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HOW DO DRAINING AND RE-WETTING AFFECT CARBON STORES AND GREENHOUSE GAS FLUXES IN PEATLAND SOILS?

Systematic Review

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Summary

1. Background
Draining peatland and lowering water tables has traditionally been carried out to prepare land for afforestation and agriculture, or for its extraction and use as fuel or in horticulture. This practice has been implicated in increased greenhouse gas (GHG) emissions from peatland together with a reduction in the total carbon (C) store. Concern about both the loss of wet peatland habitat and the global warming potential of these emissions have led to attempts in recent years at restoration by raising the water table and re-wetting peatland, for example by blocking drainage ditches (often referred to as 'grips'). This practice is intended to restore the function of the peatland as a net sink of carbon dioxide (CO_2) and a semi-permanent C store. This review assesses the evidence-base regarding change in peatland C stores and GHG fluxes in response to wetting and drying regimes, as a direct result of environmental management.

2. Objectives
The primary objective of this review is to retrieve all available evidence relating to the question 'How do draining and re-wetting affect C stores and GHG fluxes in peatland soils?' and provide a synthesis of evidence on the climate change mitigation effects of re-wetting as a management intervention.

3. Methods
Search strategy
A search for articles and datasets on draining and re-wetting peatland was conducted using a variety of electronic data bases. Website searches and organisational searches were also performed to find grey literature. An extensive consultation was also carried out to retrieve any unpublished information and to improve the search.

Selection criteria
Studies retrieved by the search were included in the review only if they included at least one alternative from each of the following categories:

- **Subjects:** Carbon in any form, or GHGs, held in, released from, or sequestered by peatland or peat-type soils.
- **Interventions:** Long-term re-wetting or draining of peatland or peat-type soils, or natural experiments comparing areas of peatland or peat-type soils in the same region with different long-term (not seasonal or sporadic) hydrology. Studies that involved peat cutting, extraction or burning were only included if draining or re-wetting was also clearly involved.
- **Comparators:** No intervention or before-after comparisons or both (BACI).
- **Outcomes:** Amount or change in C or GHG stored in, or released from, soils.

Data collection and analysis

Raw data on GHG flux (CO_2, methane (CH_4) and nitrous oxide (N_2O)) as well as fluxes of dissolved organic C (DOC), and C mineralisation were extracted. Data on storage of C as total C, microbial C and yield were also extracted. Random effects meta-analysis was used to generate effects sizes (standardised mean difference) and to examine location-level data on the effectiveness of the interventions. Sub-group analysis and random effects meta-regression were used to investigate variation in effectiveness in relation to methodological and environmental co-variates.

4. Main results

There is a greater amount of evidence on emissions from intact and drained peatland than from re-wetted peatland. A random effects meta-analysis on the five studies that measured the net efflux of all three main GHGs suggests that drained peatland has a greater net efflux of GHG than intact peatland, but the effect was not statistically significant. No studies measured all three GHG fluxes simultaneously from re-wet peatland.

More studies measured the fluxes of the individual GHGs separately. Drained peatland produces less CH_4 emissions by around 8 mg CH_4 m^{-2} d^{-1} when compared with intact peatland (27 studies). Meta-regression showed this effect to be well correlated with greater water table depth and pH, while sub-group analysis showed a larger effect in fens than in bogs. Conversely, re-wetted peatlands show increased CH_4 emissions by around 16 mg CH_4 m^{-2} d^{-1} when compared to drained peatlands (five studies).

Drained peatland soils show a net increase in N_2O emissions of around 133 μg N_2O m^{-2} d^{-1} over intact peatland. Only one study measured the effect of re-wetting peatland on nitrous oxide flux: it caused an overall reduction in efflux of 7.1 mg N_2O m^{-2} d^{-1} compared to drained peatland.

The most frequent measure of CO_2 flux was total respiration (measured in the dark only). The available evidence suggests that drained peatland has a higher net CO_2 efflux as total respiration than intact peatland (1.41g CO_2 m^{-2} d^{-1}, $p=0.094$) but this effect is not statistically significant. While, only one study measured CO_2 in re-wet peatland, as daily respiration, but showed no effect on net efflux.

5. Conclusions

The evidence-base concerning GHG emissions and C storage in peatland after re-wetting is poor. There are too few studies and those that exist have limitations in their design, often lacking sufficient replication at the location or site level to enable the overall effect to be determined. There is a greater amount of evidence on comparative emissions from intact and drained peatland; however the methodology of most of these studies is similarly limiting. Better studies are required that use greater replication, baseline measurements and improved reporting of the data (showing mean, sample size and variance) and effect modifiers. There is a particular need for studies to address the flux of all GHGs simultaneously in the same locations so that the net global warming potential can be determined. In future studies on re-wetting peatland, researchers, policy makers and managers should ensure that appropriate measurements are put in place to ascertain whether this management intervention is having the planned net benefit for climate change mitigation. The available evidence to date is not inconsistent with a re-wetting intervention mitigating climate change, but better evidence of effectiveness is urgently needed.

Main Text

1. Background

Peat is composed of partly decomposed plant material deposited under saturated soil conditions. Peatland itself is a generic term including all types of peat-covered terrain and many peatlands are a complex of swamps, bogs, and fens, sometimes called a "mire complex" (NWWG 1988). Estimates of global land surface cover by peatlands vary between 2% and 5% yet they are thought to contain between 30% and 50% of the world's soil carbon (C) store and as much C as is held in the atmosphere (Lavoie et al. 2005; Gronlund et al. 2006; Treat et al. 2006). While their net C accumulation rate may be relatively low (Vitt et al. 2000), they represent a longer-term store of C than do mineral soils that have relatively high organic matter turnover and oxidation rates (Yu et al. 2001).

Carbon in peatland occurs in a variety of forms, the majority is soil organic matter (SOM) and other organic matter (OM) such as plant material. It is also present in dissolved form, either organic (DOC) or inorganic (DIC), as microbial C, and as the gases carbon dioxide (CO_2) and methane (CH_4), which together are the main forms in which C is lost from peatlands. Methane and CO_2 are powerful GHGs (Moore and Knowles 1989; Moore and Roulet 1993) and peatlands may become a significant source of atmospheric C under a changing climate (Yu et al. 2001).

Peatlands are a potential sink of atmospheric CO_2 via photosynthesis in their vegetation and the resulting plant litter because of their ability to accumulate OM at a higher rate than its decomposition takes place, mainly as a result of high water tables and therefore anaerobic conditions. Due to these conditions peatlands are also significant emitters of the GHGs CH_4 and (sometimes) nitrous oxide (N_2O) (Gorham, 1991; Martikainen et al. 1993; Freeman et al. 1993; Nykanen et al. 1995; Hendriks et al. 2007).

Over the last several hundred years many peatlands have been transformed into agricultural and forestry land with artificially low water tables. As well as drainage for forestry and agricultural production (Gustavsen et al. 1998), peatland soils have traditionally been utilised by extraction for use as fuel or in horticulture (Charman and Warner 2002). While direct measures of changes in the peatland C pool following water table drawdown are rare, both decreases (Sakovets and Germanova 1992) and increases (Minkkinen and Laine 1998a) have been reported. Also, drier peatlands increase the risk of peat fires, further altering the C balance (Charman and Warner 2002).

Since mitigation of GHG release into the atmosphere is a key aim of the Kyoto Protocol (Dumanski 2004), scientists and environmental mangers are exploring ways to offset the C emissions caused by economically valuable activities, such as energy production, through altering environmental management. One such proposal involves the re-wetting of drained peatland for long-term sequestration of C. However, despite a range of individual studies on this topic, the evidence of the overall long-term, rather than transient effects on GHG flux balance of this practice is uncertain. Therefore synthesis of the available literature is required.

2. Objectives

2.1 Primary objective

The primary objective of this review is to retrieve and synthesise all available evidence relating to the question ‘How do draining and re-wetting affect C stores and GHG fluxes in peatland soils?’

This review considers the long-term rather than transient effects of these interventions.

3. Methods

3.1 Question formulation

The need for review of this subject was identified by the Environment Agency Wales (EAW) Climate Change Strategy Implementation Plan (CCSIP). The question was formulated as part of a Knowledge Exchange partnership between the EAW and Centre for Evidence-Based Conservation (CEBC) at Bangor University.

A workshop involving EAW policy and science staff and CEBC addressed particular issues in the CCSIP and developed questions for systematic review. The question for this review was developed during discussion on Issue number 5 of the CCSIP; ‘Develop understanding of the role of soils and forestry in C release and sequestration and advocate land management approaches to minimise emissions’.

This question was particularly relevant for the EAW as they currently advocate the practice of ‘grip blocking’ on peatlands as a management practice to control water quality. However, the additional benefit, or cost, of this for C sequestration and GHG flux balance was not well known. Many other stakeholders also share an interest in these issues and following an extensive consultation on the protocol (Appendix I), the final question elements were:

Subject: Total C, dissolved organic C and GHGs (CO_2, CH_4 and N_2O) in peatland soils.

Intervention: Draining and re-wetting / cessation of draining, or areas in the same region with different long-term hydrological regimes.

Outcome: Change (storage or release) in amount of C or GHG flux.

Comparator: Control area with no intervention or before-after studies. Natural studies that compare wet and dry areas of the same peatland that have permanently different hydrological regimes, i.e. not short-term or seasonal hydrological changes caused by flooding, or wet winters compared with dry summers.

3.2 Search strategy

The search aimed to capture an unbiased and comprehensive sample of the literature relevant to the question, whether published or unpublished. Different sources of information were searched in order to maximise the coverage of the search.

3.2.1. Search terms

Combinations of the following search terms (where * denotes a wild card, and inverted commas indicate that the search engine was forced to look for these terms as a phrase) were applied to the databases listed below. The search terms were devised in order to maximise the sensitivity of the search. Where possible, all the different terms that are used in different countries and regions were included to obtain studies carried out on peatland soils from as wide a range of locations as possible. Search terms are separated into those that describe the habitat, i.e. peatlands; those that describe the intervention, i.e. draining and re-wetting; and those that describe the outcome, i.e. C or GHG flux.

Habitat search terms

Peat*, Bog*, Muskeg, Pocosin*, Quag*, Mire, Slough, Aapa*, Turvesuo, Tourbe, Tourbièr*, Suo, Fen, Torfmoor, Niedermoortorf, Hochmoortorf, Palsa, Swamp, Carr, Mor, Sedge, Muck

Outcome search terms

Carbon, “Greenhouse gas*”, “Green-house gas*”, “GHG*”, Methane, “Organic matter”, “Organic content”, CO_2, CH_4, N_2O, Nitrous Oxide, DOM, DOC, SOM

Intervention search terms

Flood*, Drain*, Restor*, Grip block*, Rewet*, *Re-wet*”, Plough*, Ditch*, Drought

Where possible, all search terms within a category were combined using the Boolean operator ‘OR’. Search terms between categories were combined using the Boolean operator ‘AND’. As most databases and websites vary in the way they handle complex search strings and the use of Boolean operators, the exact combinations of search terms used for each data base are tabulated in Appendix II.

3.2.2. Databases

The search included the following online databases which cover the breadth and depth of available literature on the topic:

1) ISI Web of Knowledge (inc. ISI Web of Science and ISI Proceedings)
2) Science Direct

3) Directory of Open Access Journals
4) Copac
5) Index to Theses Online
6) Agricola
7) CAB Abstracts
8) ConservationEvidence.com
9) CSA Illumina

No time, language or document type restrictions were applied. References retrieved from the computerised databases were exported into a bibliographic software package (Endnote 9) and duplicates removed prior to assessment of relevance using inclusion criteria (Section 3.2).

3.2.3. Websites

An Internet search was also performed using meta-search engines and recommended sites:

http://www.alltheweb.com
http://www.dogpile.com
http://www.google.com
http://scholar.google.com
http://www.Scirus (All journal and web sources)
http://data.esa.org/

The search was limited to Word and/or PDF documents where possible and the first 50 hits examined for appropriate data for retrieval (Section 3.2.). The first 50 is an arbitrary choice but based on a trade-off between capturing the most relevant information and expending limited resources searching large numbers of irrelevant hits.

3.2.4 Specialist sources

Websites of relevant specialist organisations, listed below, were also searched. Bibliographies of included material were searched for relevant references. Authors of relevant articles were contacted for further recommendations, and for provision of any unpublished material or missing data. Links pages of websites were followed to look for relevant organisations that may have been missed by these searches.

Agriculture and Agri Foods Canada
Agri-Food and Biosciences Institute
Alterra
British Association for Shooting and Conservation
British Ecological Society
Centre for Ecology and Hydrology
Countryside Council for Wales
Department for the Environment, Food and Rural Affairs
Dŵr Cymru / Welsh Water
Environment Agency

Environment Canada
Environmental Protection Agency
Environment Protection Agency Ireland
EHS –Northern Ireland Environment Agency
European Commission Joint Research Centre
European Environment Agency
Finnish Peatland Society
Farmers Unions - UK
Finland's environmental administration (www.ymparisto.fi/)
Food and Agriculture Organization of the United Nations
Forest Research
Forestry Commission
Global Environment Centre
Greenpeace
Intergovernmental Panel for Climate Change
International Association for the Study of the Commons
International Mire Conservation Group
International Union for Conservation of Nature
International Peat Society
Irish Agriculture and Food Development Authority (Teagasc)
Irish Peatland Conservation Council
Joint Nature Conservation Committee
Macaulay Land Use Research Institute
Ministry of Natural Resources of the Russian Federation
Moorland Association
Moors for the Future
National Council for Forest Research and Development (COFORD)
National Parks
National Soil Resources Institute
National Trust
Natural England
Natural Resources Canada
Peat-Portal.net
Plantlife UK
RAMSAR
Research Councils UK
Royal Society for the Protection of Birds
Russian Guild of Ecologists (www.ecoguild.ru)
Russian Regional Environmental Centre (www.rusrec.ru/en)
Severn Trent Water
Scottish Agricultural College
Scottish Executive
Scottish Environment Protection Agency
Scottish Natural Heritage
Society for Ecological Restoration
Society for Wetlands Scientists
Tyndall Centre for Climate Change Research
UK Climate Impacts Programme
UK Universities
United Nations Environment Programme
United States Environment Protection Agency

United Utilities
Welsh Assembly Government
Wetlands International
Wildfowl and Wetlands Trust
Wildlife Trusts UK
World Wildlife Fund (organised by country)
Yorkshire Water

3.3 Study inclusion criteria

Articles retrieved by the search strategy were subject to a three stage process to identify the relevant studies for the review question. The aim of this process was to systematically remove studies that were not relevant or did not contain relevant information or data. At each stage, if there was insufficient information to exclude a study it was retained until the next stage.

In the first instance, the inclusion criteria, which are identified below, were applied to title only in order to remove spurious citations. Articles remaining were then filtered on viewing abstract and finally full text.

To assess and limit the effects of between-reviewer differences in determining relevance, two reviewers (JB and JRH) applied the inclusion criteria to 200 articles, at the start of title and abstract filter. The kappa statistic (Edwards et al. 1985) was calculated 0.46 which indicates moderate agreement. After a meeting between the two reviewers, areas of uncertainty were identified, mostly related to modelling studies. As these do not contain primary data, they were excluded from the review.

To reduce duplication of effort, web searches were performed after inclusion at full text of primary literature from databases. The first 50 hits from web searches were filtered initially with the inclusion criteria on the title and abstract of articles (or introduction section if an abstract is not available), and then at full text. URLs for hits deemed relevant at title and abstract were maintained within an Excel spreadsheet, and subsequently viewed at full text.

The following criteria were used to assess relevance.

- **Relevant subject(s):** Carbon in any form, or GHGs, held in, released from, or sequestered by peatland or peat-related soils.

- **Types of intervention:** Long-term re-wetting or draining of peatland or peat-related soils. Natural experiments comparing areas of peatland or peat-related soils in the same region with different long term (not seasonal or sporadic) hydrology. Studies that involved peat cutting, extraction or burning were only included if clear draining or re-wetting was also involved.

- **Types of comparator:** No intervention or before after comparisons or both (BACI).

- **Types of outcome:** Amount or change in C or GHG stored in or released from soils.

- **Types of study:** Any primary study* comparing measures of C or GHG storage or release from peatland or peat-related soils in relation to flooding or draining.

*Because of the great challenges in extrapolating from measured GHG fluxes (over limited time periods at a limited number of locations), it is frequent for these results to be incorporated into process-based models which take into account variation in the environmental factors known to influence these fluxes (e.g. light, temperature and leaf area index). However, the results of these models cannot be readily synthesised to assess objectively the evidence for effects of draining or re-wetting peatland on GHG fluxes. The outputs depend as much on the assumptions in the model as the input data and do not retain any information about the relative strength of evidence (e.g. due to variation in replication) between studies. Therefore, this review is confined to the primary field measurements of GHG fluxes. Whilst it would be very unwise to draw conclusions from these primary data for just a single study, treating each study as an independent sample allows a systematic review to obtain an objective assessment of the overall weight of measured evidence of particular effects.

3.4 Study methodology quality assessment

Critical appraisal of study methodology was conducted for all articles accepted at full text. Studies with before-after control-impact (BACI) designs were considered higher quality than those that were only a comparison between sites, or a before-after comparison. Notes on general study quality were taken and added to the data extraction sheet including sample size, effectiveness of intervention technique and quality of data recording (see Appendix III in supplementary material at www.environmentalevidence.org/SR49.html). Most studies were considered to be of similar quality and therefore quality co-variates were not added to the analyses.

