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# A programme to address evidence gaps in greenhouse gas and carbon fluxes from UK peatlands

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# Contents

# 1 Introduction

This report provides the proposed structure for a measurement programme, which is intended to quantify the carbon (C) and Greenhouse Gas (GHG) fluxes to and from UK peatlands, incorporating the range of major UK peatland types, and to determine the extent to which these are influenced by management. The measurements obtained would be intended to provide the basis for the development of robust emission factors (EFs) appropriate to UK peatlands, suitable for GHG reporting, emissions trading and the optimisation of peatland management.

Following the Evidence Review[1], peatlands were classified into blanket bogs, upland and lowland raised bogs, and fens. While blanket bogs comprise by far the largest area, raised bogs and fens have been disproportionately affected by disturbances such as peat extraction and conversion to intensive agriculture, and are thus relatively important in terms of overall GHG budgets (*see Evidence Review section 4 "Spatial extent of peatland types and land-uses).* The peat management issues considered in the research programme also follow those considered in the Evidence Review, taking account of the extent of the activity, its potential significance for C and GHG budgets, and the level of current uncertainty.

The main focus of the programme is on the quantification of EFs for peats under 'steady-state' management, including drained peats; forested peats; peats subject to managed burning; peats used for extraction; grazed peats; peats used for intensive agriculture (particularly fen peats); and peats under conservation management. Transitions between these states (e.g. drainage/drain-blocking, afforestation/deforestation, re-vegetation, and agricultural intensification/de-intensification) are also taken into consideration. As in the Evidence Review, 'peats' were defined as soils with an organic horizon depth of > 40cm (England and Wales) and > 50cm (Scotland), and consideration was given to the full range of identifiable C and GHG fluxes, including gaseous, fluvial and biomass off-take fluxes. Other, non-management related factors with the potential to affect peatland C/GHG budgets (*see Evidence Review section 9 "Influence of other factors on C and GHG fluxes from peatlands")* were taken into consideration, but did not form the main focus of this report.

The research programme blueprint outlined here is intended to provide a pragmatic, flexible network of measurement sites, designed to produce quantitative information regarding the C and GHG balances of representative UK peatlands under a range of management conditions. The proposed structure builds cost-effectively on existing research activity, by aligning methods and measurements to provide data comparability, identifying additional measurements needed to provide full C/GHG budgets, and identifying gaps in the current coverage of key management issues or peatland types where new study sites may be needed.

The programme comprises two main, closely linked components:

i A programme of measurement activities to reliably characterise the C and GHG flux from ongoing 'steady state' situations;

ii A programme of field-based research activities designed to a) provide a direct comparison of GHG fluxes from peat under different management at the same location, and b) to assess the fluxes associated with transitions between these states.

[1] The accompanying review (*Worrall et al A review of current evidence on carbon fluxes and greenhouse gas emissions from UK peatland*) provides the evidence base for the research programme outlined here.

The first part of this report (section 2) describes the design for a measurement programme intended to provide reliable, multi-year C and GHG balance measurements across a range of representative UK peatland sites.  Several measurement levels are defined, from comprehensive, high-frequency measurements at a small number of sites to lower-intensity (and lower cost) measurements suitable for application to a wider range of locations.  This combination of intensive and extensive measurement is intended to provide both detailed understanding of processes and management impacts, and a basis for upscaling results to the whole of the UK peatland landscape.

The measurement programme also provides the platform for a set of research activities (section 3), including  robustly designed field experiments specifically designed to quantify the impacts of different management practices on each component of the peatland C and GHG budgets, and to evaluate the changes in flux that occur during management transitions.

Issues relating to a larger, survey-based peat C stock assessment are briefly addressed in section 4, and section 5 presents proposals for network structure and coordination, data analysis and modelling of a peat monitoring network.  Annex 1 provides a more detailed description of the components of the peatland C flux, methods for measuring them, and requirements for ancillary measurements such as vegetation and condition monitoring. Annex 2 provides some outline estimates of the costs associated with the measurement activities described.

# 2 Design of a measurement programme

## 2.1 Rationale

The objective of this part of the research programme is to provide quantitative evidence on the current C and GHG balances of UK peatlands, taking account of the range of peatland types, conditions and management, to generate robust emissions factors for each of these states and types. The focus of this section is on obtaining emission factors for peatlands under 'steady state' management, although it does not preclude the monitoring of transitions at sites that are subject to large-scale management change in future. As noted above, the aim has been to identify the key measurements required to achieve these objectives, and to maximise the use of existing data and ongoing studies within a coordinated programme in order to minimise costs, and to provide at least five years of complete data. The following sections include:

i a brief overview of the major components of the peat C/GHG budget and current techniques for measuring them, further details of which are provided in Annex 1;

ii a design for a tiered measurement programme;

iii an assessment of potential core sites for such a network, including current sites and identified gaps in coverage.

## 2.2 Methods for carbon and GHG flux measurement and peat carbon stock and condition assessment

The C balance of peatlands comprises a large number of individual fluxes, which vary in importance according to the type and condition of the peatland. The (net) transfer of $CO_2$ between atmosphere and the land is typically the largest single flux, but the smaller flux of methane ($CH_4$), usually emitted from peats to the atmosphere, is important due to its greater strength as a greenhouse gas. Similarly, nitrous oxide ($N_2O$), although not relevant to the C budget, acts as a powerful greenhouse gas, and may be emitted in significant quantities from nutrient-rich peats. Peatlands are also characterised by large fluvial C losses. These are usually dominated by dissolved organic carbon (DOC), although in eroding systems the flux of particulate organic carbon (POC) can become larger. Drainage waters also provide a conduit for the export of $CO_2$ from the peat, which can be 'evaded' from the water surface to the atmosphere. In managed peatlands, the transfer of C in biomass removed from the site (in crops or livestock) may represent a significant component of the overall C budget.

