestored peatland catchment. We did, however, observe some evidence of a short-lived pulse of high DOC concentrations in streamwater following ditch-blocking, and of a more sustained (two-three year) increase in porewater DOC concentrations affecting the whole hillslope. This suggests that disturbance during restoration may cause some increase in DOC levels, but that the impacts of this on stream DOC export are likely to be minor and transient.

In policy terms, results from the project suggest that some caution is needed with regard to the level of water quality benefit (in terms of carbon loss and the quality of drinking water supplies) that may be achieved through peat restoration. Our findings confirm that, as might be expected, blocking ditches reduces the amount of C flowing directly down the ditch network, but suggest that this carbon simply finds its way into the natural stream network via other hydrological pathways such as overland flow. Therefore, there may be little or no net reduction in total waterborne carbon loss, and no change in DOC or water colour levels in downstream water supplies. Whilst this is essentially a negative result, at least two caveats apply. Firstly, the experiment took place in an area of blanket bog subject to relatively modest drainage which, although typical of many parts of the UK, may not reflect conditions in more severely drained or otherwise degraded areas, where drainage may have caused greater DOC and/or POC increases in the past, and where re-wetting and restoration may therefore provide greater water quality benefits. Secondly, previous studies outside the UK have shown stronger effects of drainage and re-wetting on DOC losses, and it appears that the different hydrological functioning of blanket bogs (compared to raised bog and fen systems) may make them less susceptible to drainage in relation to waterborne C losses; other UK peatland types may therefore show greater susceptibility.

Taking an alternative interpretation of our results, we also found no evidence that ditch-blocking leads to sustained increases in the export of any component of the fluvial carbon flux, and thus that it is very unlikely that it will have any detrimental impacts on either the quality of water supplies or on the magnitude of GHG emissions associated with this flux. In this sense, the implication of our results is that, in terms of waterborne carbon fluxes, peatland restoration represents at worst a ‘no regrets’ option.

3.6 Process studies

The effects of re-wetting on CH_4 dynamics have been little researched, while the processes that underpin any CH_4 response are even more poorly resolved. Hence, a series of laboratory and field experiments were used to improve understanding of peatland CH_4 production and consumption processes in ditch drained and blocked-ditch systems (see Appendix F). In the first investigation, we used peat samples from the experimental area to examine how ditch-blocking methods, distances from the ditch, and plant functional types affected CH_4 and CO_2 fluxes. We used $^{13}CH_4$ stable isotope tracer techniques to compare the CH_4 oxidation activity of low- and high-affinity methanotrophs (methane consuming bacteria) in the peat. Our results showed no effects on overall CH_4 fluxes, but ^{13}C isotopic tracer studies revealed higher CH_4 oxidation potential in peat adjacent to re-profiled ditches compared to peat next to control (open) and dammed ditches. This finding is contrary to what might be expected; a reasonable prior assumption was that CH_4 oxidation potential would be greater in more oxic peat which one might expect to find next to open ditches. In addition, CH_4 oxidation potential increased with distance in the control and dammed ditch treatments, though this pattern was reversed in reprofiled plots. Again, this pattern is difficult to explain and may owe more to subtle variations in the microtopography and sedge abundance in the inter-ditch areas, both of which can be expected to influence CH_4 production and oxygen availability in the peat (for methanotrophs to thrive a ready supply of CH_4 and oxygen is needed). In a second set of tracer studies, we undertook two $^{13}CH_4$ isotope pulse-labelling experiments in the field. These were designed to examine differences in CH_4 oxidation between the blocking treatments and in plots with and without *Sphagnum* moss. Results of these field experiments showed that CH_4 oxidation was active across all treatments and in both *Sphagnum*-removal and control plots, but that there were not any significant variations between treatments. The implications of these findings are that neither peat microbial CH_4 production potential nor oxidation were strongly influenced by short term changes in ditch management conditions or by *Sphagnum* moss cover.

3.7 Vegetation dynamics

As noted in the literature review (Appendix A) it is often assumed that ditch blocking will lead to an increase in the cover of *Sphagnum* and a reduction in the cover of sedges (particularly the cotton grasses) (*cf*. **Lindsay (2010)**). Contrary to this expectation, our data (see Appendix G) have shown no treatment effects on the abundance of sedges and *Sphagnum* mosses. We did find an influence of time on both sedge and *Sphagnum* abundance, with abundance varying significantly between some years. There is the suggestion that both *Sphagnum* and sedges, but the latter to a lesser extent, were more abundant at the end of the project than at any other time. However, there were no clear temporal trends (i.e., no systematic changes) in the data so it is difficult to attribute the inter-annual variability to anything other than inter-annual variability in other conditions, probably the weather. Although we have good weather information for the site, the length of the experiment was too short to undertake a time-series analysis of the data. It is likely that plant response to weather conditions shows lags of at least two years so that, with a data set of five years in total, it is not possible to investigate such lags and the relative contributions of different meteorological variables (rainfall depth and regime, growing season frost days and so on) on plant abundance. What is clear is that factors other than those associated with the ditch blocking have to be invoked to explain the variations seen in the data.