3.5 Data extraction

Data on the primary outcome variables were extracted from studies where there was sufficient information to calculate an effect size for use in meta-analysis (section 3.6). Given the range of intervention and outcome combinations in this review, as well as the diversity in methodologies and reporting strategies in individual studies, a detailed data extraction protocol was devised (see supplementary material at www.environmentalevidence.org/SR49.html). This enabled consistency in data extraction between studies, allowing for a more robust analysis, as well as maintaining the transparency of the review. For extraction purposes studies were allocated to the following groups:

Re-wetted peatland
Drained peatland
Comparison of naturally wet and dry areas of peatland

3.5.1. Rules for extraction from field studies

Data were preferentially extracted from BACI studies as control-impact over 'before and after' data. The level of baseline confounding was recorded. In studies which compared between sites, if data were presented from different sites within a single study, data were extracted from each site (location) separately as long as they had separate comparators. With time-series data where multiple years after intervention were measured, the data presented from the longest possible time since intervention were extracted in order to allow extraction of maximum effect – especially as re-wetting and drainage are usually long-term management options.

However in all studies data were only extracted from comparable sites or micro-sites, e.g. ditch bottoms with ditch bottoms, banks with banks, hummocks with hummocks and hollows with hollows. When samples were taken along a transect or gradient the maximum difference in water table was used in selecting which data to select for each of the two situations being compared.

Most studies of gas flux used fixed chambers left in place over a period of time resulting in repeat measures. Therefore, where possible, data were averaged over a full year (seasonal cycle). If not, then data were extracted in the following order of preference if available: over the full duration of a multi-year studies, over one growing season, over one winter, and finally on a single date. Data were always extracted from the last year, season or date after intervention for the reason stated above. Spatial, not temporal, repetition of measurements was treated as true replication. Therefore, sample size was determined as the lowest number of chambers used, not the number of dates sampled. This resulted in a more conservative estimate of effect size. If errors were presented for each sampling date then these were also averaged, if not they were calculated from the means or from the overall data for the sampling period.

If results were reported from different soil depths then the data were extracted from every depth and soil depth was added as an effect modifier. Again, sample size was maintained at the number of sites, chambers or mesocosm used per sampling time in the study. Variances were calculated taking the average of means and average of standard deviation where possible, if variance was not reported then the mean and standard deviation were calculated across groups (depths).

In studies of re-wetting where there was a choice of 'drained' comparator sites: either those that were still undergoing active drainage and utilization (e.g. by peat cutting) and drained sites that had been abandoned (e.g. with drainage ditches no longer maintained or peat cutting having ceased and the site left to natural processes), the abandoned sites were preferentially selected as the comparator. This reflected the majority of the literature and therefore increased the number of comparable studies. Also, abandoned sites will have undergone some natural regeneration and recovery of ecosystem function, therefore this was a more conservative approach.

In studies that compared naturally wetter and drier sites, the wettest site was extracted as the control and driest site as the intervention.

In all cases, only directly measured data were extracted. Data on 'potential' gas flux, i.e. under aerobic and anaerobic conditions, were excluded as these were calculated values or not representative of the natural situation. However, for CO_2 data, total respiration was preferentially extracted, then measured net ecosystem exchange (NEE) at ambient light levels, then NEE at all light levels if manipulated using shade. This represents a hierarchy of precision in each estimate of the gas flux.

3.5.2 Recording of effect modifiers

Between-study effect modifiers for use in meta-analysis (e.g. pH, temperature) were extracted from the intervention sites (see meta-regression and sub-group analysis in section 3.6). The level of within-study confounding was assessed against their comparator where possible. A data extraction sheet was produced to extract effect sizes and effect modifiers consistently. Data were extracted from text and tables where possible. If written data were not extractable then data were extracted from figures after digitisation. The full spreadsheet is available as supplementary material at www.environmentalevidence.org/SR49.html.

3.6 Data synthesis

Standardised mean difference was calculated from means, standard deviation and sample size for intervention and control from the relevant studies. Comparisons were made between;

Drained and undrained (intact) peatland
Re-wetted and drained peatland
Naturally wet and dry peatland

The transient effects (the measurable effects during the time that the intervention is being imposed) of moving from one state to the other were not the objective of this review. Overall effect size for each outcome/intervention combination was calculated where possible through meta-analysis in Stata™.

The data were analysed using a standard framework:

- Meta-analysis using a random-effects model was applied to generate overall effect size and investigate the level of heterogeneity between studies. Standardised mean difference was used as the effect size to compare studies that measure outcomes at different scales and in different units. As it is standardised it is unitless. If a subset of the effect sizes were measured on the same scale a non-standardised meta-analysis was carried out to estimate the magnitude of the effect in real units. The level of heterogeneity assesses whether there are significant differences in the effects sizes between each study. Significant heterogeneity would suggest that there are differences in outcome caused by the way each study was conducted (e.g. location, timing, environmental conditions) and can be explored further by sub-group analysis and meta-regression. If there is no significant heterogeneity then each study can be assumed to have been conducted under sufficiently similar conditions and only differ in their power to detect a significant effect.

- Egger's test with Begg's funnel plot (effect size against standard error of effect size) were used to investigate possible publication bias (Sterne et al. 2001). Significant publication bias can be caused by non publication of studies that find small negative or inconclusive results. This often results in a skewed or asymmetrical distribution in a funnel plot of effect size against standard error of effect size.

- Sensitivity analysis was primarily for study-level and location-level effects. In some cases, where multiple effects are extracted from the same study or location, the overall effect of the analysis can be biased. Sensitivity analyses assess the effect of these approaches by averaging effects within studies or locations and assessing the impact on the overall mean effect.

- Sub-group analysis was used primarily on method, peatland type, microsite type and season of measurement. Differences between groups were tested by meta-analysis analogous to a one-way ANOVA test of difference between groups termed Metaf (http://mason.gmu.edu/~dwilsonb/ma.html).

  Categories in sub-groups were usually as follows:

  > *Method of measure*: examples are closed chamber and acetylene inhibition.
  > *Peatland type*: fen or bog were the most common and well-reported peatland types and therefore this sub-group was limited to these categories. If no information on peatland type was reported then it was not included in the sub-group analysis.
  > *Microsite:* hollow, hummock or lawn/field
  > *Season of measurement*: Summer or growing season was the most common time that studies were carried out. Often growing season included spring or autumn or both. Occasionally measurement was carried out in winter only. However, studies were often done over a full year. Season categories therefore were all year, summer only, winter only, summer plus one season and summer plus two seasons.
  > *Tropical or Temperate*.

- Meta-regression of effect modifiers was used only if there was significant heterogeneity between studies. Most studies recorded additional data, such as environmental variables or location descriptions to support and inform their findings. When these are reported consistently they can be used to assess the possible reasons for heterogeneity between studies. Possible continuous variables included on meta-regression, therefore, fall into two categories, those that represent the whole site or study:

  > Time since intervention, mean study air temperature, mean annual air temperature, mean annual precipitation, latitude, year of study.

  And those that are measured in the intervention site, although not necessarily a result of the intervention:

Difference in water table between intervention and control, depth of water table in intervention in relation to surface (both of these are obviously related and reflect the magnitude of the intervention), soil bulk density, pH, peat thickness, depth of sample, soil temperature, density of trees.

This list reflects those variables reasonably well reported in the literature. The actual meta-regression and sub-group analyses depended on the amount and quality of data presented in the relevant studies.

Overall effects were calculated for every outcome-intervention combination. However, there were several combinations where the number of extracted effects was so low (<5) that no estimate was made of bias or sub-group analysis performed.

If studies reported gas flux or C store in the same, or similar, units (such as g m^{-2} d^{-1} and kg ha^{-1} yr^{-1}) then all were easily transformed to the same unit between studies, and a non-standardised meta-analysis was carried out to estimate the gas flux or C store in real terms. Additionally, for N_2O and CH_4 the 100-year global warming potential was calculated as CO_2 equivalents (x1 for CO_2, x25 for CH_4, x298 for N_2O) (Forster et al. 2007).

4. Results

4.1 Review statistics

Our search strategy returned a search library of 8180 articles, of which 273 articles met our inclusion criteria for review of full text. Searching was completed in early 2009. Twenty articles were not available with the time and resources available to us. On reading the remaining 253 at full text, 194 did not meet our inclusion criteria leaving 52 articles. Articles were excluded because they presented only abstracts (10 studies), they simply compared different microsites with no other treatment or comparison that influenced moisture availability (11), the data were extracted elsewhere (7), they measured only potential production of gas (9), there was no comparator (33), there were no primary data (28), data were not relevant (9), there was no relevant intervention (31), there was no relevant outcome (3), there was no relevant subject (11), not enough information was presented (28), they were not in English and no translation was available (9) or they measured only seasonal changes (5) or they constituted short term laboratory studies only (7). A list of the studies that were included and excluded at this stage is shown in Appendix II.

Thirteen separate outcomes were covered in the included studies combined with the five different interventions (Table 1). The majority of the effect sizes were generated from studies measuring CH_4 in drained peatland or comparing naturally dry and wet areas in peatlands, or measuring total respiration in drained peatlands (Table 1). Only five field studies measured the three GHGs N_2O, CH_4 and CO_2 simultaneously and these were all on drained peatland.

Table 1. Number of effects sizes extracted from number of included studies (in parentheses) for each outcome/intervention combination. NEE is net ecosystem exchange. See Appendix III in supplementary material at www.environmentalevidence.org/SR49.html for more details of included studies.

	Interventions		
Outcomes	Drain Field	Drain Lab	Natural field
$CH_4/CO_2/N_2O$ measured simultaneously	5(4)	1(1)	
CH_4 flux	27(13)	4(4)	20(9)
CO_2 flux – total respiration	21(10)	3(2)	2(1)
CO_2 flux – vegetation removed	1(1)		
CO_2 daily respiration		1(1)	
CO_2 flux – NEE in light	5(3)		
CO_2 flux – NEE in light, vegetation removed	3(2)		
N_2O flux	13(9)	3(3)	2(1)
Dissolved organic C (DOC) flux	3(3)		
Microbial C (store)			

4.2 Study methodology quality assessment

A summary of each study from which data were extracted is included in Appendix III (see supplementary material at www.environmentalevidence.org/SR49.html). The majority of studies involved repeat measures of paired areas of peatland (sample size at site level is 1). Sometimes baseline data were available from before the application of the intervention which allowed for assessment of change following intervention and of baseline confounding. While many measures were often taken over a period of time, the actual sample size on each occasion was usually low.

4.3 Quantitative synthesis/meta-analysis .

4.3.1 Studies reporting combined fluxes of all three GHGs

Four studies compared fluxes of all three GHGs in drained and undrained peatland, in five locations. Studies by Alm et al. (1999) and Nykanen et al. (1995) were carried out in eastern Finland while the study by von Arnold (2005) was in southern Sweden. The studies, by Melling et al. (2005a,b,c), were carried out in Sarawak, Malaysia. Each mean and variance was converted to the same units (g m^{-2} d^{-1}) for each gas and then the 100- year CO_2 equivalent was calculated (x1 for CO_2, x25 for CH_4, x298 for N_2O (Forster et al. 2007)). The mean and variance of the measures for each gas, after conversion to CO_2 equivalents, within location were summed and a random effect meta-analysis was performed (Figure 1). The overall difference in net GHG emissions between drained and undrained peatland was not significantly different from 0 (d=0.46, z = 1.14, p = 0.253) with no significant heterogeneity between studies (chi square=2.87, p=0.579) and no evidence of publication bias (t=-0.14, p=0.9). Removing the one tropical study by Melling et al. does not significantly change the result (d=0.78, z=1.72, p=0.086) with no significant heterogeneity between studies (chi squared=0.62, p=0.892). No studies of the effects of re-wetting peatland measured all three GHGs simultaneously.

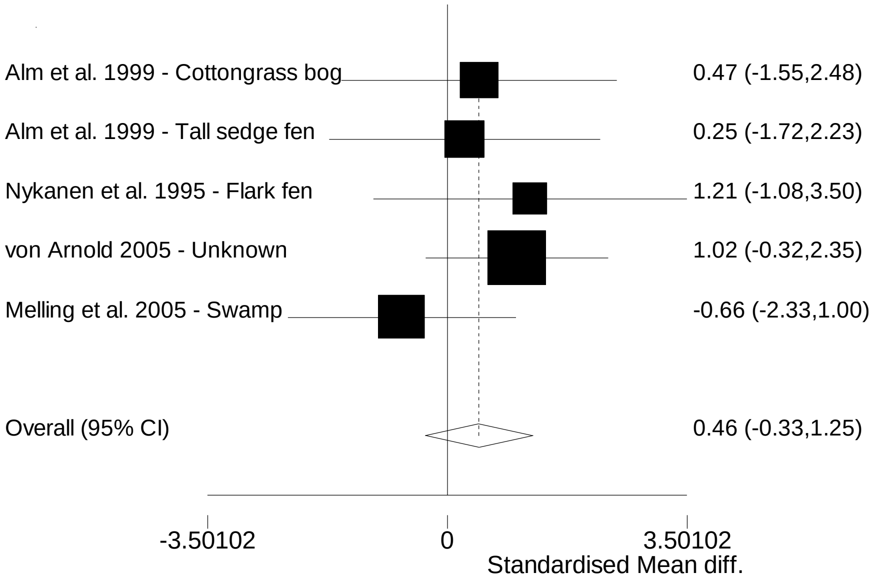

Figure 1. Forest plot of meta-analysis of effect sizes (standardised mean difference) from drained versus undrained peatland on net GHG emissions (100-year equivalent) for datasets providing measures of flux of CO_2, CH_4 and N_2O in the same study. These fluxes were converted, a posteriori, to CO_2 equivalents and then summed to give an overall effect of draining peatland on GHG flux for each study. The vertical line represents no effect, and boxes show the weight of that study in the analysis, horizontal lines are 95% confidence intervals of the effect. Positive values show a greater net GHG efflux from the drained than undrained peatland, and vice versa. The diamond shows the overall effect (a weighted average of all the effect sizes) of d = 0.46 with confidence intervals that cross the line of no effect indicating no significant effect of draining peatland on net GHG flux.

4.3.2 Comparison of CH_4 flux in drained, undrained and re-wetted peatland.

Drained versus undrained peatland

Twenty seven effect sizes (standardised mean difference) were calculated from 13 studies in drained peatlands. All of these studies were of similar quality in experimental design. Most of the studies used a static chamber technique to measure gas flux at a number of locations in paired (drained and un-drained) peatland fields. Measurements were frequently taken at different times throughout the year, the frequency of which varied between studies. However, measurements were usually taken from the same fixed location resulting in a repeated measures design. Only two studies combined the site comparison measure with before-after measures (Freeman et al. 2002; Strack and Waddington 2007) with Freeman et al. (2002) being the only study to remove soil and incubate it with acetylene to facilitate gas recovery. Drained peatland showed lower net CH_4 emissions than undrained; a random effects model meta-analysis produced an overall effect size of d = -1.29 (95% CI -1.78 to -0.80) which was significantly different from 0 ($z = 5.14$, $p < 0.001$). Effect sizes in 26 of the 27 individual studies were less than 0 (Figure 2) **though there was significant heterogeneity between studies (chi-squared = 44.93, d.f. = 26, p = 0.012)**. There is evidence of potential publication bias (Egger's test t = -4.8,7 $p < 0.001$). Only two points fall outside the 95% confidence intervals of the Begg's plot yet there is a classical pattern of asymmetry (see Appendix IV in supplementary material at www.environmentalevidence.org/SR49.html).