The wide range of C/GHG flux pathways and forms requires an integrated approach to their measurement. The methods available vary in complexity and cost, and the tiered approach described below is intended to provide a balance between intensive (and expensive) measurements at a limited number of core sites, and more extensive, lower-cost measurements at a wider range of locations. Annex 1 provides more detailed background information on the main fluxes and options for their measurement, along with approaches for peat stock and condition assessment (Box 1).

| Carbon and GHG flux | Peat carbon stock and condition |
|---|---|
| **Gaseous flux measurement** | **Carbon stock** |
| • *Eddy covariance methods* | **Vegetation and peat condition** |
| • *Chamber methods* | **Remote sensing methods** |
| **Fluvial flux measurement** | **Site history and peat accumulation rate** |
| • *Water flux measurement* | |
| • *Dissolved Organic Carbon flux measurement* | |
| • *Inorganic C flux measurement* | |
| • *Particulate Organic Carbon flux measurement* | |
| • *Dissolved $CH_4$* | |
| **Biomass transfers** | |

**Figure 1.** Carbon fluxes and measurement methods described in Annex 1.

## 2.3 Structure of measurement programme

### 2.3.1 Rationale

As noted in the preceding section, and described more fully in Annex 1, the accurate quantification of all components of the peatland carbon and greenhouse gas budget is technically challenging, and potentially expensive. For this reason, we believe that it would not be economically efficient, or indeed scientifically desirable, to develop an entire new monitoring network. In recent years there has been a significant growth in the number of UK peatland sites at which flux measurements are being made. These sites encompass many (but not all) of the key peatland types and management activities identified in the Evidence Review, and therefore provide a strong foundation from which to develop a network. Most of these studies have developed independently, operated as individual monitoring or experimental sites by different institutions, and thus currently lack coordination and full comparability and consistency of measurements.

We believe that there is clear potential to augment these studies in order to provide a cost-effective, scientifically robust and representative network of UK peatland carbon and GHG research sites. The added value provided by coordinated networks has been recognised in other areas of environmental monitoring, such as the Environmental Change Network (ECN) and the Acid Waters Monitoring Network (AWMN). In the latter example, 20 years of consistent monitoring of 22 sites has revealed a high degree of spatio-temporal coherence in upland water quality which supports upscaling of observed trends, process understanding and model-based predictions from monitoring sites to the landscape scale (Evans *et al* 2010), and has played a key role in underpinning the development of UK policy in relation to the ecosystem impacts of air pollution, and on the causes and consequences of rising upland water DOC concentrations.

The integration of existing sites within a network increases the power of the overall measurement programme relative to an equivalent number of unconnected individual sites, for example by permitting discrimination between external factors (affecting many or all sites) and management factors (affecting only the sites subject to that management); identifying the differential sensitivity of peatland types to the same factor (such as effects of drainage on blanket bogs vs. fens); and the identification of under- (or over-) represented site types in the network, based on the extent to which sites show convergent or divergent behaviour.

### 2.3.2 Proposed network structure

The proposed design for a tiered measurement programme addresses the potential of utilising existing study sites to form the core of a UK-wide peatland network. Within the remit of this review, this design is focused primarily on the measurement of carbon and GHG fluxes, but we recognise the need for supporting measurements such as vegetation monitoring to enable the interpretation of measured fluxes, as well as the potential wider value that might be achieved if a broader programme of ecological monitoring could be linked to these flux studies. We also recognise, in the context of maximising use of existing data and measurement infrastructure, that the sites where these are available do not adequately represent the full range of peatland types and status across the UK, and that it will therefore be necessary to instrument additional sites from a lower current measurement baseline. This is discussed further below. Finally, while it is highly desirable to intensively instrument a representative set of sites in order to provide the best possible quantification of UK peatland C and GHG budgets, we appreciate that the costs involved are likely to limit the number of sites at which such a level of investment could be achieved. Hence, any additional investment should be focused on those peatland/management types which have the greatest significance for the overall C/GHG budget, and for which the evidence base is currently poorest, as identified in the Evidence Review.

On this basis, we have proposed three monitoring levels, as follows:

**Level I sites**, at which all components of the C and GHG balance are measured according to current best practice, focused on high-priority peatland and management types;

**Level II sites** at which less intensive, lower-cost monitoring methods are used to provide minimum acceptable estimates of fluxes; and

**Level III sites** at which periodic survey-based approaches are used to monitor peat condition, and to provide some information on rates of carbon accumulation or loss.

'Sites' are envisaged as either monitoring catchments (particularly for Level I) or hillslope/plot-scale studies. It is intended that these measurement tiers should be complimentary and inter-changeable. Thus, Level III site measurements would form a part of the Level II site measurement protocol, and Level II site measurements part of those for Level I sites. This would permit:

i flexibility to upgrade a site, building on initial lower-level measurements;

ii flexibility to downgrade a site if this proves necessary for funding or logistical reasons, without complete cessation of monitoring;

iii the potential to verify flux estimates based on lower-level measurements against those obtained from higher-level monitoring, where both have been undertaken in parallel; and

iv a structure whereby intensive measurements from a small number of sites can be robustly upscaled to the wider UK peatland area, supported by a larger number of less intensive measurement sites.

The three measurement levels each have particular (and complimentary) strengths. Level I sites have the greatest power to accurately detect change in C and GHG budgets over time, and to attribute this change to specific drivers at that site. Level II sites provide the means to expand spatial coverage of sites with flux measurements, and may have the greatest power to detect management impacts and/or differing responses of specific peatland types, since they should incorporate multiple sites within each management type or peat classification. Level II measurements can also be incorporated within experimental studies, as discussed in section 3, further supporting the identification of management effects. Nevertheless, we consider that more intensive Level I measurements at a subset of sites are essential, in order to verify the flux estimates obtained from Level II measurement, as noted above. Finally, Level III measurements provide an effective means of quantifying variations in peat accumulation or loss rates across a wider range of peatlands, and for upscaling flux estimates and process understanding from Level I and II sites. The timescale over which Level III measurements could be used to detect change in peat C stocks is likely to be relatively long (10 years or more) but, as with other survey-based approaches such as the Countryside Survey and National Soils Inventories, should ultimately provide a basis for quantifying long-term change at the landscape scale, in response to management and other environmental drivers. It is noted that a tiered approach has been proposed for UK soil quality monitoring (Merrington *et al* 2006; Black *et al* 2008).

The tripartite site structure will be supported by a core of cross-cutting activities, specifically:

i Construction and management of a central database from which project participants, supporting organisations and the wider scientific/stakeholder community can draw;

ii Maintenance, updating and revision of the meta-analysis tools and results from this review; and

iii Modelling of results in order to understand the carbon and GHG budgets of sites plus the wider application of these results to UK peatlands.

These activities are discussed in section 5.

### a Level I sites

The Level I site network would represent the core of UK peatland C and GHG monitoring. As discussed above, it would be expected to build on the current range of study sites, potentially augmented by additional studies in under-represented, high-priority peatland/management types. Some candidate sites for primary monitoring are identified and discussed below in section 2.3.3. At each site, it would be essential to measure the full suite of carbon fluxes in order to provide annual estimates of net C sequestration or emission. Additional measurement of $N_2O$ fluxes would also be required to produce a complete GHG budget for more nutrient-rich systems (particularly agriculturally improved fen peats), but this flux has generally been found to be minor in bogs. For practical purposes, quantification of all components of the peat C balance is best achieved by operating at the scale of peat-dominated catchments with natural drainage streams, or ditched areas which drain to an identifiable point. These catchments need to be small enough (in the order of $1km^2$) to provide a manageable level of spatial heterogeneity, and to ensure that land-atmosphere flux measurements are sufficiently representative of the catchment as a whole. Quantification of fluxes based on plot-scale studies, or on 'catchments' drained via ditches, is also possible, but presents additional challenges in terms of constraining fluvial fluxes.