Our analysis also revealed no significant effect of drainage/blocking treatment on the leaf lengths of Hare's Tail Cotton Grass (*Eriophorum vaginatum*). There is the suggestion in the data that leaf lengths, which can be taken as a measure of cotton grass vigour, decreases towards the end of the study period. This decline coincides with a dip in cotton grass abundance in 2013 followed by an increase in 2014. There is a danger of over-interpreting such data, but it is possible that the decline in cotton grass abundance in 2013 is associated with the decline in leaf length. Despite the 'bounce back' in cotton grass abundance in 2014, the new growth that this implies may not have been sufficient to give a significant increase in average leaf length. Another possible interpretation of the vigour data is that, while *Eriophorum vaginatum* has remained widespread across the site, it is slowly losing vigour, perhaps as *Sphagnum* mosses expand. However, the data suggest that any such changes occur widely across the site and are not restricted to the restored areas (the blocked ditches).

4. Conclusions

The findings from the different elements of the project have proved broadly consistent. We have not found evidence of consistent differences between blocking treatments in terms of CH_4 emissions or GWP and this conclusion from the field-based GHG flux monitoring is reflected in the process studies where there is little evidence of differences in methanogenic and methanotrophic (methane-consuming and methane-producing) microbial communities between the different peats (drained, dammed, and re-profiled). Neither is there evidence that ditch blocking alters the waterborne C load entering streams and rivers. **To date, we cannot identify any GWP benefits from re-wetting of blanket peatland drained like that at the site; i.e., using shallow ditches**. In blanket peatlands such as this, it seems that ditch blocking has relatively little impact on water tables and little or no effect on peatland vegetation. In a deeper drained blanket peatland or one where the drains were more closely spaced or were actively eroding, a different conclusion might have been reached. However, drainage systems such as that at the study site are common throughout the UK, so our findings have wide relevance.

The differences in CH_4 emissions and GWP between different methods of ditch blocking seen in the mesocosm study were not observed in the field, but field conditions tended to be more complicated in terms of vegetation composition and also range of meteorological and hydrological conditions than those set up in the laboratory. The laboratory findings were also based on a much shorter run of data than those in the field. However, the finding from the laboratory study that heather bales are probably best avoided as peat dams and possibly also as an infill still holds.

By judicious use of experimental controls we were able to identify the modest effects of ditches in the wet upland environment of the Migneint on water tables. However, our work comparing GHG emissions (CH_4

and CO_2 fluxes) to water-table position (see Appendix D) over a reasonable water table range (mean annual water-table depths of 0-20 cm) suggest that **water table is not a simple control of GHG fluxes at the site and, perhaps, in blanket peatlands more widely**. Rather, GHG fluxes appear to result from a complicated inter-play between vegetation composition, the growth stage of the plant species making up the vegetation, and soil physical conditions (wetness and temperature).

Analysis of the vegetation data suggests that cotton grasses (a type of sedge) are abundant and have remained abundant across the site. *Sphagnum* mosses are now widespread, although less abundant than the sedges. We found little or no evidence that the abundance of sedges and *Sphagnum* mosses is affected by ditch blocking. Significant changes in the abundance of sedges and *Sphagnum* over time did occur but did not follow any systematic pattern, and are probably explained by variations in meteorological conditions between years and groups of years (although investigating such links between weather and vegetation would require a much longer data set than that collected).

Despite the modest effects on water tables, our hydrological analysis shows that the hydrological behaviour of the site changed abruptly after ditch blocking such that there was a substantial reduction in within-ditch flow in ditches that had been dammed or partially blocked and dammed. In the ditch blocked areas, water is diverted across the peatland surface. Our hydrological analysis also shows that the catchments of individual ditches can change markedly after blocking, a response not previously realised that may alter conclusions from previous studies in which there was little or no replication of treatments. The importance of having multi-year data is also shown in us being able to record a drift in hydrological behaviour at the site which suggests either that subsurface hydrological pathways are evolving in response to blocking (e.g., changes in permeability of the 'bulk' peat or changes in the connectivity of the largest water-conducting pores running through the peat) or that the dams in the blocked grips are becoming more leaky over time. Such changes may continue and warrant further study, whether at this site or others.

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Appendices.

Appendix A. Update of the Defra SP0574 literature review (update completed April 2010).
Appendix B. Systematic literature review on blanket peatland soil properties (completed July 2014) (Excel file).
Appendix C. The impact of ditch blocking on blanket peatland hydrology.
Appendix D. The effect of drainage ditch blocking on the CO_2 and CH_4 budgets of blanket peatland.
Appendix E. Fluvial carbon flux and water quality responses to ditch-blocking of a blanket peatland.
Appendix F. Microbial methane oxidation in a blanket peat ditch-blocking experiment: evidence from ^{13}C tracer investigations.
Appendix G. Vegetation responses to ditch-blocking of a blanket peat bog.