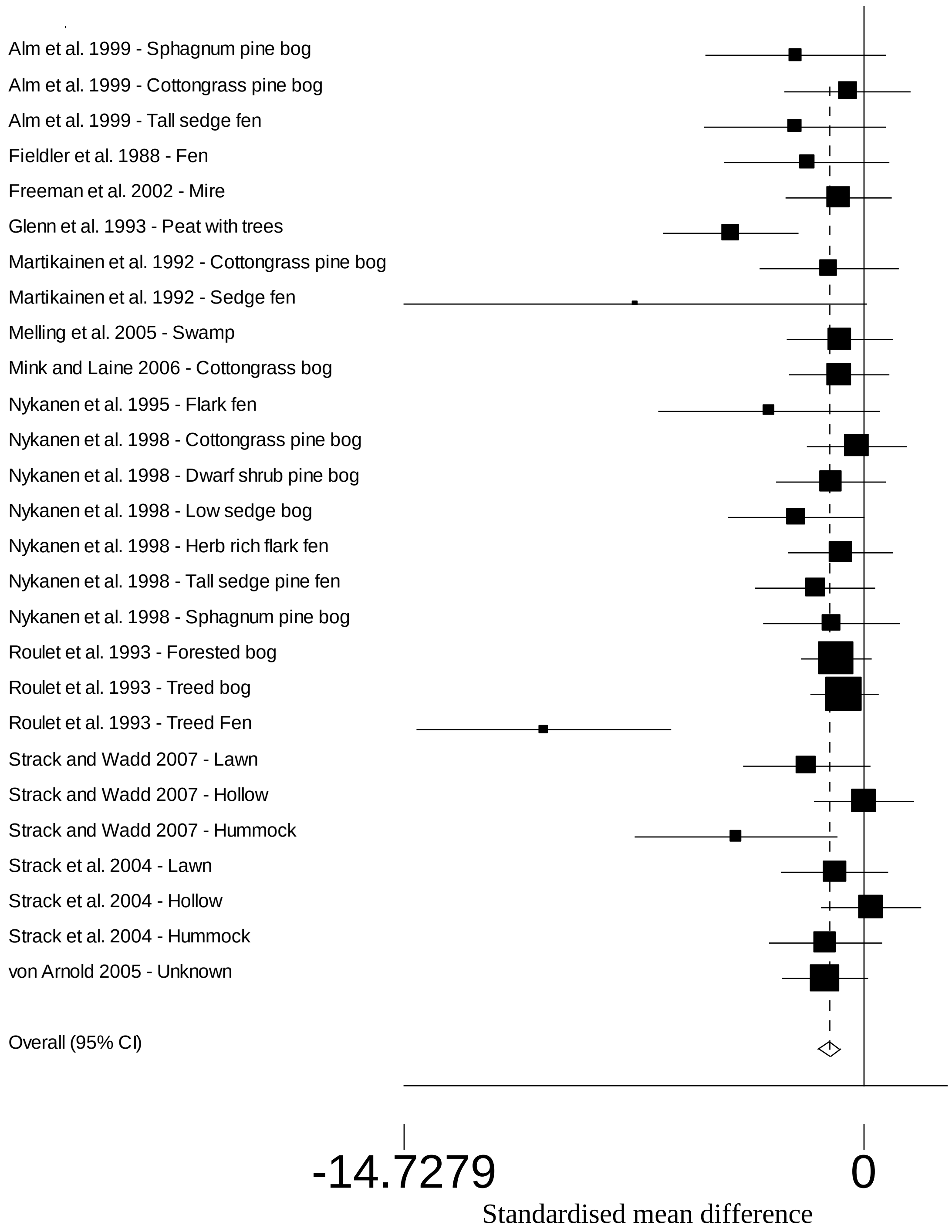

Figure 2. Forest plot of meta-analysis of effect sizes (standardised mean difference) comparing drained with undrained peatland on CH_4 emissions. The vertical line represents no effect, the boxes show the weight of that study in the analysis and the horizontal lines are 95% confidence intervals of the effect Positive values indicate a greater CH_4 efflux from the drained than undrained peatland , and vice versa. The diamond is the overall effect (a weighted average) of d = -1.33 with confidence intervals, which indicate that draining peatlands causes a reduction in CH_4 emissions. The labels for studies which made measurements in different locations indicate the type of site or microsite.

Only one study (Freeman et al. 2002) measured CH_4 (per volume of soil rather than area) in a way that prevented it from being converted to the units used in the other studies. Conversion of the CH_4 flux measurements in all the other studies allowed calculation of a revised non-standardised effect size of d = -8.04 mg CH_4 m^{-2} d^{-1} (95% CI = -11.2 to -4.8). Therefore there is 8.04 mg CH_4 m^{-2} d^{-1} less efflux from drained peatlands compared with controls. This amount of CH_4 has a 100-year global warming potential equivalent to 201 mg CO_2 m^{-2} d^{-1} (95% CI = 280 to 120).

Extracting multiple effects from the same study can sometimes bias the overall mean effect. Given that most studies contributed multiple effect sizes (Figure 2) a sensitivity analysis was carried out on the effect of extracting multiple effects from the same study on the overall mean effect. By averaging all data across each study so that there were 13 effect size estimates (one per study) and rerunning the analysis we can investigate the influence of multiple extraction on the overall effect. The sensitivity analysis increased the mean effect size in a negative direction (d = -1.53 95% CI = -2.09 to -0.94), with no significant heterogeneity between studies (chi squared = 14.01, d.f. = 12, p = 0.30). However, the increase in effect was marginal and, therefore, there is no evidence that extracting multiple effect sizes from the same study biases the overall result.

To carry out a sensitivity analysis for effect of location all data were averaged across each location which gave nine effect size estimates (one per location). This had a very similar effect of causing the overall effect of peatland drainage on CH_4 emissions to be larger (d = -1.55,CI = -2.28 to -0.82) which was significantly less than 0 (z = 4.17, $p < 0.001$) with no heterogeneity between locations (chi-squared = 11.45, d.f. = 8, p = 0.178). Again, the increase in effect was marginal and there is, therefore, no evidence that extracting multiple effects sizes from the same location biased the overall mean effect.

Of the possible categories for sub-group analysis only peatland type, microsite type and season of measurement were performed (Table 2). Method of measurement and location could not be analysed because all but one study used static chambers to measure gas flux and all but one study was undertaken in temperate locations.

The overall effect size of drainage on reduction of CH_4 emissions for fens is much bigger than for bogs (Metaf Q = 4.803, d.f. = 1, p = 0.028). However, this result could be caused by other study-level factors, and the significant heterogeneity between studies on fens suggests the need for caution in the interpretation of this result.

Three micro-site types were identified from the literature; hummocks, hollows and lawns or fields. The lack of significant effect of drainage on CH_4 emissions in hollows may be due to a naturally higher water table in this microsite type. However, there is also no significant effect of drainage in hummocks which have a naturally lower water table. There is no significant differences between these microsite sub-groups (Q = 0.882, d.f. = 2, p = 0.643).

All the studies in this analysis made measurements at more than one time. However, the distribution of these measurements over a year is different between the studies. Most made measurements over at least one season, usually summer, while others spanned more than one season, usually seeking to record the whole time period during the year when the vegetation was growing (the 'growing season'). This sub-group analysis looks at differences between these groups. While the largest effect size of drainage is for the studies measuring CH_4 emission in summer plus one other season, there appears to be no consistent distinction between specific seasons, say, summer and winter. All confidence intervals overlap and there is no difference between groups (Q = 2.589, d.f. = 3, p = 0.459).

Table 2. Sub-group analysis of the influence of peatland type, microsite and season on the difference in CH_4 efflux between drained and undrained peatland showing the unitless standardised effect size (d, where negative this indicates a reduced efflux), test statistic (z), probability (p), confidence interval around d (CI), chi-squared statistic for heterogeneity (X^2) with associated degrees of freedom (d.f.) and probability (p).

Sub-group	Overall effect				Heterogeneity		
	d	z	p	CI	X^2	d.f.	p
Peatland type							
Fen	-1.83	3.42	0.001	-2.9, -0.8	32.26	12	0.001
Bog	-0.86	3.25	0.001	-1.4, -0.3	3.18	9	0.957
Microsite							
Lawn	-1.26	3.07	0.002	-2.1, -0.4	3.07	6	0.799
Hollow	-1.35	1.58	0.114	-3.0, 0.3	23.19	4	<0.001
Hummock	-2.33	1.67	0.094	-5.1, 0.4	2.26	1	0.132
Season							
Winter	-1.32	1.81	0.07	-2.8, 0.1	1.32	2	0.517
Summer	-0.95	2.19	0.02	-1.8, -0.1	5.94	4	0.204
Summer +1	-2.00	3.30	0.001	-3.2, -0.8	29.22	9	0.001
Summer +2	-0.79	1.52	0.128	-1.8, 0.2	4.85	4	0.303
Whole year	-1.05	1.93	0.054	-2.1, 0.01	0.18	1	0.670

The significant heterogeneity in the random effects model indicates a greater variability between studies than expected by chance alone. Meta-regression was performed between the studies on those continuous variables where there were sufficient data (Table 3). The difference in water table between intervention and control (effectively a measure of the extent of the intervention), depth of water table from the soil surface in the intervention and pH had a significant impact on the estimated effect of drainage on long-term CH_4 emissions. These results indicate that for each cm increase in the difference in water table depth (between the drained and undrained sites), or for each cm increase in the water table of the drained sites, the standardised mean difference in CH_4 emission (due to drainage) will decrease by 0.06 and 0.02 respectively. Similarly, for each unit increase in soil pH the standardised mean difference will decrease by 1.23. The relationship between these variables and effect size is shown in Figure 3. These data suggest that increasing water table depth (measured either as difference between intervention and control or as depth of water table in intervention) and increasing pH will decrease the amount of CH_4 released from peatlands. These relationships, however, appear to be strongly influenced by the three data points with the largest (negative) effect sizes. Removal of these three points from the meta-regression resulted in the loss of significance for all these relationships.

Table 3. Results of meta-regression of the effect modifiers on the difference in CH_4 emissions between drained versus undrained peatland, showing the number of effects included in the regression (n), the slope of regression equation (Coeff), the test statistic (z-slope) and the probability that the slope is different from zero (p > |z|).

Effect modifier	n	Coeff	z-slope	p > |z|
Year of study	26	0.045	1.16	0.245
Latitude	26	-0.044	-0.31	0.760
Time since intervention	25	-0.001	-0.02	0.983
Study temperature	18	0.137	1.23	0.220
Mean annual temperature	16	0.006	0.19	0.852
Soil temperature	22	0.028	0.73	0.464
Mean annual precipitation	20	0.001	0.27	0.783
Tree cover	8	-0.004	-0.46	0.646
Difference in water table level	26	-0.057	-3.03	0.002
Depth of water table	26	-0.020	-2.32	0.020
Soil bulk density	12	-0.001	-0.29	0.770
Peat thickness	23	0.001	0.10	0.921
Soil pH	17	-1.231	-2.49	0.013

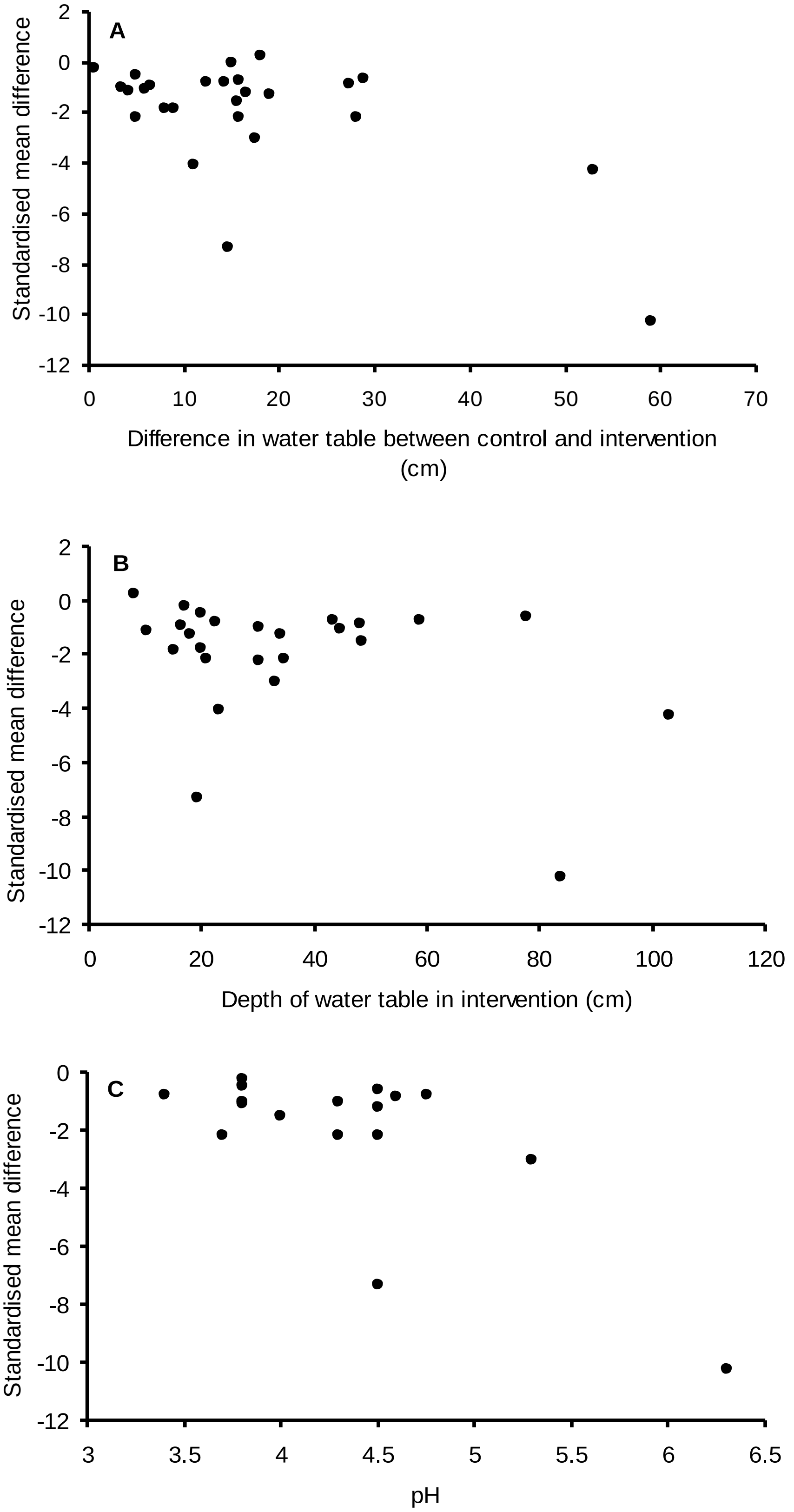

Figure 3. Variation in standardised mean difference of the difference in CH_4 emissions between drained vesus undrained peatland (negative values show a reduction in efflux) with the significant effect modifiers a) difference in water table between control and intervention, b) depth of water table in intervention, c) pH, from meta regression.

Re-wetted versus drained peatland

Just two studies, that met our inclusion criteria, reported comparison of CH_4 emissions between re-wetted and drained peatland. Five effect sizes were calculated from these studies. Both studies adopted a repeated measures design, however, Komulainen et al. (1998) also took before-after measurements. For CH_4 measurement Komulainen et al. (1998) used an in-situ closed-chamber and gas chromatography technique and Best and Jacobs (1997) used an incubation and acetylene inhibition method on extracted soil samples.

A random effects model meta-analysis produced an overall effect size comparing re-wetted versus drained peatland of d=1.52 (95% CI 0.76 to 2.28) which was significantly different from 0 ($z = 3.93$, $p < 0.001$). This effect is equivalent to an increase in efflux to the atmosphere of 16.1 mg CH_4 m^{-2} d^{-1} (95% CI = 0.4 to 31.7) from re-wet compared with drained peatland which has a 100-year global warming potential equivalent to 403 mg CO_2 m^{-2} d^{-1} (95% CI = 10 to 793. All effect sizes from individual studies were greater than 0 (Figure 4). Despite the major differences in their measurement methods, which might have been expected to have a large influence on the results (the chamber method being sensitive to the additional physical

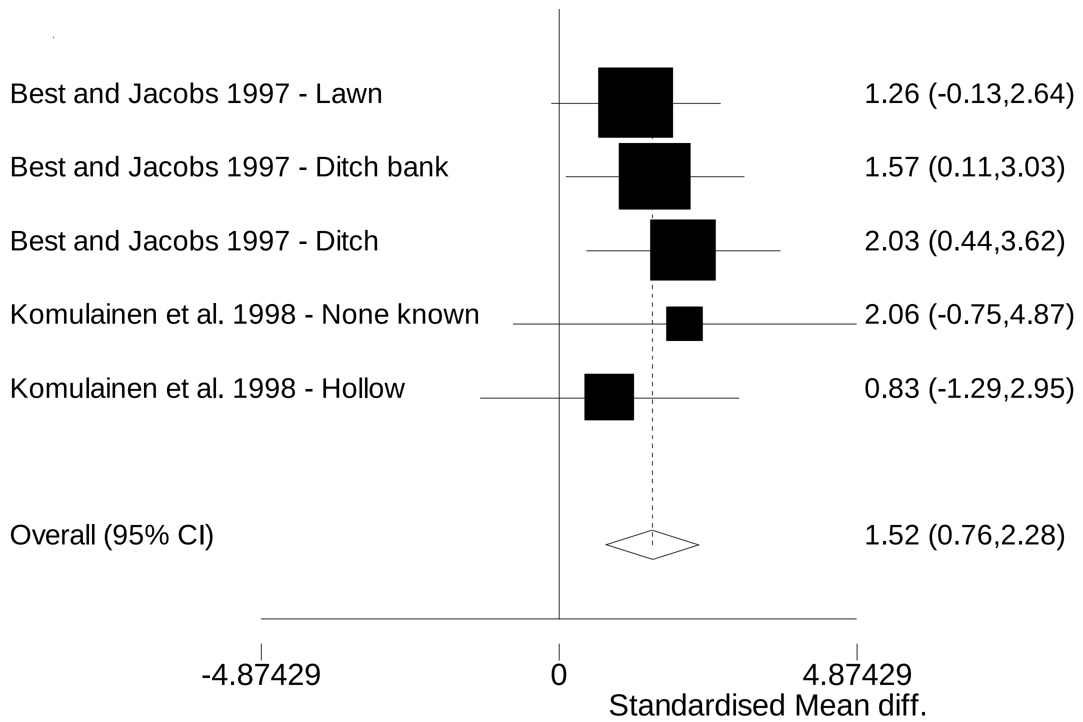

Figure 4. Forest plot of meta-analysis of effect sizes (standardised mean difference) of CH_4 emissions from re-wetted versus drained peatland. The vertical line represents no effect, the boxes show the weight of that study to the analysis and the horizontal lines are 95% confidence intervals of the effect. Individual values of effect sizes and confidence intervals are shown on the right. Positive values indicate a greater CH_4 efflux from re-wetted peatland and vice versa. The diamond is overall effect (a weighted average) of d = 1.52 with confidence intervals indicating that re-wet peatland emits more CH_4 than drained peatland. The labels for studies which made measurements in different locations indicate the type of site or microsite.

processes of CH_4 transport from soil to atmosphere), there was no significant heterogeneity between the two studies (chi squared = 1.09 d.f. = 4, p = 0.896). There is no evidence of publication bias (Egger's test t = -0.02, p = 0.984) however interpretation of the funnel plot is difficult due to small sample size (see Appendix IV in supplementary material at www.environmentalevidence.org/SR49.html). Sensitivity analyses suggest no study level or location level effects but sample sizes are small. Sub-group analysis was carried out on outcome measure method, season of measure and peatland type.