Based on currently available measurement techniques, an 'optimal' flux monitoring programme is proposed for Level 1 sites, as follows:

| | |
|---|---|
| Automatic weather station (AWS) measuring air temperature, rainfall, humidity, pressure, wind speed and direction, soil temperature and solar radiation. | |
| LI/1 | Co-located flux tower comprising a sonic anemometer for three-dimensional wind measurement, and high-frequency $CO_2$ and $CH_4$ sensors for eddy covariance flux measurement. This should be located within a 'footprint' of around 100-300m radius (depending on tower height) of level ground within an area of peat considered representative for the catchment as a whole and broadly homogeneous in terms of management impacts or peat condition. Note that AWS and eddy covariance systems operate continuously, and require either an external power supply (rarely available at remote sites) or on-site power generation by wind turbines and solar panels. |
| LI/2 | Replicated static chamber gas flux measurement sites for each of the major vegetation types in the catchment and/or areas under different management or in contrasting condition. This requires the permanent installation of bases, and periodic (recommended minimum monthly) site visits for the measurement of $CO_2$ fluxes using an infra-red gas analyser (IRGA), and $CH_4$ (and where relevant $N_2O$) fluxes by gas sampling and subsequent lab analysis using a gas chromatograph (GC). Boardwalks should be installed to minimise vegetation and peat disturbance that might affect flux measurements (Robroek *et al* in press). |
| LI/3 | A network of dipwells across the catchment for periodic measurement of water table depth. A subset of these should be instrumented with continuous water table loggers. Dipwells should be located spatially with reference to either management features and/or the topography. |
| LI/4 | Continuous stream discharge monitoring using a pressure transducer to measure water depth in combination with a v-notch weir, flume or gauged section. |
| LI/5 | Continuous monitoring of stream DOC, pH and $CO_2$ concentrations using calibrated sensors (optical sensors for DOC, and modified atmospheric $pCO_2$ sensors for $CO_2$). Optical turbidity sensors might also be used to measure POC, but this requires further testing. Most stream sensors can be maintained using batteries, but use of on-site power sources (solar or wind) would reduce the need for battery changes. |
| LI/6 | Regular stream spot-sampling (recommended minimum fortnightly) for direct measurement of DOC, POC, $CO_2$, DIC, pH, alkalinity and calcium concentrations. Samples could also be taken measurement of DOC and POC turnover, although this would not be required for all sampling occasions. |
| LI/7 | Periodic sampling of high-flow events (using autosamplers deployed on a campaign basis) in order to obtain (and update) flux estimates for POC during storms, and for calibration of optical sensors. |
| LI/8 | Monitoring of ebullition gas fluxes (particularly for $CH_4$) in wetter areas using ebullition funnels (Baird *et al* 2009). |

This suite of continuous or regular flux measurements should be accompanied by detailed catchment characterisation, carbon stock and condition assessments. These form the basis for the Level III monitoring, and are therefore described later, but should be considered an essential element of the overall suite of measurements required at all Level I and Level II sites.

In managed systems, estimates of carbon offtake in biomass should be quantified annually based on recorded harvesting and grazing information (Lloyd, 2006). Fen systems will provide additional challenges for measurement in relation to the quantification of fluvial fluxes (where systems are supplied or drained via groundwater, and in some cases maintained via pumping) and in the measurement of fluxes by static chambers in tall vegetation. These issues will need to be taken into account during the instrumentation of fen sites.

The Level I monitoring sites proposed in section 2.2.3 would provide high quality 'platforms' for additional research. Most importantly, they could provide baseline measurements for embedded or co-located experimental studies (see section 3). This linked approach has been exemplified by the combined monitoring and experimental studies undertaken at Moor House, and a similar model is being applied at other peatland sites such as the Migneint. Intensive monitoring sites can also provide 'ground-truthing' for remote sensing based upscaling approaches, such as the aircraft-mounted gas measurements undertaken at the Vyrnwy site, and core locations for the development, parameterisation and testing of carbon models.

The continuous monitoring systems (AWS, flux tower, in-stream water quality sensors, water table loggers and discharge gauging) have a high initial cost, but once established should operate with limited on-site maintenance. Water quality sensors do require periodic calibration and cleaning, particularly during the growing season to avoid sensor fouling (although some self-cleaning sensors are available). Requirements for site visits can also be reduced by the use of telemetry systems for data transfer, which also enables rapid identification and rectification of equipment failures, but add to initial costs.

### b Level II sites

Level II monitoring is conceived as the minimum level of measurements from which a reasonable set of annual C flux estimates could be obtained. The measurements described would inevitably lack the accuracy or completeness of the monitoring programme described for the Level I sites, but would provide a lower-cost option which may, for example, form the basis for establishing initial flux monitoring at new sites. All Level II measurements form a subset of the Level I measurement programme, which should permit quantification of the additional uncertainty associated with the use of less intensive measurement approaches. Proposed core measurements for Level II sites are as follows:

| | |
|---|---|
| LII/1 | Automatic weather station |
| LII/2 | Continuously measured discharge in a stream or drainage channel. |
| LII/3 | Monthly static chamber measurement of $CO_2$ and $CH_4$ fluxes at replicated, representative locations. In fens, $N_2O$ should also be measured, and cultivated systems should be monitored more intensively following fertiliser applications. |
| LII/4 | Monthly spot-sampling of drainage water for DOC, POC, pH, alkalinity and calcium. |

Level III site C stock (LIII/2,3) water table (LIII/5) and peat condition (LIII/4,6) measurements would also be required. It must be emphasised that this tier of monitoring should be considered a minimum standard, rather than a fixed guideline. In other words, adding additional monitoring elements, even if this did not result in the site meeting all the requirements for Level I monitoring, would nonetheless be beneficial in reducing the uncertainty of measured C and GHG fluxes. It is also worth noting that the less stringent requirements of Level II monitoring are somewhat more compatible with the range of measurements typically collected during field experiments, and this may enable effective utilisation of a wider range of existing studies to be incorporated in a more formalised network (see also section 3).

### iii **Level III sites**

At Level III sites, annual C fluxes would not be measured. Rather, the objective of this tier of measurement would be to establish lower-cost, long-term monitoring of carbon stock, vegetation status and site condition based on infrequent site surveys. As described above, the same suite of measurements would be undertaken at more intensive monitoring sites according to the same protocols, providing supporting data for interpretation of measured fluxes, and comparability between sites with different intensity of monitoring. Because the cost of monitoring would be much lower than at the intensive flux measurement sites, it should be possible to undertake lower-level assessment at a wider range of sites, thereby supporting the extrapolation of data from intensive flux measurement sites to the wider UK peatland area.