Outcome measure method and season of measure are the same group and separate at study level. Studies from Best and Jacobs (1997) used acetylene inhibition to measure CH_4 over a whole year and the three effect sizes they generated were significantly greater than 0. Effects sizes from Komulainen et al. (1998) used static chambers and gas chromatography to measure CH_4 but only over summer and autumn and their effect sizes were not significantly greater than 0 suggesting a possible sub-group difference however the confidence intervals of these two groups do overlap and differences are not significant (Metaf; Q = 0.238, d.f. = 1, p = 0.625).

There was no difference arising from peatland type although fens were only used in one of the five studies, bogs were the subject of the other four. Meta-regression was not performed on continuous variables as there was no significant heterogeneity between studies. Given the low sample sizes and levels of correlation between variables these results were not considered further.

Natural peatland

Twenty effect sizes from nine studies comparing CH_4 emissions from areas of naturally wet and dry peatland in the same area indicate that dry areas emit less CH_4 than wet areas (d = -0.60, CI = -1.03 to -0.13, z = 2.52, p = 0.012) with significant heterogeneity between studies (chi-squared = 57.19, d.f. = 19, p < 0.001) (Figure 5). This effect size is equivalent to 2.03 mg CH_4 m^{-2} d^{-1} (95% CI = 3.02 to 1.03) lower efflux from drier than wetter peatlands, which has a 100-year global warming potential equivalent to 50.75 mg CO_2 m^{-2} d^{-1} (95% CI = 75.5 to 25.75). All studies were paired site comparisons using static chambers and repeat measures over time. Only Bubier et al. (1993) moved chambers between sampling times within site introducing an element of independence between sample times.

There is no evidence of publication bias (t = -1.42, p = 0.172) but there is evidence of non-independence between effects (see Appendix IV in supplementary material at www.environmentalevidence.org/SR49.html). A sensitivity analysis performed by averaging over study level (and location) increases the effect size (d = -0.85, CI = -1.87 to 0.18) but reduces the power of the meta-analysis (z = 1.62, p = 0.105) while there is still heterogeneity between studies (chi-squared = 30.87, d.f. = 8, p < 0.001).

All confidence intervals overlapped (Table 4) and the only subgroup that retained a significant negative effect of peatland dryness on CH_4 efflux was from studies that only took measurements at one month in time. However none of the differences in effect size were significant (Season: Q = 3.72, p = 0.156, Peatland type: Q = 1.20, p = 0.273: Microsite: Q = 2.00, p = 0.367).

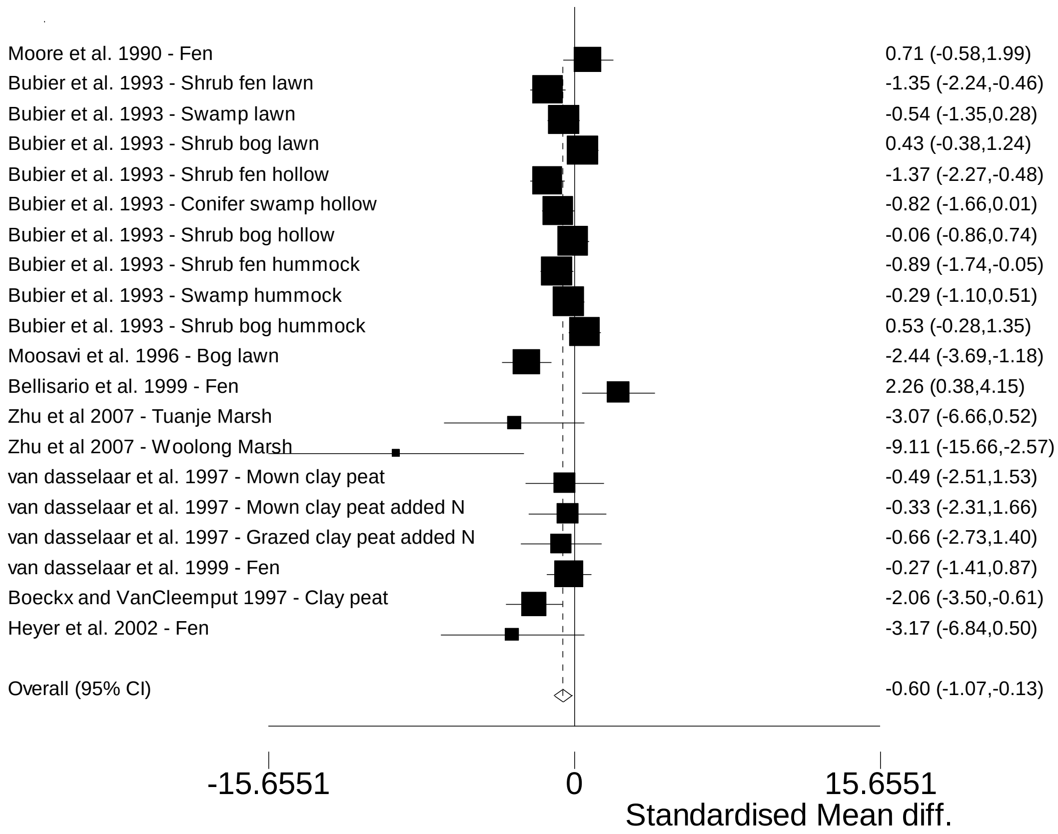

Figure 5. Forest plot of meta-analysis of effect sizes (standardised mean difference) comparing CH_4 emission of drier versus wetter natural peatlands. Each study label is annotated with type of peatland and microsite where available to differentiate between multiple extraction from the same study. When this was not available, location names have been given (Zhu et al. 2007). The vertical line represents no effect, the boxes show the weight of that study to the analysis and the horizontal lines are 95% confidence intervals of the effect. Individual values of effect sizes and confidence intervals are shown on the right. Positive values indicate a greater CH_4 efflux from drier than from wetter peatlands, and vice versa. The diamond is the overall effect (a weighted average) of d = -0.60 with confidence intervals that do not overlap the line of no effect indicating that wetter peatlands emit more CH_4 than drier peatlands.

There were many more significant relationships of effect modifiers on the impact of dryness on CH_4 efflux in studies comparing natural peatlands than those of manipulated peatlands (Table 5). Mean annual temperature, soil temperature, mean annual precipitation and latitude all had significant positive relationships with effect size. Therefore, as these variables increase, the difference in the amount of CH_4 emitted from drier areas compared with wetter areas decreases until, in some cases, drier areas emit more CH_4 than wetter areas. The biggest regression co-efficient was a negative correlation of effect size with pH suggesting that as soil becomes more acidic the difference in CH_4 efflux between dry and wet peatland is reduced, although this was not statistically significant. The coefficient relates to the expected change in effect size for each unit increase in the relevant effect modifier.

Table 4. Sub-group analysis of the influence of peatland type, microsite and season on the effect of site moisture on CH_4 efflux from drier versus wetter natural peatlands indicating effect size (d), test statistic (z), probability (p) confidence interval around d (CI), chi-squared statistic for heterogeneity (X^2) with associated degrees of freedom (d.f.) and probability (p).

Sub-group	Overall effect				Heterogeneity		
	d	z	p	CI	X^2	d.f.	p
Peatland type							
Fen	-0.67	1.59	0.111	-1.5, 0.2	9.22	4	0.056
Bog	-0.29	0.53	0.593	-1.4, 0.8	17.16	3	0.001
Microsite							
Hollow	-0.73	1.92	0.054	-1.5, 0.01	4.70	2	0.096
Hummock	-0.21	0.52	0.604	-1.02, 0.6	5.75	2	0.057
Lawn	-0.91	1.62	0.105	2, 0.19	16.96	3	0.001
Season							
One month	-2.21	3.21	0.001	-3.6, -0.9	0.31	1	0.580
Summer	-0.51	1.8	0.072	-1.1, 0.1	50.41	13	<0.001
Whole year	-0.38	0.9	0.366	-1.2, 0.4	0.12	3	0.989

Table 5. Summary results of meta regression of the effect modifiers from studies of the difference between drier versus wetter natural peatlands in CH_4 efflux showing number of effects included in regression (n), slope of regression equation (Coeff), test statistic (z-slope) and probability that the slope is different from zero (p > |z|).

Effect modifier	n	Coeff	T^2	z-slope	p > |z|
Mean annual temperature	14	0.271	0.716	2.41	0.016
Soil temperature	8	0.239	0.270	2.33	0.020
Mean annual precipitation	18	0.004	0.469	2.70	0.007
Difference in water table	19	-0.011	0.576	-0.59	0.555
Depth of water table	19	0.001	0.637	0.06	0.949
Year of study	20	-0.219	0.638	-2.27	0.023
Latitude	20	0.122	0.570	-2.45	0.014
pH	16	-0.493	0.397	-1.93	0.054

4.3.3 Comparison of CO_2 flux between drained, undrained and re-wetted peatland

Measurement of CO_2 fluxes falls into several different categories due to the relationship with photosynthesis and respiration and subsequently the influence of the diurnal cycle and vegetation on peatlands. Frequently, CO_2 flux measurements are taken in the dark only, resulting in an estimate of total respiration (i.e. plant and soil combined). This is often accompanied by removal of the above-ground vegetation giving an estimate of soil and root respiration only.

In other studies measurements were taken in full light or a range of light conditions, and reported as net ecosystem exchange (NEE). This measure combines photosynthetic uptake with respiration loss. This measure was also made where vegetation had been removed giving an estimate of soil NEE. Finally, two studies measured CO_2 flux over 24 hours (a full diurnal light-dark cycle), and this has been termed daily respiration.

Total respiration in drained versus undrained peatland

Measurements of total respiration in drained peatland were most numerous. Twenty one effect sizes were calculated from 10 studies (Figure 6). Most studies were fairly simple site comparisons using static or dynamic chambers to measure gas flux.

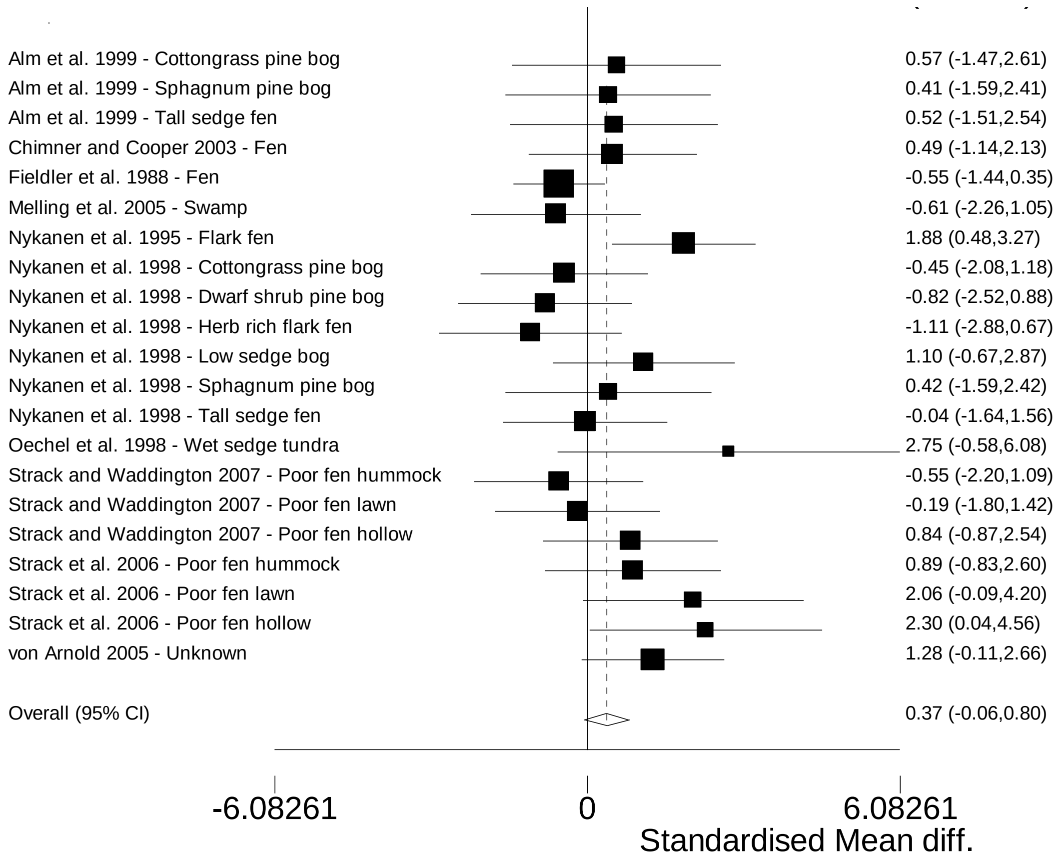

Figure 6. Forest plot of meta-analysis of effect sizes (standardised mean difference) comparing CO_2 emission as total respiration of drained versus undrained peatland. The labels indicate the study and either type of bog or microsite to distinguish between multiple effects from the same study. The vertical line represents no effect, the boxes show the weight of that study to the analysis and horizontal lines are 95% confidence intervals of the effect. Actual values of effect size and confidence interval are shown on the right. Positive values indicate a greater CO_2 efflux from drained than undrained peatland and vice versa. The diamond is overall effect (a weighted average) of d = 0.37 with confidence intervals that cross an effect size of 0 indicating that there is no difference in CO_2 emitted as total respiration between drained and natural peatlands.

Measurements were taken from a number of chambers at each site at different times using the same fixed chamber each time. Two studies took before and after measurements (Freeman et al. 2002; Strack and Waddington 2007). Two studies manipulated water level at much smaller scales than the others (Chimner and Cooper 2003; Oechel et al. 1998) using mesocosms again utilising a repeated measures approach.

The overall effect size in terms of CO_2 emissions generated by comparing drained with undrained peatland was d = 0.37 (95%CI = -0.06 to 0.8), which is not significantly different from 0 (z = 1.67, p = 0.094). Nonetheless, the raw data from each extraction were converted to the same units, a non-standardised meta-analysis was performed and the overall effect was that drained peatlands showed greater estimated total respiration emissions of CO_2 by 1.41g CO_2 m^{-2} d^{-1} (95% CI = 0.4 to 2.4). Sensitivity analysis indicated there was no difference in overall effect between single and multiple extraction of effects from the same studies or location.

There is some evidence of publication bias (Egger's test; t = 2.13, p = 0.46), however, most points fall within the 95% confidence interval on the funnel plot (see Appendix IV in supplementary material at www.environmentalevidence.org/SR49.html). The funnel plot does show a pattern of asymmetry and there is some evidence of non-independence in the data as there is a parabolic relationship between some of the effects. This could account for a lack of heterogeneity between studies despite both positive and negative effect sizes (chi-squared = 27.34, d.f. = 20, p = 0.126). Measures of respiration from Laine et al. (1996) were not included in this analysis as they measure only soil and root respiration with no surface vegetation. Also, the quality of the experimental design was such that extracted sample size was one and therefore could not be included in a meta-analysis.

Sub-group analyses were possible on type of peatland, season of measurement and microsite. All studies used a gas chamber to measure CO_2, the only real difference was in Chimner and Cooper (2003) who manipulated water level in mesocosms rather than at the field scale. Oechel et al. (1998) used a factorial randomised design and Strack and Waddington (2007) a BACI design in which the data were extracted as a site comparison and not confounded at baseline. All other studies were simple comparisons of drained and undrained fields. Confidence intervals overlapped for all sub-group analyses (Table 6) and Metaf analysis revealed no significant differences between groups in the effect of peatland draining on CO_2 efflux. Meta-regression of continuous variables was not done as there was no significant heterogeneity between studies.

Table 6 Summary of sub-group analysis of the influence of peatland type, microsite and season on CO_2 effluxes of drained versus undrained peatland showing the unitless standardised effect size (d), test statistic (z), probability (p) confidence interval around d (CI), chi-squared statistic for heterogeneity (X^2) with associated degrees of freedom (d.f.) and probability (p).

Sub Group	Overall effect				Heterogeneity		
	d	z	p	CI	X^2	d.f.	p
Peatland type							
Fen	0.417	1.33	0.183	-0.2, 1.0	18.85	11	0.064
Bog	0.134	0.35	0.766	-0.6, 0.9	3.17	5	0.674
Microsite							
Lawn	0.920	2.74	0.006	0.3, 1.5	6.65	7	0.466
Hollow	1.373	1.95	0.052	-0.01, 2.8	1.03	1	0.310
Hummock	0.147	0.2	0.838	-1.3, 1.6	1.42	1	0.234
Season							
Winter	0.497	0.84	0.403	-0.6, 1.7	0.01	2	0.993
Summer	0.282	0.69	0.488	-0.5, 1.1	3.9	4	0.420
Summer +1	0.561	1.47	0.141	-0.2, 1.3	16.03	9	0.066
Whole year	0.389	0.41	0.678	-1.4, 2.2	2.92	1	0.087

Total respiration in re-wet peatland
There were no studies comparing total respiration of re-wetted versus drained peatland, although data on daily respiration rate are reported below.

Total respiration in natural peat
Only two effect sizes from one study (Chapman and Thurlow 1996) were extracted on total CO_2 respiration comparing naturally wetter and drier areas of peatland. Both were bog sites in Scotland, one with pine and one dominated by heather. A paired comparison approach was used with gas chambers in fixed locations and repeat measures over time. The overall effect (d = 2.66) indicates a significantly greater efflux of CO_2 (z = 2.15 p = 0.32) from drier peatlands than from wetter peatlands of 78.39 mg CO_2 m^{-2} d^{-1}. Given the lack of available data no further analysis was carried out.

Daily respiration
Three effects sizes were extracted for CO_2 as daily respiration measured over 24 hours comparing re-wetted with drained peatland and these were from the same study (Best and Jacobs 1997) and the same field but different microsites within that field; lawn, ditch bank and ditch bottom (Figure 7). However, there was no overall difference in CO_2 production using the acetylene inhibition method (d = 0.02, CI = -0.7 to 0.74, z = 0.05, p = 0.957).

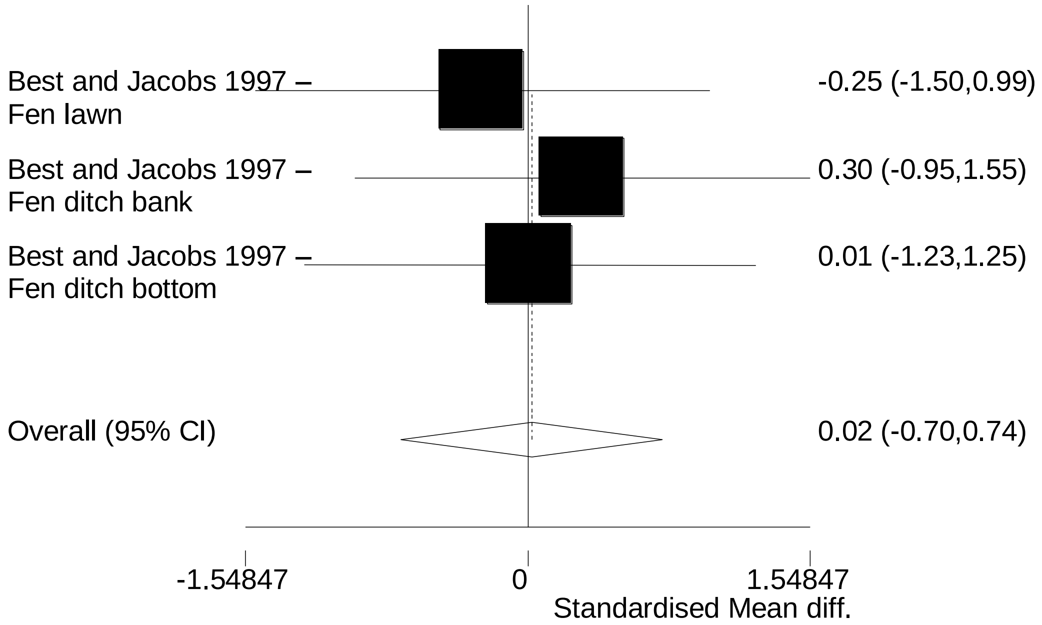

Figure 7. Forest plot of meta-analysis of effect sizes (standardised mean difference) from Best and Jacobs (1997) on CO_2 (daily respiration) emissions comparing re-wetted with drained peatland. The labels indicate microsite. The vertical line represents no effect, the boxes show the weight of that study to the analysis and the horizontal lines are 95% confidence intervals of the effect. Actual values of effects sizes and confidence intervals are shown on the right. Positive values indicate a greater CO_2 emission from re-wetted compared with drained sites and vice versa. The diamond is overall effect (a weighted average) of d = 0.57 with confidence intervals that overlap the line of no effect indicating no difference in CO_2 flux.

Net ecosystem exchange in drained peatland

Net ecosystem exchange (NEE) was defined in these studies as the CO_2 flux in light conditions. Light levels were manipulated using shade to give flux measurements at a range of photosynthetically active radiation (PAR) levels. In many studies respiration and NEE were combined to give an estimate of gross ecosystem photosynthetic rate. These latter, combined data were not extracted (in accordance with the extraction protocol) as they were not directly measured.

Only three studies comparing NEE on drained with undrained peatland met the inclusion criteria; they yielded five effect sizes (Figure 8). All three studies took slightly different approaches. One adopted the simple site comparison approach using repeated measures (Riutta et al. 2007). Strack and Waddington (2007) combined this design with before-after measurements indicating no baseline confounding. Finally, Chimner and Cooper (2003) manipulated water level in situ using mesocosms at a relatively small scale.

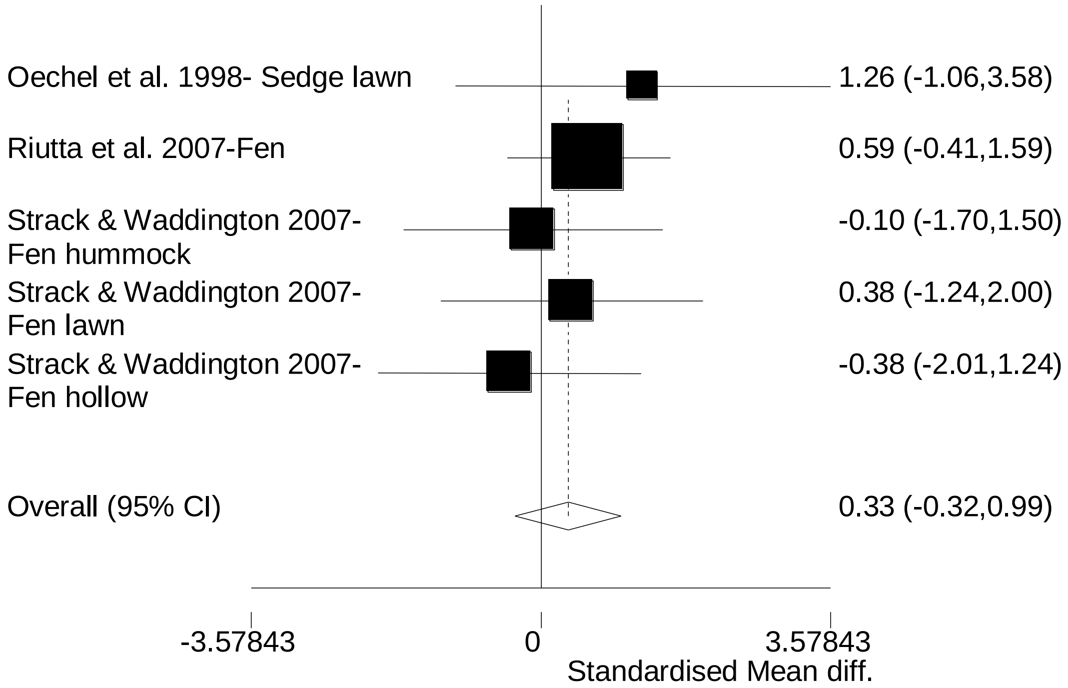

Figure 8. Forest plot of meta-analysis of effect sizes (standardised mean difference) comparing CO_2 emissions as net ecosystem exchange in drained with undrained peatland. The labels indicate study, type of peatland and microsite where known. The vertical line represents no effect, the boxes show the weight of that study to the analysis and the horizontal lines are 95% confidence intervals of the effect. Actual values of effects sizes and confidence intervals are shown on the right. Positive values indicate a greater CO_2 emission as NEE from the drained than undrained peatland, and vice versa. The diamond indicates the overall effect (a weighted average) of d = -0.17 with confidence intervals that cross an effect size of 0 indicating that there is no difference in NEE between drained and undrained peatlands.

The overall effect size generated by comparing NEE in drained with undrained peatland (d = 0.33, CI = -0.32 to 0.99) was not significantly different from 0 (z = 1.0, p = 0.317) when measured as NEE in non-standardised meta-analysis. There was also no significant heterogeneity between studies (chi squared = 1.94, d.f. = 4, p = 0.754). There was no evidence of publication bias (t = -0.13, p = 0.902) however with such a small amount of studies interpretation of the funnel plot is difficult (see Appendix IV in supplementary material at www.environmentalevidence.org/SR49.html).

Sensitivity analysis and sub-group analysis were not performed due to small sample size and insufficient data in each group. Also as there was no heterogeneity between studies meta-regression was not carried out. There were no studies comparing NEE in re-wetted and drained peatland.

4.3.4 Comparison of N_2O flux between drained, undrained and re-wetted peatland

Drained versus undrained peatland

Thirteen effects sizes were calculated from 8 studies comparing N_2O emissions of drained versus undrained peatland (Figure 9). Most studies reported gas flux from single-site comparisons using static chambers and gas chromatography over time in a repeated measures design. Only one study (Davidsson and Leonardson 1997) extracted cores and used an acetylene inhibition and incubation method of gas extraction. However, this was also still essentially a site comparison with repeated measures although the sample size was relatively large.

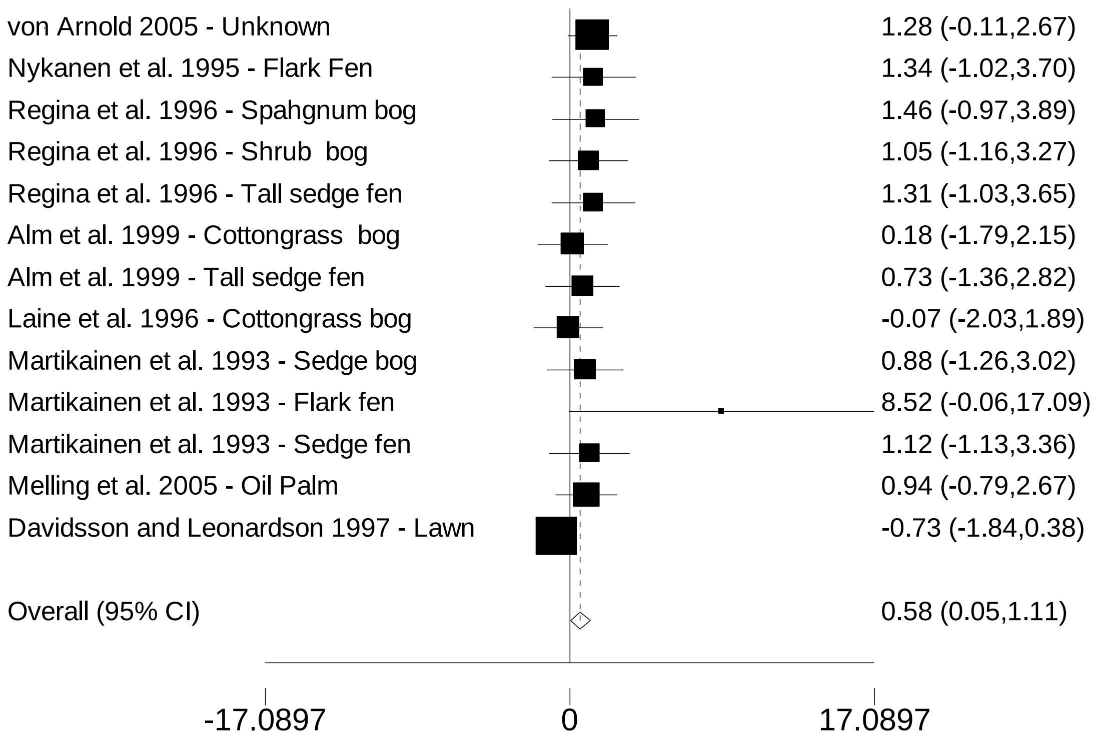

Figure 9. Forest plot of meta-analysis of effect sizes (standardised mean difference) comparing N_2O emissions of drained with undrained peatland. The labels indicate the study and, where known, type of peatland and microsite. The vertical line represents no effect, the boxes show the weight of that study to the analysis and the horizontal lines are 95% confidence intervals of the effect. Actual values of effects sizes and confidence intervals are shown on the right. Positive values indicate greater N_2O emission from drained than undrained peatland, and vice versa. The diamond is overall effect (a weighted average of all effect sizes) of d = 0.58 with confidence intervals that do not cross the line of no effect indicating that drained peatlands emit more N_2O compared with undrained controls.

Drained peatland showed greater emission of N_2O than undrained with an overall effect size (d = 0.58, CI = 0.05 to 1.11) which was significantly different from 0 (z = 2.13, p = 0.033) with no significant heterogeneity between studies (chi-squared = 12.13, d.f. = 12, p = 0.436). Conversion of raw data to common units shows that drained peatland N_2O emission 95.36 µg m^{-2} d^{-1} (95% CI = 63 to 128) was greater than un-drained controls; this has a 100-year global warming potential equivalent to 28.3 mg CO_2 m^{-2} d^{-1} (4.1 to 65.5). There is evidence of publication bias (t = 4.00, p = 0.001) with a skewed distribution in the funnel plot (see Appendix IV in supplementary material at www.environmentalevidence.org/SR49.html).

Sensitivity analyses examining non-independence at the study-level resulted in a meta-analysis of nine effect sizes. The overall effect (d = 0.47, CI = -0.14 to 1.08) was no longer significant (z = 1.51, p = 0.131). However, the study by Davidsson and Leonarson (1997), which has the greatest weight in the analysis, was the only one to extract soil cores then measure gas emission in the laboratory. All other studies took gas samples in-situ using static or closed chambers. When this study was excluded from the analysis the resulting overall effect of d = 0.99 (CI = 0.26 to 1.72) is significantly greater than 0 (z = 3.12, p = 0.002). Sensitivity analysis of location-level effect (averaged across locations) gives an overall effect size of d = 0.42 (CI = -0.28 to 1.13) which is not significantly greater than 0 (z = 1.18, p = 0.236). However, with the study by Davidsson and Leonardson (1997) removed the effect increases to d = 1.19 (CI = 0.29 to 2.10) which is significantly greater than 0 (z = 2.58, p = 0.01). Therefore there is evidence to suggest that multiple extraction from the same studies or locations may cause bias in the results. However, there is also some evidence to suggest that not taking gas samples in the field can change the direction of the effect size.

Sub-group analysis was possible on type of peatland, location and season of measurement. There was insufficient information to look at differences between microsites as only results from lawn or field sites were reported, or type of site was not stated and is therefore assumed to be lawn. The outcome measurement was always made using a static or closed chamber for gas extraction followed by gas chromatography in the laboratory. Only one study was different, that of Davidsson and Leonardson (1997) mentioned above.

All confidence intervals in the sub-groups overlap indicating no difference between groups in effect of drained versus undrained peatland on N_2O efflux (Table 7). However, the overall effect size for fens is significantly greater than 0 whereas it is not for bogs, with equal numbers of individual effect sizes. Also Lakkasuo Mire in Finland has an overall significant effect size but this group benefits from much greater power than the others in the analysis. Metaf analysis indicates no difference between fen and bogs (Q = 3.13, p = 0.07) but differences between location (Q = 6.26, p = 0.043) and season (Q = 20.66, p < 0.001).

Table 7. Summary of sub-group analysis of the influence of peatland type, location and season on the difference in N_2O effluxes of drained versus undrained peatland showing the unitless standardised effect size (d), test statistic (z), probability (p) confidence interval around d (CI), chi-squared statistic for heterogeneity (X^2) with associated degrees of freedom (d.f.) and probability (p).

Sub Group	Overall effect				Heterogeneity		
	d	z	p	CI	X^2	d.f.	p
Peatland type							
Fen	1.24	2.17	0.03	0.1, 2.4	2.99	4	0.560
Bog	0.75	1.52	0.129	-0.2, 1.7	1.09	4	0.895
Location							
Vombs, Sweden	-0.73	1.28	0.199	-1.8, 0.4	-	-	-
Asa, Sweden	1.28	1.81	0.07	-0.1, 2.7	-	-	-
Sarawak	0.9	1.07	0.287	-0.7, 2.7	-	-	-
Lakkasuo	0.85	2.07	0.038	0.05, 1.6	4.18	7	0.759
Ilomantsi	1.4	1.62	0.105	-0.3, 3.1	0.01	1	0.943
Season							
Winter	0.75	1.00	0.318	-0.7, 2.2	0	1	0.993
Summer	8.51	1.95	0.052	-0.1, 17.1	-	-	-
Summer +2	0.86	1.71	0.088	-0.1, 1.9	1.32	4	0.859
Whole year	0.23	0.59	0.555	-0.5, 1.01	5.71	2	0.057

Re-wetting peatland

Only one study measured N_2O emission in re-wetted versus drained peatland (Davidsson et al. 2002); the measurement was made as soil background concentration using an acetylene inhibition method in a single paired site comparison at only two times**.** Re-wetted peatland showed lower emission of N_2O than drained peatland with an overall effect (d = -2.46, CI = -3.65 to -1.27, z = 4.05, $p < 0.001$) equating to 4.3 mg N $m^{-2}d^{-1}$or 7.1 mg N_2O $m^{-2}d^{-1}$ with a 100-year global warming potential equivalent to 2.1 g CO_2 $m^{-2}d^{-1}$.

Natural peatland

Only two effects sizes from one study (Huttunen et al. 2002) were extracted comparing N_2O flux on naturally wetter and drier areas of the same peatland. Both were paired comparison fen sites in northern Finland using static chambers with repeat measures over time. There was no significant overall effect on N_2O emission of dry areas of peatland compared to wet sites (d = 0.61, z = 1.02, p = 0.306).