Proposed measurements at Level III sites are as follows:

| | |
|---|---|
| LIII/1 | Initial and 5-yearly vegetation surveys at permanent quadrats as described in Annex 1 (proportional cover of major plant functional types and key indicator species, to include cover estimation for key plant functional types and indicator species, and recording of bare peat areas). |
| LIII/2 | Initial C stock measurement based on whole-profile coring, and 5-yearly soil C stock change measurements based on shallow core sampling (depth, bulk density and %C) to a dateable horizon or fixed point. |
| LIII/3 | Initial collection of a full peat core for basal age measurement, long-term C accumulation rate and contemporary C accumulation rate estimation. |
| LIII/4 | Initial collation of aerial photograph and LIDAR data, if available for the site, and recording of ditches, bare peat or burnt areas, erosion features and microtopography. |
| LIII/5 | Installation and monitoring of a network of dipwells, to provide an indication of average water table. Water table loggers may be more cost-effective than manual recording, depending on the frequency of existing site visits (e.g. by wardens or land-managers). |
| LIII/6 | Annual fixed-point photographs to provide a record of vegetation and site condition. |
| LIII/7 | Annual recording of site management, biomass offtake (if relevant), restoration activities, burning etc. |

An additional option for providing an indicative measure of the magnitude of fluvial C fluxes would be to undertake monthly spot-sampling (as described for Level II sites), with accompanying flow gauging, to coincide with the 5-yearly soil and vegetation surveys. This would not be sufficient to reliably determine rates of change, but might be used to identify whether any individual component of the fluvial C flux was of sufficient magnitude to merit further investigation.

### 2.3.3 Potential Level I sites

Sites from the inventory of studies collated in the review were evaluated in relation to their potential suitability for inclusion as Level I monitoring sites. Based on the preceding assessment, priority was given to sites where relevant measurements and experiments are currently being undertaken, since this will increase the affordability and value of the network. Additional consideration was given to the representativeness of the site in terms of the overall spatial coverage of UK peatland types, their importance for GHG balances, as identified in the Evidence Review, and to the extent to which part or all of a site is affected by management.

As noted in section 2.2 of the Evidence Review, there is a dearth of current information for UK peatlands that can be considered genuinely 'pristine' peat-forming systems, although the available flux data do suggest that systems with little or no current management are still operating as net C sinks. The inclusion of 'pristine' (or at least semi-natural) systems is desirable as part of the measurement programme, to provide a reference condition for more degraded systems. However, the measurement programme should represent as many as possible of the peatland/management types considered to be important for GHG fluxes at a national scale, and also different levels of management intensity within some key classes (e.g. intensity of cultivation of drainage). Where important peat types were considered to be under-represented by current research activities, sites with less intensive current levels of measurement have been suggested that have the potential to be upgraded, although this list is not intended to be in any way restrictive. All selected sites were located on deep peat (rather than organo-mineral soils).

Key criteria were thus:

- i Current measurement of gaseous fluxes by eddy covariance or static chamber methods;
- ii Current measurement of fluvial C fluxes;
- iii Extent to which site is representative of the wider UK peatland area (taking account of the number of other sites representing the same peatland type);
- iv Extent to which site is representative of management issues affecting UK peatlands (taking account of the number of other sites representing this management issue);
- v Existence of current field experiments investigating impacts of changing land-management, including restoration (also relevant to the study of management transitions, see section 3);
- vi Geographical coverage of sites.

In a number of cases, several independent research studies are being undertaken within the same area which, if linked, could provide complementary data; an example is the range of university studies, CEH experiments and monitoring being carried out on Bleaklow in the Peak District. These 'clusters' have been treated as single sites for this assessment.

The shortlist of 14 sites identified from this assessment is shown in Table 1, and their locations in Figure 1.

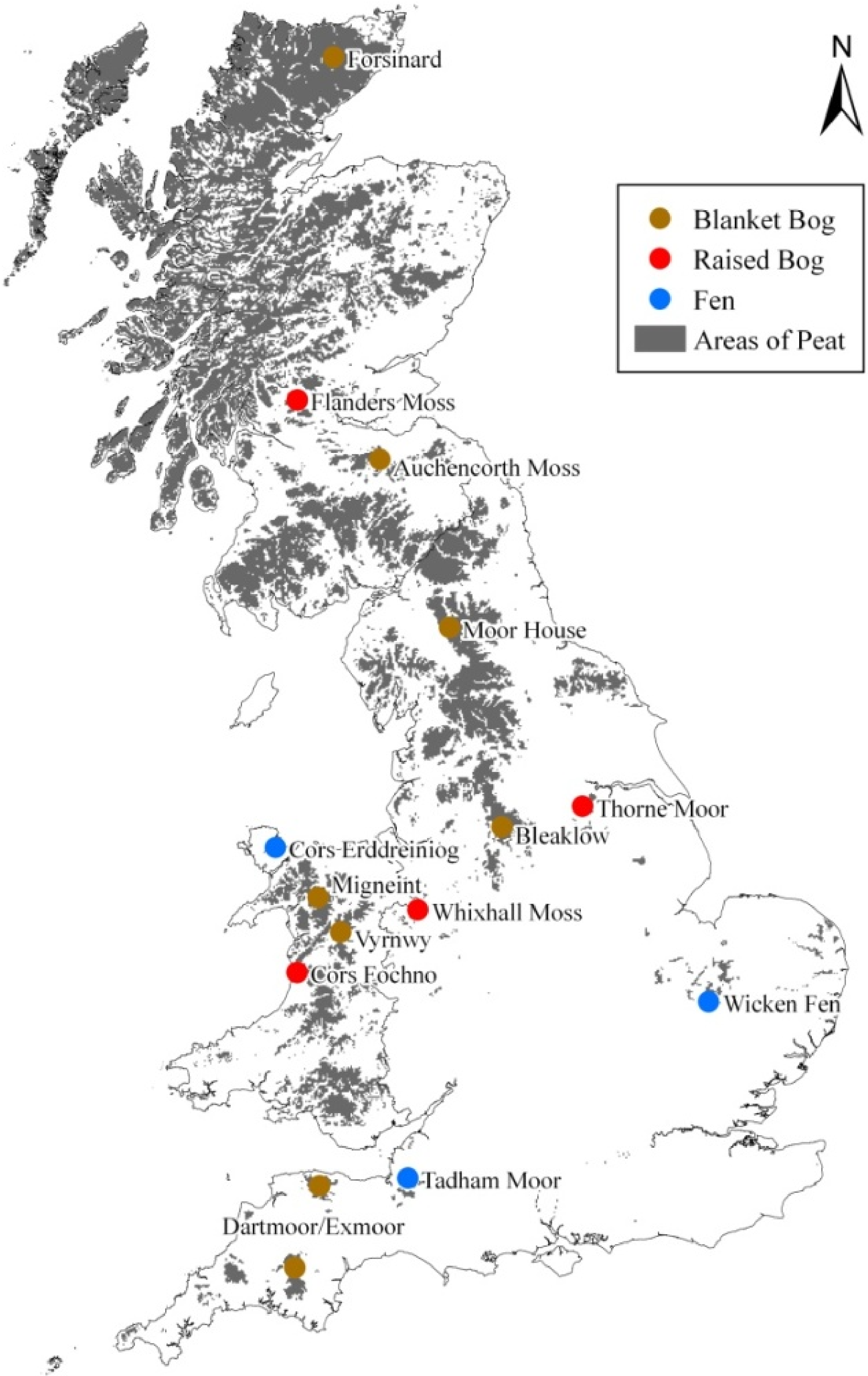


**Figure 1.** Location of potential Level I sites with existing or planned measurements. Peat map is based on the Hydrology of Soil Types classification (HOST, for more information see http://www.macaulay.ac.uk/host/index.html). Location of Dartmoor/Exmoor (Mires on the Moors) sites to be finalised.

**Table 1.** List of potential Level I monitoring sites with existing or planned measurements, showing site type and relevant management issues.

| Site | Peatland type | Drainage | Burning | Forestry | Grazing | Arable | Extraction | Erosion | Restoration |
|---|---|---|---|---|---|---|---|---|---|
| Forsinard | Lowland blanket bog | ●● | | ●● | | | | | ●● |
| Flanders Moss | Lowland raised bog | ●● | | ●● | | | | | ●● |
| Auchencorth Moss | Lowland blanket bog | ○ | | | ● | | ○ | | |
| Moor House | Upland blanket bog | ●● [2] | ●● | | ●● | | | ● | |
| Thorne Moor | Lowland raised bog (cut-over) | ●● | | | | | ● | | ● |
| Bleaklow | Upland blanket bog | | ● | | | | | ●● | ●● |
| Migneint | Upland blanket bog | ●● | | ○ | ● | | | | ●● |
| Vyrnwy | Upland blanket bog | ●● | | | ● | | | | ●● |
| Wicken Fen | Rich fen | ●● | | | | ● | | | ●● |
| Cors Erddreiniog | Rich fen | ● | | | ● | | | | ● |
| Tadham Moor | Intermediate fen | ● | | | ● | | ○ | | |
| Cors Fochno | Estuarine raised bog | ● | | | ○ | | ○ | | ○ |
| Whixall Moss | Lowland raised bog (cut-over) | ● | | | | | ● | | ● |
| Dartmoor/Exmoor [1] | Upland blanket bog | ●● | | | ● | | | ● | ●● |

[1] *Sites to be finalised for Mires on the Moors project*
[2] Cronkley Fell grip-blocking experimental site located nearby

●● Directly addressed by existing experiments
● Relevant issue on study site
○ Relevant issue in the wider area

Measurements currently being undertaken at the sites are shown in Table 2. Collectively, the sites listed provide fairly extensive coverage of blanket bogs, which represent 87% of all UK peatlands (seven sites), and for lowland raised bogs (four sites, including two restored cutover sites) (**key criterion 3**). Collectively, these sites cover semi-natural areas, and sites in a range of important ‘steady state’ land-management activities or conditions (**key criterion 4**). They include sites subject to drainage, management burning, grazing, forestry and erosion, as well as restored cutover sites. Experiments are also ongoing in at least one location to study the effects of land-management transitions, including grip-blocking, deforestation, altered burning and grazing regimes, and restoration of eroded peat (**key criterion 5**, see also section 3).

A full set of intensive gaseous and fluvial C and GHG measurements is currently being made at three sites (the CEH Carbon Catchments at Moor House, Auchencorth Moss and the Migneint) (**key criteria 1,2**) based on consistent methods. Other proposed sites would need some additional infrastructure and measurement in order to provide complete C/GHG budgets (i.e. to fill the gaps in Table 2), although most of the required measurements are also being made at the Forsinard, Flanders Moss, Bleaklow and Vyrnwy.

The geographical spread of sites is fairly wide (**key criterion 6**), with three sites in Scotland, five sites in England, and three sites in Wales. Relative to the overall distribution of peatlands across the UK, Scotland must be considered under-represented. Scotland includes much of the less management-impacted peatland area, and additional pristine/semi-natural peatlands in areas such as the Western Highlands and Hebrides would therefore be desirable, to provide a baseline against which to compare emissions from more managed areas. The peatlands of Galloway and the Southern Uplands are also currently unrepresented. Another clear omission from current site coverage is Northern Ireland; the Beaghs Burn Acid Waters Monitoring Network site in Antrim is a possible candidate here (for which a long fluvial record is available). This would require major investment and local involvement to establish a flux monitoring site, but would clearly be highly desirable to ensure UK-wide coverage.

A ‘Dartmoor/Exmoor’ site is included in the shortlist, despite limited current data, since this region is considered to be important as having marginal climatic conditions for peat formation, and therefore high sensitivity to management and climate change. Experimental restoration studies are currently being established in this area as part of the Mires on the Moors partnership project (supported by the Environment Agency, Southwest Water, English Nature and the National Park Authorities), with the active involvement of Exeter University, and have clear potential for enhancement to measure C/GHG fluxes. The North York Moors is another climatically marginal (and heavily managed) area, for which no measurements are currently available.