4.3.5 Comparison of dissolved organic C (DOC) in drained, undrained and re-wetted peatland

Drained versus undrained peatland

Data providing eight effect sizes from four studies were extracted comparing concentration of DOC in soil water in drained with undrained peatland. The sample size in Moore (1987) was effectively created by pseudo-replication so this study was excluded from the synthesis (Figure 10). The remaining studies were all single paired-site comparisons with repeat measures over time. Only Hughes et al. (1998) took before-after measurements as well as a site comparison.

The overall effect suggests a greater concentration of DOC in drained than undrained peatlands (d = 1.20, CI = 0.46 to 1.95) which was significantly greater than 0 (z = 3.18, p = 0.001). A non-standardised meta-analysis on data converted to the same units indicated this effect size was approximately equivalent to an increase of 7 mg/l DOC in drained peatland compared with controls. There was significant heterogeneity between studies (chi-squared = 44.76, d.f. = 6, p < 0.001). There was no evidence of publication bias (t = 0.86, p = 0.431).

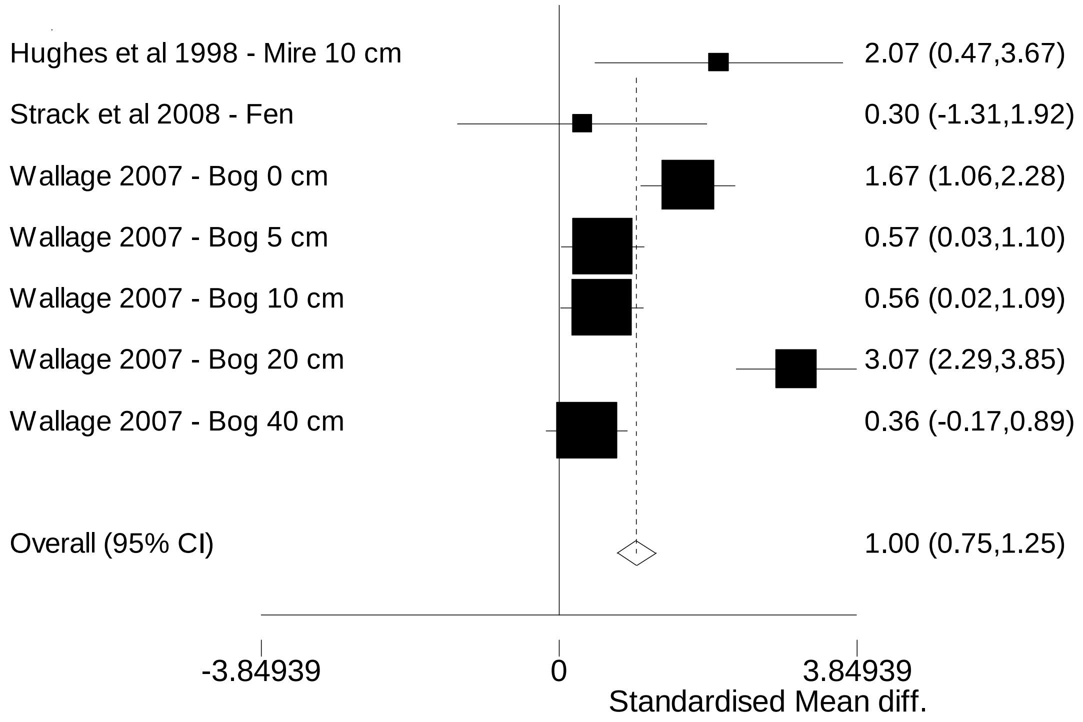

Figure 10. Forest plot of meta-analysis of effects sizes (standardised mean difference) of concentration of DOC in soil water in drained versus undrained peatland. The labels indicate study and, where known, peatland type and depth of sample. The vertical line represents no effect, the boxes show the weight of that study to the analysis and horizontal lines are 95% confidence intervals of the effect. Actual effects sizes and confidence intervals are given on the right. Positive values indicate a greater concentration of soil water DOC in drained peatland than in undrained controls, and vice versa. The diamond is overall effect (a weighted average of all effect sizes) of d = 1.20.

Sensitivity analysis of the study-level effect by averaging the effects across depths in Wallage (2007) resulted in no difference to the original result (d = 1.40, CI = 0.68 to 2.18, z = 3.83, p < 0.001) except that there was now no heterogeneity between studies (chi-squared = 2.56, d.f. = 2, p = 0.278) presumably due to the loss of power in the analysis. Given the low number of studies and insufficient reporting of variables, it was not considered sensible to perform multiple sub-group analysis or meta-regression.

Re-wetted versus drained peatland
Three studies provided 11 effect sizes on DOC concentration in soil water in re-wetted versus drained peatland. One study (Glatzel et al. 2003) had an extractable sample size of 1 so was excluded from the synthesis (Figure 11). All other studies were based on a single paired-site comparison with repeat measures over time. Wallage (2007) presented data from different depths and this was extracted separately.

The overall difference in soil water DOC concentration between re-wetted and drained peatland (d = -0.39, CI = -1.77 to 0.99) was not significantly different from 0 (z = 0.55, p = 0.583). There was, however, significant heterogeneity between effects (chi-squared = 208.8, d.f. = 10, p < 0.001). When a sensitivity analysis on the study level was conducted, the effect size remained non-significant (d = 0.25, CI = -3.44 to 3.94) and heterogeneity between studies remained (chi-squared = 84.6, d.f. = 2, p < 0.001) suggesting that extracting multiple effects from a study did not bias the result. There was no evidence of publication bias (t = -1.63, p = 0.137) although there was, unsurprisingly, evidence of a lack of independence in the funnel plot (see Appendix IV in supplementary material at www.environmentalevidence.org/SR49.html).

Sub-group analysis was performed on type of peatland and method of measuring DOC concentration (both correlated by reporting), and on year of study, location and season of measurement (all correlated by reporting). Several variables were inseparable and correlated with study level effects (Table 8). Because of this, despite clear differences in each sub-group (Peatland type/measure method Q = 10.09, d.f. = 1, p = 0.001 and Year/location/season Q = 22.62, d.f. = 1, p < 0.001), any interpretation of these differences would be speculative. There was a significant positive relationship between pH and effects size (Table 9) which indicates a unit increase in pH will increase the effect size by 2.025 (i.e. is associated with a greater reduction in DOC concentration with re-wetting of peat). However, pH is correlated with study and this can also therefore be interpreted as a study level effect.

Overall, these results suggest that soil water DOC concentrations are higher in drained than undrained peatland. While re-wetting appears to have either no effect on DOC concentration or uncertain effects as multiple effect sizes from two studies (Meissner et al. 2003, Wallage 2007) produced opposing results.

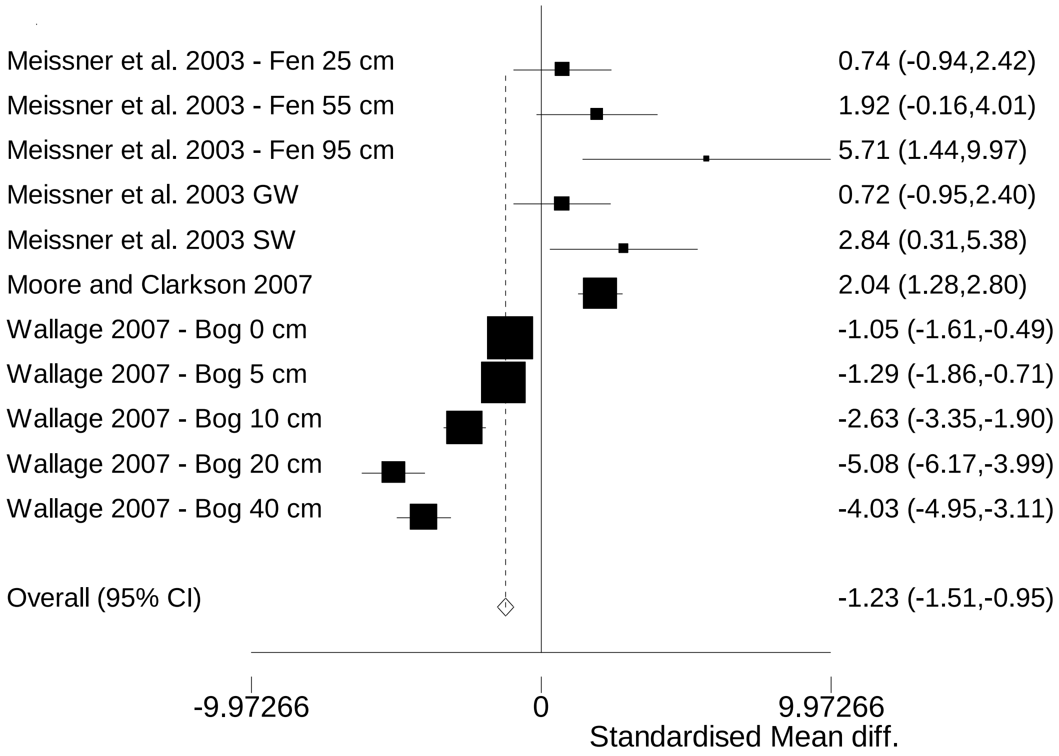

Figure 11. Forest plot of meta-analysis of effect sizes (standardised mean difference) comparing DOC concentration in soil water of re-wetted versus drained peatland. The labels indicate study and, where known, type of peatland and depth of sample in cm or ether groundwater (GW) or surface water (SW). The vertical line represents no effect, the boxes show the weight of that study to the analysis and the horizontal lines are 95% confidence intervals of the effect. Actual effects sizes are given on the right. Positive values indicate a greater concentration of DOC in the re-wetted than drained peatland, and vice versa. The diamond is the overall effect (a weighted average) of d = -0.39 with confidence intervals that overlap the line of no effect indicating that concentration of DOC does not differ between re-wetted and drained peatlands.

Table 8. Summary of sub-group analysis of the influence of peatland type/measurement method and year/location/season on the difference in soil water DOC concentration of re-wetted versus drained peatland showing the unitless standardised effect size (d), test statistic (z), probability (p) confidence interval around d (CI), chi-squared statistic for heterogeneity (X^2) with associated degrees of freedom (d.f.) and probability (p).

Sub Group	Overall effect				Heterogeneity		
	d	z	p	CI	X^2	d.f.	p
Peatland type/Measurement method							
Fen/Standard German	1.71	2.67	0.008	0.5, 3.0	6.58	4	0.160
Bog/TC analyser	-1.98	2.27	0.025	-3.7, -0.3	165.51	5	<0.001
Year/Location/Season							
2006/NZ/March	2.03	5.25	<0.001	1.3, 2.8	-	-	-
2005/UK/Year	-2.76	4.02	<0.001	-4.1, -1.4	68.52	4	<0.001
1997/Germany/1.5 Year	1.71	6.58	<0.001	0.5, 3.0	6.58	4	0.160

Table 9. Summary results of meta-regression on effect modifiers on the difference in soil water DOC concentration in re-wetted versus drained peatland showing the number of effects included in regression (n), slope of regression equation (Coeff), test statistic (z-slope) and probability that the slope is different from zero (p > |z|).

Effect modifier	n	Coeff	z-slope	p > |z|
Depth of sample	8	0.07	-2.20	0.051
pH	10	2.025	4.27	<0.001

4.3.6 Comparison of soil microbial C in re-wetted versus drained peatland

Soil microbial C concentration was only compared between re-wetted and drained peatland. Twelve effect sizes from two studies were calculated and synthesised (Figure 12). Both studies were paired-site comparisons with measures repeated over time and at different depths.

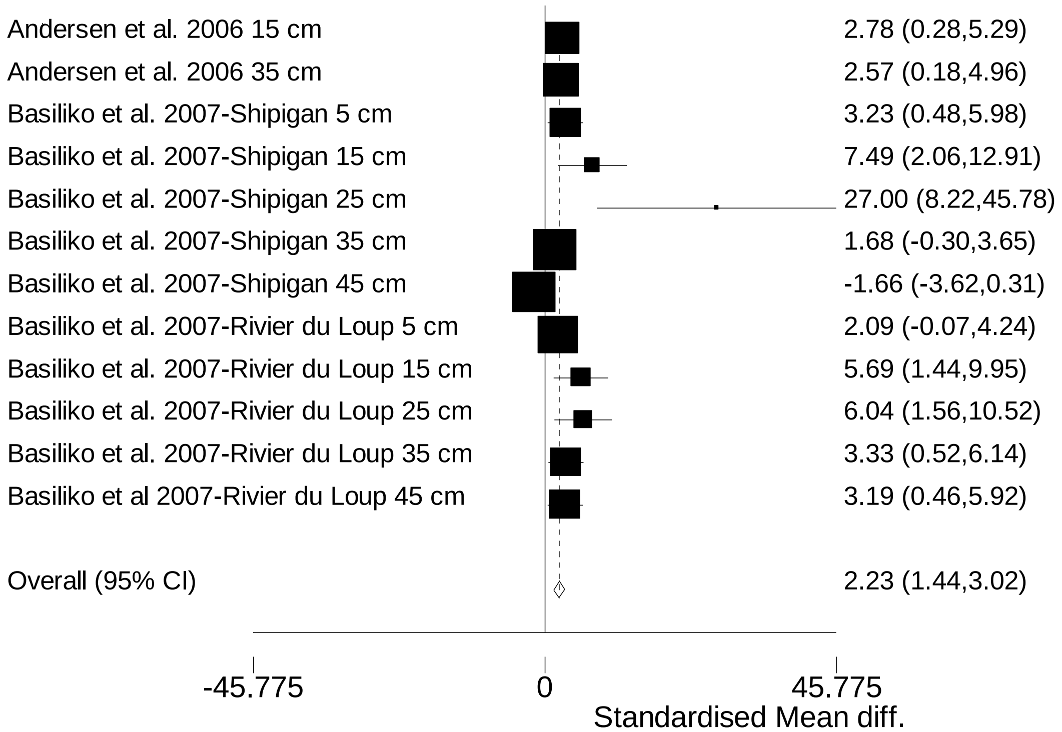

Figure 12. Forest plot of meta-analysis of effect sizes (standardised mean difference) comparing soil microbial C concentration in re-wetted with drained peatland. The labels indicate study, location and depth of sample. The vertical line represents no effect, the boxes show the weight of that study to the analysis and the horizontal lines are 95% confidence intervals of the effect. Actual effects sizes and confidence intervals are given on the right. Positive values indicate a greater soil microbial C concentration in the re-wetted than the drained peatland, and vice versa. The diamond is overall effect (a weighted average) of d = 2.95 with confidence intervals indicating that re-wetted peatlands have greater soil microbial C concentration than drained peatland by approximately 1.68 mg C g^{-1} of peat.

The overall effect (d = 2.95, CI = 1.48 to 4.42) was significantly greater than 0 (z = 3.93, p < 0.001) with only one of the individual effects being negative. A non-standard meta-analysis shows that re-wetted peatland has a greater soil microbial C concentration by 1.68 mg C g^{-1} compared with drained controls. There is significant heterogeneity between studies (chi-squared = 32.72, d.f. = 11, p = 0.001). There is also evidence of publication bias (t = 4.85, p = 0.001) and obvious lack of independence in the funnel plot with clear asymmetry (see Appendix IV in supplementary material at www.environmentalevidence.org/SR49.html).

The difference in soil microbial C concentration between re-wetted and drained peatland remains when averaged over study level (d = 3.10, CI = 1.19 to 5.02, z = 3.18, p = 0.001) and location level (d = 3.28, CI = 1.66 to 4.90, z = 3.96, p < 0.001) with no heterogeneity remaining between effects, suggesting that multiple extraction from the same studies does not bias the results.

Table 10. Summary of sub-group analysis of the influence of study/year, location and outcome measure method on the difference in soil microbial C concentration of re-wetted versus drained peatland showing the unitless standardised effect size (d), test statistic (z), probability (p) confidence interval around d (CI), chi-squared statistic for heterogeneity (X^2) with associated degrees of freedom (d.f.) and probability (p).

Sub Group	Overall effect				Heterogeneity		
	d	z	p	CI	X^2	d.f.	p
Study/Year							
Andersen/2003	2.67	3.02	0.002	0.9, 4.4	0.01	1	0.905
Basiliko/2001	3.17	3.34	0.001	1.3, 5.0	32.3	9	0.001
Location							
Shipigan	2.94	1.66	0.097	-0.5, 6.4	22.77	4	<0.001
Riviere-du-Loup	3.07	5.75	<0.001	2.0, 4.1	4.2	6	0.645
Outcome measure method							
Fumigation extraction	2.56	2.22	0.026	0.3, 4.8	24.88	6	<0.001
Water extraction	3.29	4.92	<0.001	2.0, 4.6	3.87	4	0.423

Table 11. Summary results of meta regression of the effect modifiers on the difference in soil microbial C concentration of re-wetted versus drained peatland showing number of effects included in regression (n), slope of regression equation (Coeff), test statistic (z-slope) and probability that the slope is different from zero (p > |z|).

Effect modifier	n	Coeff	z-slope	p > |z|
Depth of sample	12	-0.063	-1.46	0.145
Time since intervention	12	-0.104	-0.70	0.487
C:N	12	0.109	0.48	0.632
pH	12	0.137	0.04	0.966

Sub-group analyses were performed on location, year of measure (a surrogate for study level) and outcome measure method. All confidence intervals overlap (Table 10). Although there was a difference in the significance of the overall effect at the location level (Table 10) this was no significant difference between effect sizes ($Q = 3.24$, d.f. = 1, $p = 0.072$). Meta-regression was performed on the continuous variables depth of sample, time since intervention, C:N and pH but no significant relationships between them and the effect of re-wetting were identified (Table 11).

5. Discussion

5.1 Evidence of long-term impact of draining and re-wetting

This study set out to review the available evidence relevant to the question 'How do draining and re-wetting affect carbon stores and GHG fluxes in peatland soils?' Addressing this question involved a large number of intervention-outcome combinations, the results of which are summarised in Table 12.

Overall the most substantial body of evidence is on the effects of draining peatlands. This probably reflects the amount of time there has been to carry out studies on this process due to the historical use of peatlands for agriculture and extraction of peat as a domestic and industrial fuel. Re-wetting, by comparison, is a relatively recent practice (Farrell and Doyle 2003, Rupp et al. 2004), and there is a shortage of long-term large-scale studies, which present a major practical challenge in terms of selection of suitable comparator sites and the duration of up to 20 years that may be required (see limitations below). In studies that measured all three main GHGs (CO_2, CH_4 and N_2O) draining peatland, on average, increased GHG emissions but this was not a statistically significant effect. However, there were no studies that simultaneously measured all three GHGs on re-wetted peatland.

There is good evidence that draining peatland reduces long-term CH_4 efflux, while re-wetting has the opposite effect. Naturally wetter and drier areas of the same peatland are unlikely to differ to the same extent in soil structure, chemistry or vegetation as is the case when peatland is drained or re-wet by man followed by a change in land use (e.g. commencement or cessation of agriculture). Nonetheless, studies comparing naturally wetter and drier areas of peatland have shown the same trends in long-term CH_4 flux as those studying the effects of draining or re-wetting. While the causes of CH_4 efflux from peatland are complex (Moore and Dalva 1997) this result supports the current paradigm that a raised water table increases anaerobic decomposition of soil organic matter and therefore increases CH_4 efflux (Charman 2002).

The balance between aerobic and anaerobic conditions in the peatland will determine the balance between CO_2 and CH_4 efflux. Under aerobic conditions CO_2 efflux will occur due to both microbial and plant root respiration (Moore and Dalva 1997). However, per gramme CH_4 has 25 times the global warming impact of CO_2 over 100 years (Forster et al. 2007). Evidence for this trade-off between CO_2 and CH_4 efflux due to changes in peatland hydrology was, however, surprisingly unclear across the reviewed studies. In part this may be due to the variety of ways in which CO_2 flux was measured. While the mean rate of CO_2 efflux measured as total respiration was greater in drained peatland than undrained controls, this difference was not statistically significant. Similarly, drainage had no significant effect on the rate of CO_2 efflux measured as daytime net ecosystem exchange. Evidence of the effect of re-wetting peatland on CO_2 flux is very poor. Only one study measured daily respiration and it showed no evidence of an effect. Even in natural peatlands evidence of a difference between wetter and drier areas is weak; there was only one study, though it reported two effects both of which did show the expected result that drier peatland had higher rates of total respiration CO_2 efflux than wetter peatland.

There was good evidence in 14 effects from nine reviewed studies that peatland drainage increases the efflux of the third main GHG, N_2O. This can be attributed to microbial aerobic nitrification whose rate is linked positively to oxygen levels as well as the availability of N-substrate and is reduced by greater water table level (Hyvonen et al. 2009). As with other outcomes, the evidence on the effects of re-wetting peatland is much poorer than for drainage; only one effect was extracted, although it does show the expected decrease in N_2O emissions. This trend is supported, albeit weakly, by the one reviewed study on natural peatlands which showed greater N_2O emissions in the drier than the wetter areas of peatland.

Combining the evidence of the effect of peatland drainage on the three GHGs, thirteen field studies (giving 27 effect sizes) showed a mean reduction in CH_4 efflux equivalent (over 100 years) to 201 mg CO_2 m^{-2} d^{-1}; ten field studies (giving 21 effect sizes) showed a mean increase in CO_2 efflux as total respiration by 1.41 g CO_2 $m^{-2}d^{-1}$; and 9 field studies (giving 14 effect sizes) showed a mean increase in N_2O efflux equivalent (over 100 years) to 39.7 mg CO_2 m^{-2} d^{-1}. Together they indicate a net mean effect of draining peatland of an increase in 100-year CO_2 equivalent efflux of 1.25 g m^{-2} d^{-1}; this is a comparable value to the mean increase of 1.52 g CO_2 m^{-2} d^{-1} from the four studies that measured the fluxes of all three gases.

As well as gaseous emissions, loss of C from peatland stocks in solution into streamwater is also a very important component of the C budget. Draining peatlands increases the amount of peat exposed to oxidation, which is likely to increase the production of DOC (Worral et al. 2004). The available evidence of dissolved C concentrations is compatible with this proposal, showing that draining peatland increases DOC concentration (seven effects from three studies), while re-wetting peatland reduces DOC concentration (11 effects from three studies). There is, however, significant heterogeneity in these data with different studies of the same treatment showing opposite effects (see below – variation in effectiveness). Nonetheless, interpretation of these changes in concentration must be extremely limited. In the absence of information on the effect of peatland draining or re-wetting on the quantity of water flowing out from the peatland, they provide no information about the actual rate, or even direction, of effect on losses of soil C by this pathway. An assessment of the global greenhouse effect significance of these losses would also need to take into account the fate of the dissolved C in the streamwater. Similarly the loss of DIC to streamwater and groundwater also needs consideration

There is a much greater evidence-base for fluxes of GHG or dissolved C from peatland than there is for C storage in peatland. No studies that met the inclusion criteria measured total soil C stocks or a complete C budget. Two studies did measure the effects of draining peatland on total C concentration in the soil; they showed no effect of drainage, but the impact of this on C storage is likely to be minor compared

Table 12. Summary of effect sizes and significance from each intervention/outcome combination of draining and re-wetting peatland on GHGs effluxes and concentrations of different forms of soil C. n = number of effects, nS =number of studies. ES = effect size as standardised mean difference, Sig = statistically significant, FP Asy = funnel plot asymmetry, Bias = result of Eggers' test, Ind = pattern of non-independence in funnel plot, Het = significant heterogeneity between effects, S-gp = result of sub-group analysis if differences between groups were significant, Mr = result of meta-regression, SA = result of sensitivity analysis, DOC = dissolved organic carbon, - = not done, MAT = mean annual temperature, ST = soil temperature, MAP = mean annual precipitation, Lat = latitude, year = year of study.

Intervention and outcome	n	nS	ES	Sig	FP Asy	Bias	Ind	Het	S-gp	Mr	SA
Draining - field studies											
CH_4	27	13	-1.33	y	y	y	y	y	Fens > Bogs	-ve with water level and pH.	No effect
CO_2 (total respiration)	21	10	0.37		y	y	y		No diffs	-	No effect
CO_2 (Net Ecosystem Exchange)	5	3	0.33			y			-	-	-
N_2O	14	9	0.58	y	y	y	y		Location and season	-	Location and study level may affect but methodology important
DOC	7	3	1.20	y				y	No diffs	None significant	No effect
All GHGs in same study separately	15	5	0.25		-	-	-	-	-	-	-
All GHGs combined	5	5	0.46		-	-	-	-	-	-	-
Re-wetting - field studies											
CH_4	5	2	1.52	y					No diffs	-	No effect
CO_2 (daily respiration)	3	1	0.02		-	-	-	-	-	-	-
DOC	11	3	-0.39					y	Too many correlated variables	+ve with pH	No effect

Intervention and outcome	n	nS	ES	Sig	FP Asy	Bias	Ind	Het	S-gp	Mr	SA
Microbial C	12	2	2.95	y	y	y	y	y	No diffs	None significant	No effect
N_2O	1	1	-2.46	y	-	-	-	-	-	-	-
Natural variation - field studies											
CH_4	20	9	-0.6	y	y		y	y	No diffs	+ve with MAT, ST, MAP, Lat. –ve with year.	No effect
CO_2 (total respiration)	2	1	2.66	y	-	-	-	-	-	-	-
N_2O	2	1	0.61		-	-	-	-	-	-	-

with the effects of drainage on shrinkage, erosion and subsidence (Glenn et al. 1993; Wosten et al. 1997; Minkkinen and Laine, 1998a) .

5.2 Reasons for variation in effect

Drawing general conclusions on the effects of draining and re-wetting is obfuscated by numerous environmental variables that might modify the 'average' outcome of these interventions. The predictive power of any synthesis of this kind is heavily dependent on the extent to which the impact of such effect modifiers on the primary outcomes can be predicted. Appropriate analyses can be performed when the relevant variables have been reported in the reviewed studies. Unfortunately, reporting was inadequate in many of the studies.

Of those intervention-outcome studies which provided adequate evidence to determine effect, several reported effect modifiers, though to a varying degree. Draining peatland reduced CH_4 emissions to a greater extent in fens than in bogs. There was also a significant negative relationship between the effect of draining peatland on CH_4 emission and both water table depth and soil pH. As the water table depth increases there is a greater proportion of aerobic soil resulting in less production of CH_4 during decomposition of organic matter, so draining a soil that was already more aerobic would be expected to cause a smaller decrease in CH_4 emission than draining a more anaerobic soil.

In studies of the effects of re-wetting peatland there were no significant relationships between effect size and effect modifiers and none apparent in sub group analysis but sample size was low. In studies of naturally wetter and drier peatlands, however, there were positive relationships between effect size and temperature, rainfall and latitude.

Soil pH was also significantly positively correlated with the effect size of re-wetting peatland on DOC concentration. However, this relationship merely reflects differences between the two largest studies. Wallage (2007) measured a pH of 3.4 on bogs where there was a negative effect of re-wetting, while Meissener et al. (2003) measured a pH of 5.7 on fens where there was a positive effect of re-wetting.

5.3 Review limitations

Peatland drainage and re-wetting may occur in many different ways over different timescales and their effect cannot simply be attributed to lowering and raising the water table. The many other environmental variables that may influence GHG emissions could potentially be included in a systematic review and synthesis (e.g. drainage depth, vegetation cover, subsequent land use). Regrettably very little of this information is reported in the reviewed studies. Consequently, the outputs of our syntheses need to be treated with caution against a background of considerable uncertainty relating to the historical ecology of the study sites.

There is a paucity of studies meeting the inclusion criteria of the effect of peatland drainage or re-wetting on total C stocks or C budget. While the directly measured fluxes of CO_2, CH_4 and N_2O are very important for the review question, as they are powerful GHGs, they do not in themselves allow assessment of impacts on the capacity of peatland to sequester long-term C stores. As well as these gas fluxes, C stocks can be lost in streamwater in the form of dissolved C, and limited evidence on the effects of drainage and re-wetting on the concentration of dissolved C was available, and no data on its rate of efflux from the system. However, there is extensive evidence on the effect of drainage and re-wetting on shrinkage and swelling of peat (with large changes in bulk density being reported, e.g. Minkkinen and Laine 1998a,b) as well as erosion. Some studies have reported these physical processes to be a more important factor than the oxidation of organic matter in subsidence of the peatland soil surface following draining (Glenn et al. 2003), whereas others have come to the opposite conclusion (e.g. Nieuwenhuis and Shocking 1997; Wosten et al. 1997). Subsidence has been shown to be correlated with water table level (Hillman 1992; Wosten et al. 1997). There is little consensus about the relative importance of these processes to changes in peatland C stores, with some studies even suggesting that peatland soil surface subsidence following drainage was accompanied by an increase in the size of the C store, which was attributed to an increase in inputs through net primary production, especially through tree fine roots (Minkkinen and Laine 1998a,b). This review, therefore, cannot provide any clear findings concerning the effect of draining and re-wetting on C stores in peatland soils.

Validity of some of the syntheses is challenged by evidence of publication bias and patterns of non-independence between effects sizes. Non-independence is usually caused by extraction of multiple effects from the same study, location or both. Sensitivity analyses often showed this affect to be insignificant. However, the patterns in the funnel plots (see Appendix IV in supplementary material at www.environmentalevidence.org/SR49.html) also indicate some publication biases. While this test is not conclusive, if publication bias is real, it may lead to an overestimate of effect size where the results of all the reviewed studies are combined.

There are several other sources of bias in the results. The main or most consistent of these is the time of measurement of gas flux. Most studies make more measurements during warmer months of summer. Even if studies make measurement over a whole year, winter, or snow covered measurements are usually restricted to one or two times. While sub-group analysis suggests this is not important, sample sizes in each group were low. There is much less gas flux in winter than in summer due to lower temperatures, however the reduced light will increase net respiratory release of CO_2. Chamber studies do not include the gross primary production of trees (because they do not fit in the chambers), even though they do include the respiration of tree roots below the collar. Therefore, any NEE calculations based on the results of chamber studies that do not include an estimate of tree carbon assimilation (gross primary production) are likely to over-estimate net emissions. Thus, measures and estimates of GHG fluxes excluding the above-ground biomass do NOT provide a basis for determining the effects of draining or re-wetting peatlands on ecosystem carbon storage. This determination also requires adequate quantification of fluxes of dissolved (and solid) carbon into and out of the peatland.

In some cases, we have imputed variances from means across sampling times. This was necessary when variances for individual means were not reported. Sometimes, where the number of sampling occasions was greater than the number of samples, this will result in an estimate of the variance being based on a greater sample size than at the study level. This could introduce bias into the results as the mean variance may be smaller in our calculated mean compared to the true variance due to increased sample size. However, to offset this, sample size in the resultant meta-analysis was set at the minimum number of samples taken on each occasion in each study.

Most of the studies in this review use a similar experimental design. The majority are paired-site comparisons with repeated measures at the same points in the same installed chambers in each site over time. Only a few studies have taken baseline data. A repeated measure on the same fixed collar, used to place gas measurement chambers, inserted into the surface of the soil reduces the external validity, i.e. reduces the generalisation of results to other situations, of most studies, particularly as sample size is often low. While the use of fixed sample points reduces variability in the data due to spatial variation, allowing a clearer picture of temporal change, sufficient replication needs to be employed for that temporal pattern to be indicative of the whole site and not just the small areas covered by each collar. The potential artefacts caused by the installation of fixed collars on measured greenhouse gas fluxes are widely acknowledged. However, we are aware that there is a conflict of opinion about whether these artefacts decrease over time since installation or increase (e.g. due to the decomposition of severed roots). Clearly this issue needs to be resolved before recommendations can be drawn up for the optimal use of installed chambers to obtain most accurate measurements of greenhouse gas fluxes across experimental plots or whole landscapes.

There is also often only one drained or re-wet site and one control site with several collars inserted in each. Allocation of treatment is often not random, with measurement being carried out after implementation of land management practices. While the sites may not necessarily be available, greater replication at the field/site level would also improve the external validity of most studies. However, for those intervention-outcome combinations where there are a large number of effect sizes over a wide geographic range, the meta-analysis may partly compensate for the lack of external validity.

For many intervention-outcome combinations we were only able to extract a few, or no, effect sizes. This has limited the conclusions we can make. Even in those analyses where there are a large number of effects, multiple extractions from the same study resulted in effect modifiers in sub-groups being correlated with other variables and with study level. Also, effect modifiers are sometimes poorly reported in some studies, for example temperature at the time of measurements, making reasons for heterogeneity between studies difficult to separate.

To deal with problems of temporal variability in GHG fluxes, studies are increasingly using continuous high frequency measurements from towers using eddy covariance methods. Because of the high cost of this equipment it is very unusual for there to be any spatial replication of the sampling. As a result they provide no evidence of spatial variance and no basis for calculating an effect size. As such they could not be included within this systematic review. However, we acknowledge the importance of the vastly greater evidence of variation over time produced by this approach and recommend that a synthesis be made between these data and results of this systematic review. Together with the output of process-based modelling of GHG fluxes they would provide the broadest possible evidence base of the effects of peatland draining and re-wetting.

6. Reviewers' Conclusions

6.1 Implications for policy

There is good evidence that draining peatland decreases CH_4 emissions but increases emissions of CO_2 and N_2O. Combining the results provides evidence that draining causes a net increase in global warming potential estimated from available studies to be equivalent (over 100 years) to 1.25 g CO_2 m^{-2} d^{-1}. There is evidence that draining peatland causes a significant increase in soil DOC concentration, and its efflux is also an important potential pathway for reduction in total peatland C stores. There is more limited evidence that re-wetting peatland increases CH_4 and decreases N_2O emissions, but there is no clear evidence of its effect on CO_2 efflux (which does dominate the net global warming potential) or soil DOC concentration. The evidence base for re-wetting peatland, however, is much smaller and there are no studies that combine measures of all three GHGs.

It is important to put these findings into an appropriate scientific and policy context. Changes in net C storage in peatlands are hard to measure because of soil depth, their long time scale, spatial variability etc. Therefore, most studies have carried out shorter-term measures of gas and dissolved C fluxes. However, these are sensitive to environmental variables, showing high rates of inter-annual variability, and therefore may not correlate well with longer-term changes in C storage. Nonetheless, by all these indicators draining peatland should be avoided if minimization of GHG emissions is a policy priority. Protection of existing peatlands is important as the peatland C store will be far harder and more costly to replace by any subsequent attempts at restoration.