**Table 2.** Current measurement activity at potential Level I monitoring sites with existing or planned measurements, showing site type and relevant management issues.

| Site | Peatland type | Weather station | Flux tower | Static chamber GHGs | Hydrology | DOC | POC | DIC/CO2 |
|---|---|---|---|---|---|---|---|---|
| Forsinard | Upland blanket bog | ● | ● | | ● | ● | ● | ● |
| Flanders Moss | Upland blanket bog | ●[1] | ●[2] | ● | | | | |
| Auchencorth Moss | Upland blanket bog | ● | ● | ● | ● | ● | ● | ● |
| Moor House | Upland blanket bog | ● | ● | ● | ● | ● | ● | ● |
| Thorne Moor | Upland blanket bog | ● | | ● | | | | |
| Bleaklow | Upland blanket bog | ● | | ● | ● | ● | ● | ● |
| Migneint | Upland blanket bog | ● | ● | ● | ● | ● | ● | ● |
| Vyrnwy | Upland blanket bog | ● | | ● | ● | ● | ● | |
| Wicken Fen | Rich fen | ● | ●[3] | | | | | |
| Cors Erddreiniog | Rich fen | ● | | | ● | | | |
| Tadham Moor | Intermediate fen | ●[4] | ●[4] | ●[4] | ●[4] | | | |
| Cors Fochno | Lowland raised bog | ● | | ● | ● | ● | | |
| Whixall Moss | Lowland raised bog | ● | | ● | ● | ● | | |
| Dartmoor/Exmoor | Upland blanket bog | | | | ● | ● | ● | |

[1] *Soil temperature and rainfall logged, manual temperature recording during sampling visits*

[2] *Flux tower planned for 2011-12, after forest felling*

[3] *Two flux towers on intact and restored semi-natural fen*

[4] *Past measurements, site not currently active*

Compared to bogs, fens comprise a small fraction (6%) of the UK peatland area, but have been disproportionately impacted by anthropogenic modification, particularly for agriculture. The peats of the East Anglian fens are largely under cultivation, and current rates of wastage are likely to lead to the complete loss of peat from some areas within decades; the Evidence Review has identified these areas as being among the most significant for peatland GHG emissions at a UK scale. Three fen sites have been identified with current, historic or planned future C flux monitoring. Tadham Moor is a grazed and hay-cut wet meadow in the Somerset Levels, which was studied intensively (including flux tower measurements) between 2000 and 2003 (Lloyd, 2006), but is currently inactive. Cors Erddreiniog on Anglesey is a relatively intact calcareous fen, where a current CCW EU-LIFE project involves hydrological restoration and potentially GHG flux measurement. Wicken Fen is the only fen with current flux tower $CO_2$ monitoring, with two sites (operated by CEH and Leicester University) on areas of intact fen and restored former arable land respectively. Given the relative heterogeneity of fens, and their significance for the overall UK peatland C and GHG balance, priority should be given to establishing full GHG monitoring at these and (if possible) other fen sites. In particular, there is a pressing need to establish monitoring of one or more cultivated fen sites. Arable areas adjacent to the existing Wicken Fen study site may provide a cost-effective option, which would provide directly comparable data for intact, cultivated and restored areas at the same location. An intensively drained grassland on fen peat (for comparison to the wet grassland at Tadham Moor) would also be a useful addition to the network.

### 2.3.4 Selection of Level II and Level III sites

At this stage, we have not attempted to identify potential Level II and III sites. As recognised above, potential Level I sites are realistically likely to be restricted, at least to some extent, to those with existing measurements, augmented by a limited number of the highest priority peat/management types not captured by existing research activities. However, a considerably larger pool of less intensively instrumented research and/or restoration sites exist throughout the country (see for example the Moors For the Future Peat Compendium, http://www.peatlands.org.uk/) which could form part of a larger, less intensive measurement tier. Parallel application of high- and low-intensity measurement techniques at Level I sites would provide a 'calibration' of lower-intensity measurements at Level II and III sites, supporting interpretation and upscaling. As discussed in the section 3, a substantial set of ongoing field experimental studies already incorporate many of the measurements required for Level II monitoring, and could thus form a part of this network.

For the development of a larger-scale, lower-intensity network, and for Level III monitoring in particular, caution is required to ensure spatial representation of monitoring sites. Existing research and restoration sites are likely to be biased towards areas subject to active conservation management, so there will be a need to include sites under continued intensive management for agriculture and forestry, as well as unmanaged sites. If Level III monitoring is to be used to directly report peat C stock change at a national scale, then additional statistical constraints will apply to site selection. Monitoring programmes such as the Countryside Survey (CS) employ a strict random site selection procedure, to enable measured changes to be used to infer national-scale change. Other schemes such as the National Soil Inventories use a grid-based model. Either approach would effectively preclude the use of *any* existing study sites. Furthermore, schemes such as the CS are subject to restrictions on site location and access, such that specific site locations cannot be revealed, and additional sampling activity is generally not permitted between the (approximately decadal) surveys.

On the basis of these considerations, two (non-exclusive) options for large-scale peat C monitoring are possible. The first is an extension of current CS measurement protocols to include a more robust methodology for measuring peat C stock change, and to include a greater number of bog and fen survey sites. This possibility was discussed (in a Welsh context) by Evans *et al* (2009). The second option, which could be linked to the first through the use of consistent methodologies, is the establishment of a network of Level III sites at known, accessible locations covering a representative range of peatland types and conditions, and building where possible on existing study sites.

The option of utilising existing study sites would not support a direct statistical extrapolation of results to the UK peat area as a whole, due to the non-random nature of site selection, but would provide reliable measurements of stock and condition changes for a wide range of sites, supported by strong contextual information, and directly integrated with more intensive Level I and II monitoring. Provided that observed changes can be related to management or other environmental drivers, and that these drivers can be mapped at a UK scale, the national-scale estimation of stock and condition change should still be possible. Process models could also be used to support upscaling based on these data. This approach is considered preferable for the Level III sites, to maintain integration with Level I and II monitoring, and should provide the capacity to upscale process understanding, rather than simply to report change. A somewhat analogous situation is represented by the use of data from the AWMN catchments (which were not selected on any statistical basis) to infer upland surface water change at the wider scale based on demonstrated consistency of behaviour among sites (Evans *et al* 2010). The issues for larger-scale peat C stock assessment are discussed in section 4.

### 2.3.5 Number of sites required to provide necessary evidence

This study has not performed a formal power analysis to assess the appropriate number of sites in order to judge the minimal probable detectable difference between managements and sites. What has been noted above is the experience of Worrall *et al* (2007) who considered the experimental design and experimental power of the Hard Hill experiment at Moor House relative to water table and water quality differences (including DOC) between three burn treatments. Power analysis is a powerful tool for assessing the adequacy of an experimental design; however, formal, frequentist power analysis requires a knowledge of the underlying structure of the data, i.e. an estimate of the variance of the data distribution relative to the factors being considered. Such an analysis cannot be carried out for a consideration of carbon budgets where at present there is complete information for no more than four sites and these cover several types of management (i.e. there is no replication upon which to estimate underlying distributions). Nevertheless there are methods for addressing the issue of power analysis that could be used in these circumstances, such as consideration of certain components of the carbon budget where there is enough information for this approach to work. We do recommend that some form of power analysis is considered as one of the supporting activities in this programme.