Whilst a protected wet peatland, or a previously drained peatland that has been re-wetted, may be slowly accumulating stored C through primary production and the incomplete respiration of its C inputs, the emissions of CH_4 might exceed the benefits of small increases in C storage (at least in the short-term). A parallel can be drawn with the important contribution to global warming of CH_4 emissions from anaerobic paddy rice ecosystems (Schutz et al. 1989; Le Mer and Roger 2001). Therefore although protection or restoration of wet peat bogs may be of value for many ecosystem services, we should be cautious in assuming their short-term contribution to mitigating GHG emissions.

6.2 Implications for research

Research to obtain more reliable evidence of the effect of draining and re-wetting peatlands must measure all of the variables required to calculate a full C budget. This includes not only soil C content, but also fluxes in DOC, POC, DIC, and Volatile organic compounds as well as CO_2 and CH_4, whilst measurement of N_2O should also be made to give a fuller picture of GHG fluxes. Improved experimental and sampling design over that employed in most previous studies is required. However, because of the large spatial and temporal scales of impact of hydrological treatments, obtaining a well-replicated, randomised and blocked experimental design will be a major logistical challenge (with major implications for the cost, as with much hydrological research). A more consistent and co-ordinated approach to study design would help to reach consensus. So there remains much value in studies of existing drained and re-wet sites or natural peatlands which contain variation in hydrological conditions. In these cases, selection of appropriate controls, maximising the use of the available true replication, and baseline monitoring to allow before-after treatment comparisons should all be utilised to the greatest extent possible. However, great care must be taken in extrapolating from such natural peatland studies to predict impacts of draining and re-wetting peatland where that is associated with a change in land use (such as the commencement or cessation of agriculture) with its much greater potential impacts on factors likely to influence greenhouse gas emissions such as vegetation, soil structure and soil chemistry.

Measurement of CO_2 is difficult given its relationship to the diurnal cycle. Very few studies report multiples measures of CO_2 emissions over a full day. In general, greater standardisation of units of measurement and reporting of data is encouraged, e.g. to facilitate their conversion to CO_2 equivalents to provide a better estimation of the global warming potential of the intervention. When reporting results, authors should, as a minimum, include mean, sample size and variance of their estimates. Similarly, good reporting of other variables likely to be effect modifiers is also required.

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Wosten, J.H.M., Ismail, A.B., vanWijk, A.L.M. 1997. Peat subsidence and its practical implications: A case study in Malaysia. Geoderma **78**, 25-36.
Yu, Z.C., Campbell, I.D., Vitt, D.H., Apps, M.J. 2001. Modelling long-term peatland dynamics. I. Concepts, review, and proposed design. Ecological Modelling **145**, 197-210.
Zhu, R. B., Liu, Y. S., Sun, L. G., Xu, H. 2007. Methane emissions from two tundra wetlands in eastern Antarctica. Atmospheric Environment **41**, 4711-4722.

10. Appendices

10.1 Appendix I. Summary of search terms used and results from individual data bases.

Web of Knowledge. The following search was performed on 6 September 2008:

Topic=(Peat* OR Bog* OR Muskeg OR Pocosin* OR Quag* OR Mire OR Slough OR Aapa* OR Turvesuo OR Tourbe OR Tourbier* OR Suo OR Fen OR Torfmoor OR Niedermoortorf OR Hochmoortorf OR Palsa OR Swamp OR Carr OR Mor OR Sedge OR Muck) AND Topic=(Carbon OR "Greenhouse gas*" OR "Green-house gas*" OR GHG* OR Methane OR "Organic matter" OR "Organic content" OR CO2 OR CH4 OR N2O OR "Nitrous Oxide" OR DOM OR DOC OR SOM) AND Topic=(Flood* OR Drain* OR Restor* OR Grip* OR Rewet* OR "re-wet*" OR plough OR ditch).

Science Direct. The following search was performed on 7 October 2008:

TITLE-ABSTR-KEY((Peat* OR Bog* OR Muskeg OR Pocosin* OR Quag* OR Mire OR Slough OR Aapa* OR Turvesuo OR Tourbe OR Tourbier* OR Suo OR Fen OR Torfmoor OR Niedermoortorf OR Hochmoortorf OR Palsa OR Swamp OR Carr OR Mor OR Sedge OR Muck)) and TITLE-ABSTR-KEY((Carbon OR "Greenhouse gas*" OR "Green-house gas*" OR GHG* OR Methane OR "Organic matter" OR "Organic content" OR CO2 OR CH4 OR N2O OR "Nitrous Oxide" OR DOM OR DOC OR SOM) AND (Flood* OR Drain* OR Restor* OR "Grip block*" OR Rewet* OR plough OR ditch)).

Directory of Open Access Journals. Only habitat terms were used in separate searches and the following terms returned hits:

Peat (72)
Bog (14)
Mire (9)
Fen (84)
Swamp (29)
Carr OR Mor (133)
Sedge OR Muck (4)

Copac. One subject term (searched in subject field) with one intervention (as keyword) term was used in this search on 11 August 2008. For non-English language subject terms, the subject word was searched individually. The following combinations returned articles:

Bog AND Drain
Bog AND Flood
Bog AND Restor
Bog ANDRewet
Fen AND Drain
Fen AND Restor
Mire AND Drain

Mire AND Flood
Mire AND Restor
Mire AND Rewet
Peat AND Drain
Peat AND Flood
Peat AND Restor
Peat AND Rewet
Slough AND Drain
Slough AND Restor
Swamp AND Drain
Swamp AND Flood
Swamp AND Restor
Aapa
Pocosin
Torfmoor
Tourbe
Tourbier

Index to theses. The search was modified to accommodate the search engine limitations on 10 September 2008.

Peat* OR Bog OR Mire OR Fen OR Swamp OR Carr OR MOr OR sedge OR Muck AND Flood OR Drain OR Restor* OR Grip* OR Rewet* OR Plough OR Ditch

Other subject search terms were not used as they returned no hits and the engine could not cope with such long search strings.

Agricola. Both Agricola databases were searched simultaneously and to comply with Agricola's use of search terms the search was altered to this:

Peat? Bog? Muskeg Pocosin? Quag? Mire Slough Aapa? Turvesuo Tourbe Tourbier? Suo Fen Torfmoor Niedermoortorf Hochmoortorf Palsa Swamp Carr Mor Sedge Muck Carbon Greenhouse GHG? Methane Organic CO2 CH4 N2O Nitrous DOM DOC SOM Flood? Drain? Restor? Grip Rewet? Plough? Ditch?

Only the phrases such as 'greenhouse gas' were changed to remove gas so that lots of hits about gas were not generated unnecessarily.

Search completed on 10 September 2008.

CAB Abstracts. Phrases removed as not possible to search in this way in CAB. The following databses within CAB were searched:

Animal sciences
Plant sciences
Ecology and environmental sciences
Agricultural economics and rural studies

Using the following search on 14 September 2008:

(Peat* OR Bog* OR Muskeg OR Pocosin* OR Quag* OR Mire OR Slough OR Aapa* OR Turvesuo OR Tourbe OR Tourbier* OR Suo OR Fen OR Torfmoor OR Niedermoortorf OR Hochmoortorf OR Palsa OR Swamp OR carr OR Mor Or sedge OR muck) AND (Carbon OR Greenhouse OR GHG* OR Methane OR Organic OR CO2 OR CH4 OR N2O OR Nitrous Oxide OR DOM OR DOC OR SOM) AND (Flood* OR Drain* OR Restor* OR Grip* OR Rewet* OR plough* OR ditch*).

Conservation Evidence. Only habitat terms were searched due to limited capability of the database. Only one relevant reference retrieved.

CSA Illumina. The following CSA databases were included:

Aqualine
ASFA: Aquatic Sciences and Fisheries Abstracts
Ecology Abstracts
Biology Digest
BioOne Abstracts and Indexes
Conference Papers Index
EIS: Digests of Environmental Impact Statements
Sustainability Science Abstracts
Water Resources Abstracts

Using the following search on 11th September 2008

(Peat* OR Bog* OR Muskeg OR Pocosin* OR Quag* OR Mire OR Slough OR Aapa* OR Turvesuo OR Tourbe OR Tourbier* OR Suo OR Fen OR Torfmoor OR Niedermoortorf OR Hochmoortorf OR Palsa OR Swamp OR Carr OR Mor OR Sedge OR Muck) AND (Carbon OR "Greenhouse gas*" OR "Green-house gas*" OR GHG* OR Methane OR "Organic matter" OR "Organic content" OR CO2 OR CH4 OR N2O OR "Nitrous Oxide" OR DOM OR SOM OR DOC) AND (Flood* OR Drain* OR Restor* OR "Grip block*" OR Rewet* OR plough OR ditch)

10.2 Appendix II – Full Text Assessment

The following is a list of studies that were assessed for relevance at full text. The list is divided into those included in later stages of the review and those excluded (further divided by reasons for exclusion from the review).

1. Articles included

Alm, J., Saarnio, S., Nykanen, H., Silvola, J., and Martikainen, P. J. 1999. Winter CO_2, CH_4 and N_2O fluxes on some natural and drained boreal peatlands. Biogeochemistry 44, 163-186.

Andersen, R., Francez, A., and Rochefort, L. 2006. The physicochemical and microbiological status of a restored bog in Québec: Identification of relevant criteria to monitor success. Soil Biology and Biochemistry, 38, 1375-1387.

Basiliko, N., Blodau, C., Roehm, C., Bengtson, P., and Moore, T. R. 2007. Regulation of decomposition and methane dynamics across natural, commercially mined, and restored northern peatlands. Ecosystems, 10, 1148-1165.

Bellisario, L. M., Bubier, J. L., Moore, T. R., and Chanton, J. P. 1999. Controls on CH_4 emissions from a northern peatland. Global Biogeochemical Cycles, 13, 81-91.

Best, E. P. H., and Jacobs, F. H. H. 1997. The influence of raised water table levels on carbon dioxide and methane production in ditch-dissected peat grasslands in the Netherlands. Ecological Engineering, 8, 129-144.

Best, E. P. H., and Jacobs, F. H. H. 2001. Production, nutrient availability, and elemental balances of two meadows affected by different fertilization and water table-regimes in the Netherlands. Plant Ecology, 155, 61-73.

Boeckx, P., and VanCleemput, O. 1997. Methane emission from a freshwater wetland in Belgium. Soil Science Society of America Journal, 61, 1250-1256.

Bubier, J. L., Moore, T. R., and Roulet, N. T. 1993. Methane emissions from wetlands in the midboreal region of northern Ontario, Canada. Ecology, 74, 2240-2254.

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Chimner, R. A., and Cooper, D. J. 2003. Influence of water table levels on CO_2 emissions in a Colorado sub alpine fen: An in situ microcosm study. Soil Biology and Biochemistry, 35, 345-351.

Davidsson, T. E., and Leonardson, L. 1997. Production of nitrous oxide in artificially flooded and drained soils. Wetlands Ecology and Management, 5, 111-119.

Davidsson, T. E., Trepel, M., and Schrautzer, J. 2002. Denitrification in drained and rewetted minerotrophic peat soils in northern Germany (Pohnsdorfer Stauung). Journal of Plant Nutrition and Soil Science-Zeitschrift Fur Pflanzenernahrung Und Bodenkunde, 165, 199-204.

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Freeman, C., Nevison, G. B., Kang, H., Hughes, S., Reynolds, B., and Hudson, J. A. 2002. Contrasted effects of simulated drought on the production and oxidation

of methane in a mid-Wales wetland. Soil Biology and Biochemistry, 34, 61-67.
Glatzel, S., Kalbitz, K., Dalva, M., and Moore, T. 2003. Dissolved organic matter properties and their relationship to carbon dioxide efflux from restored peat bogs. Geoderma, 113, 397-411.
Glenn, S., Heyes, A., and Moore, T. 1993. Carbon dioxide and methane fluxes from drained peat soils, southern Québec. Global Biogeochemical Cycles, 7, 247-257.
Heyer, J., Berger, U., Kuzin, I. L., and Yakovlev, O. N. 2002. Methane emissions from different ecosystem structures of the sub arctic tundra in western Siberia during midsummer and during the thawing period. Tellus Series B-Chemical and Physical Meteorology, 54, 231-249.
Hughes, S., Reynolds, B., Brittain, S. A., Hudson, J. A., and Freeman, C. 1998. Temporal trends in bromide release following rewetting of a naturally drained gully mire. Soil use and Management, 14, 248-250.
Huttunen, J. T., Nykänen, H., Turunen, J., Nenonen, O., and Martikainen, P. J. 2002. Fluxes of nitrous oxide on natural peatlands in Vuotos, an area projected for a hydroelectric reservoir in northern Finland. Suo, 53, 87-96.
Komulainen, V. M., Nykaenen, H., Martikainen, P. J., and Laine, J. 1998. Short-term effect of restoration on vegetation change and methane emissions from peatlands drained for forestry in southern Finland. Canadian Journal of Forest Research/Revue Canadienne De Recherche Forestiere, 28, 402-411.
Laine, J., Silvola, J., Tolonen, K., Alm, J., Nykanen, H., Vasander, H., Sallantaus, T., Savolainen, I., Sinsalo, J. and Martikainen, P. J. 1996. Effect of water-level drawdown on global climatic warming: Northern peatlands. Ambio, 25, 179-184.
Martikainen, P. J., Nykanen, H., Crill, P., and Silvola, J. 1993. Effect of a lowered water table on nitrous oxide fluxes from northern peatlands. Nature, 366, 51-53.
Martikainen, P. J., NykaUnen, H., Crill, P., and Silvola, J. 1992. The effect of changing water table on methane fluxes at two Finnish mire sites. Suo, 43, 237-240.
Martin, H. W., Ivanoff, D. B., Graetz, D. A., and Reddy, K. R. 1997. Water table effects on histosol drainage water carbon, nitrogen, and phosphorus. Journal of Environmental Quality, 26, 1062-1071.
Meissner, R., Rupp, H., and Leinweber, P. 2003. Re-wetting of fen soils and changes in water quality - experimental results and further research needs. Journal of Water and Land Development, 7, 75-91.
Melling, L., Hatano, R., and Goh, K. J. 2005a. Soil CO_2 flux from three ecosystems in tropical peatland of Sarawak, Malaysia. Tellus Series B-Chemical and Physical Meteorology, 57, 1-11.
Melling, L., Hatano, R., and Goh, K. J. 2005b. Global warming potential from soils in tropical peatland of Sarawak, Malaysia. Phyton-Annales Rei Botanicae, 45, 275-284.
Melling, L., Hatano, R., and Goh, K. J. 2005c. Methane fluxes from three ecosystems in tropical peatland of Sarawak, Malaysia. Soil Biology and Biochemistry, 37, 1445-1453.
Minkkinen, K., and Laine, J. 2006. Vegetation heterogeneity and ditches create spatial variability in methane fluxes from peatlands drained for forestry. Plant and Soil, 285, 289-304.

Minkkinen, K., Vasander, H., Jauhiainen, S., Karsisto, M., and Laine, J. 1999. Post-drainage changes in vegetation composition and carbon balance in Lakkasuo mire, central Finland. Plant and Soil, 207, 107-120.

Moore, T., Roulet, N., and Knowles, R. 1990. Spatial and temporal variations of methane flux from subarctic/northern boreal fens. Global Biogeochemical Cycles, 4, 29-46.

Moore, T. R. 1987. A preliminary study of the effects of drainage and harvesting on water quality in ombrotrophic bogs near Sept-Iles, Québec. Water Resources Bulletin, 23, 785-791.

Moore, T. R., and Clarkson, B. R. 2007. Dissolved organic carbon in New Zealand peatlands. New Zealand Journal of Marine and Freshwater Research, 41, 137-141.

Moore, T. R., and Dalva, M. 1993. The influence of temperature and water-table position on carbon dioxide and methane emissions from laboratory columns of peatland soils. Journal of Soil Science, 44, 651-664.

Moore, T. R., and Knowles, R. 1989. The influence of water table levels on methane and carbon dioxide emissions from peatland soils. Canadian Journal of Soil Science, 69, 33-38.

Moosavi, S. C., Crill, P. M., Pullman, E. R., Funk, D. W., and Peterson, K. M. 1996. Controls on CH_4 flux from an Alaskan boreal wetland. Global Biogeochemical Cycles, 10, 287-296.

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Roulet, N. T., Ash, R., Quinton, W., and Moore, T. 1993. Methane flux from drained northern peatlands - effect of a persistent water table lowering on flux. Global Biogeochemical Cycles, 7, 749-769.

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microforms following water table drawdown. Journal of Geophysical Research-Biogeosciences, 111, G2.
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Van den Pol-van Dasselaar, A., van Beusichem, M. L., and Oenema, O. 1999. Methane emissions from wet grasslands on peat soil in a nature preserve. Biogeochemistry, 44, 205-220.
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Wallage, Z. E. 2007. Dissolved organic carbon and colour dynamics in drained and restored blanket peat. Ph.D. Thesis, University of Leeds, 248pp.
Zhu, R. B., Liu, Y. S., Sun, L. G., and Xu, H. 2007. Methane emissions from two tundra wetlands in eastern Antarctica. Atmospheric Environment, 41, 4711-4722.

2. Articles excluded

Abstracts only and therefore no data.

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Augustin, J. 2006. Greenhouse gas release and global warming potential during and after reflooding of a degraded fen site in the Peene river valley, northeast Germany. 5th European Conference on Ecological Resortation, Greifswald (Germany), 22-25 Aug 2006.
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Measures potential only

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No comparator

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