# 3 Design of an experimental programme

## 3.1 Rationale

The measurement programme described in the previous section is designed primarily (although not exclusively) to quantify C/GHG fluxes associated with a range of peatlands under 'steady state' management. This section describes an integrated and targeted programme of field experimental activities designed to quantify the effects of management *change* on C/GHG fluxes, in other words to quantify the trajectory of C/GHG fluxes associated with land-use transitions. Again, this focus is not exclusive; control plots within field experiments can provide information on steady-state emissions for the existing management type at the site, and long-running experiments will ultimately provide information on the new steady state emissions associated with changed management (with the advantage of having direct comparability to the 'control' management at the same location). The two approaches are therefore considered complimentary, and could be delivered through closely linked, co-located research activities.

As in section 2, a pragmatic approach has been taken of maximising the utility of existing studies, such that they deliver a comprehensive assessment of the impacts of land-management change on the overall peatland C and GHG balance (based on comparable methods), rather than of the response of a few individual components. Priority is given to the management transitions highlighted as having the greatest significance for UK peatland GHG budgets in the Evidence Review, and in particular those for which the existing evidence base is poorest. In addition, to provide a robust evidence base to support decisions on peatland management and restoration, it is essential that all activities are well constructed, meet accepted standards of experimental design, and are maintained for a sufficient period to ensure that long-term ecosystem responses are correctly determined.

The following section considers 'good practice' for field manipulation experiments. Laboratory-based mesocosm studies are not the main focus of this review, but it is emphasised that such methods remain an important tool for understanding carbon cycling processes in peatlands; in some cases they may be the only logistically or financially practicable approach available. Laboratory-based approaches provide the capacity for tight control of all environmental conditions, for example through the use of controlled environment cabinets to manage temperature, light and $CO_2$ concentrations. While this approach may lack some realism, and there are inevitably artefacts associated with collecting and transferring peat mesocosms to the laboratory, it provides an effective (and relatively low-cost) method for the identification and quantification of underlying mechanisms, and for testing specific hypotheses. The results of mesocosm studies can thus support the identification and help to prioritise management approaches for further experimental testing under field conditions.

Survey-based approaches are also considered beyond the scope of this task, but it is noted that the greater spatial representation provided by large-scale surveys may significantly augment the evidence provided by experimental studies, and support the upscaling of experimental and baseline measurement results to the wider peatland area.

The notes on design of field experiments presented in section 3.2 are intended to provide a set of guidelines rather than a prescriptive set of conditions, as it is recognised that it may not be realistic or affordable to meet all criteria in all cases; for example there is often a trade-off between spatial scale and degree of replication. Nevertheless, some minimum standards should be met within all experiments used to support policy and management at a national level. In general, the greatest weight should be given to longer-duration and/or well-replicated studies where treatment responses can be demonstrated based on rigorous statistical analysis. Although not addressed specifically, it should also be noted that comprehensive, long-term (5+ year) studies provide important support for C and GHG modelling, since they allow input parameters to be constrained, outputs to be rigorously tested against a full set of observations, and for inferences to be drawn regarding both initial transitional fluxes, and subsequent stabilisation towards a new steady state.

The second component of this task (section 3.3) provides a collation of current peatland field experimental studies, considers the extent to which they meet current evidence needs, and identifies potential gaps and future requirements for studies of management impacts on peatland C/GHG balances.

## 3.2 Guidelines on the design of field experiments

### 3.2.1 Measurements

The exact measurements made within any field manipulation experiment will depend on its specific objectives, location, type of experimental intervention, etc. However, because different experiments are established for different purposes, there is a risk that each experiment will measure only a subset of C fluxes, and thus not enable the effects of management or environmental change on the overall C and GHG budgets to be quantified. This is often a consequence of the limited financial resource available, or of the particular objectives of the funding organisation; for example, a water company may only wish to support analyses of effects on fluvial components, whereas a Research Council research grant may be focused on testing a specific hypothesis, rather than on establishing the overall ecosystem response. While it is inevitably costlier to measure all components of the C balance for each individual experiment, there should be cost savings (as well as greater knowledge gain) through undertaking comprehensive studies of fewer sites, rather than partial studies of a larger number of sites.

Guidance:

*i* *The Level II monitoring design described in section 2.4 should be used as a template for measurements to be made at an experimental site, in order that management impacts on the full C and GHG budget can be quantified;*
*ii* *Wherever possible, experimental sites should be co-located with existing Level I or Level II monitoring sites.*

Co-location with Level I or Level II measurement sites would lead to considerable cost-savings, since many of the required supporting measurements (e.g. meteorology, stream discharge) will already be available, along with longer-term, larger-scale baseline flux data, for example from established flux towers. It is also worth noting that control-site measurements made within experimental studies could contribute to the overall suite of measurements required for a monitoring site, and that full implementation of Level II measurements within an experiment would effectively provide an additional Level II monitoring site for the duration of the study.

A constraint on the completeness of flux measurements that can be made within an experimental study is the spatial scale of manipulation. In most cases, it is not possible to carry out a fully replicated manipulation study at the catchment scale, necessitating the use of smaller landscape units such as plots or individual drainage grips. For plots in particular, quantification of fluvial fluxes requires a different approach than that used in catchment studies. At this scale, effects on dissolved carbon concentrations are generally measured by analysis of pore waters, using dipwells or suction samplers. Calculation of fluxes requires estimation of the water balances, for example using models based on meteorological data.

Co-location with a gauged stream is useful in helping to constrain the water balance. Issues relating to experimental scale are considered further below.

### 3.2.2 Control sites

Results from any manipulation study which lacks suitable controls (i.e. unmanipulated sites) cannot be unequivocally attributed to the effects of the manipulation. In the case of restoration studies, it may be beneficial to have two controls, i.e. both an unrestored control and an intact area to act as a target (or reference condition) for the restoration site. There is often some reluctance by conservation managers to omit areas from planned restoration to act as controls, particularly for long-term research, so it is important that the value of this approach is well communicated; there have been occasions in the past where well-intentioned but under-researched restoration activities have had unanticipated negative consequences, and this should be avoided.

Guidance:

*iii* *The use of control sites in experimental manipulation studies should be considered essential*.

### 3.2.3 Baseline data

Many experimental research studies have been linked to existing restoration (or other land-management activities) undertaken by other organisations. This is clearly beneficial in terms of minimising costs and maximising engagement with stakeholders and land-managers. However, because such studies tend to be opportunistic, it is often difficult to secure funding, establish an experiment and collect sufficient baseline measurements before the planned manipulation occurs. It is then difficult to confidently attribute observed changes in measured C fluxes to the treatment itself, rather than to pre-existing differences between sites. This is particularly problematic for catchment-scale studies, for which suitable replication is difficult to achieve. For unreplicated studies without baseline data, differences in measured fluxes **cannot** be unequivocally attributed to treatment effects.

Guidance:

*iv* *All studies should collect pre-manipulation baseline data, if at all possible, for at least a year. Experiments without baseline data may still be acceptable if both treatment and control plots/catchments are well replicated. Unreplicated studies without baseline measurements should not be used.*

### 3.2.4 Replication and experimental design

Replication is a fundamental part of ecological study, providing a sound basis for attribution of treatment effects via statistical analysis, generally based on Analysis of Variance (ANOVA). This review will not attempt to describe this complex subject in any detail, except to highlight the importance of a robust experimental design for any new experimental study, and to provide some general guidelines as follows.

Guidance:

*v* *An absolute minimum of three replicates of each treatment type (or level) is required for statistical analysis of plot-scale experiments. Four or more replicates should be used wherever possible. Worrall et al (2007) performed a statistical power analysis* *of their design for assessing impacts of managed burning and showed that six replicates were reasonable.*

vi *Plots should be randomly allocated to different treatments. Full randomisation may be possible within homogeneous study areas, or blocked randomisation in more heterogeneous areas (whereby plots are allocated to treatments within pre-defined groups, to minimise the effects of other factors such as peat depth.).*

It is recommended that a statistician be consulted during the development of any new experimental study. As noted above, pre-manipulation data should be collected wherever possible. It is worth noting that replicated plot-scale manipulations are not the only valid method of field-scale experimentation; indeed small-scale replicated experiments have been criticised by catchment scientists for failing to capture the complexity of whole ecosystems (e.g. Schindler, 1998). The alternative approach of paired catchment manipulation studies is discussed below.

### 3.2.5 Spatial scale

#### i Plot-scale experiments

Plot-scale manipulations are, as noted above, a standard and widely used method of ecological research, enabling relatively simple and robust experimental design via the establishment of replicated treatment and control plots. A plot-scale approach is most effective for understanding the impacts of environmental drivers that operate relatively uniformly across the landscape, such as warming, burning or deposition change. For changes that impact more heterogeneously, in particular drainage and erosion, such a small-scale approach is more problematic. Plot scale approaches can also exclude part of the important complexity that operates within natural landscapes. For example, plot studies are generally located within relatively homogenous landscape units in order to meet the statistical requirements of ANOVA. This may fail to capture the changes occurring at soil or habitat boundaries, or at key locations within the hillslope continuum such as riparian zones or gully edges. Because of the degree of lateral water movement within peatlands, it is not possible to hydrologically isolate treatment plots without substantial disturbance of existing flowpaths. On the other hand, the smaller scale and relative simplicity of plot-scale experiments can increase the confidence with which observed responses can be ascribed to experimental treatments.

Guidance:

vii *Plot-scale experiments should be undertaken at a scale sufficient to encompass both the complexity of the peatland landscape, and the actions of management within it.*

#### ii Catchment-scale experiments

Catchment-scale studies have a number of important advantages: they represent physically meaningful and hydrologically distinct units within the landscape; they can encompass the effects of management change within a heterogeneous landscape; and they permit the reliable measurement of fluvial carbon fluxes. They also represent a scale of manipulation that is relatively effective for disseminating results to the wider land management community (the 'demonstration catchments' approach). However, the challenges of establishing a scientifically robust, replicated manipulation experiment at the catchment scale, involving experimental treatment of multiple catchments, are considerable, and require close and active cooperation with land-managers. The Vyrnwy study represents one of the very few examples (for any ecosystem type) where a replicated experiment on this scale has been established. Another example for peat catchments is the Cronkley drain-blocking trial, where six drained grip 'catchments' were selected and monitored for a year before three were selected for blocking, with monitoring continuing upon all six.

It should be noted that the concept of replication in a catchment context is somewhat open to question, since catchments are never truly identical, although this does not invalidate their use where treatment effects are likely to exceed between-catchment differences. Peat dominated catchments may be more homogenous, and thus conducive to this approach, than catchments in more complex terrain or intensive land-use. In general, robust catchment-scale manipulations are only likely to be possible at the scale of small headwater systems (~1km$^2$ or less) for which small-scale variability can be minimised, or at least characterised.

In previous biogeochemical and hydrological research, an alternative to replication in catchment-scale manipulation experiments has been provided by the use of 'paired catchments'. Examples include the classic deposition manipulation studies at Gårdsjön in Sweden (Moldan *et al* 2006), and Bear Brook in America (Norton *et al* 2004). In each case, one catchment was manipulated over a long period while a similar catchment was monitored as a 'reference site'. Instead of assuming true replication between catchments, treatment responses are evaluated with reference to an extended (multi-year) period of baseline measurement, which permits comparison of sites during the pre-treatment period, and the use of statistical techniques such as Randomised Intervention Analysis (Carpenter *et al* 1989) to attribute subsequent deviation post-treatment.

Guidance:

*viii* *Replicated catchment experiments are desirable if possible. The paired catchment approach provides a potential alternative, but can **only** be robustly applied if sufficient pre-manipulation data have been collected to define the baseline condition, and if post-manipulation measurements are sustained for an extended period*.

### iii Hillslope-scale experiments

Hillslope-scale studies provide a potential compromise between plot- and catchment-scale experiments, capturing more of the complexity of natural landscapes without sacrificing a replicated experimental design. This approach has been used as the basis for the recently established Defra-funded peat restoration study on the Migneint, (SP1202), with replicated small 'grip' catchments used as the basis for manipulation. This approach is effective for measuring fluvial as well as gaseous fluxes, since water draining the hillslope is captured within the grips. However, it is only effective where grips run directly downslope; where grips are aligned across the slope, hydrological interference between adjacent grips precludes the use of a hillslope approach, requiring the catchment-scale experimental approach employed at Vyrnwy.

Guidance:

*ix* *Replicated hillslope-scale experiments represent a potential compromise between the issues affecting plot-scale and catchment-scale studies, provided that the site and nature of the manipulation permit independent experimental units to be defined.*

### vi Duration

The 'default' duration of academic research projects is three years. Allowing for a period of planning, for the collection of pre-manipulation data and for final analysis of results, this is unlikely to permit more than two years of measurements to be made following the start of manipulation. While this may be adequate for studies focusing on purely chemical or physical processes, or for laboratory mesocosm studies, it is unlikely to give reliable results in field settings. In particular, this may not capture the effects of treatment-induced changes in vegetation structure and composition, which are known to be critical for determining ecosystem C balance. For example, $CO_2$ balance is dictated by the balance of plant photosynthesis and respiration; $CH_4$ emissions are strongly dependent on vegetation type (McNamara *et al* 2008); DOC exported from peatlands has been shown to largely derive from recent plant material (Evans *et al* 2007); and POC export largely occurs from unvegetated areas connected to the drainage network (Evans and Warburton, 2005). Short-term field experiments may thus capture initial transitional changes in GHG flux associated with physical and chemical changes in the peat environment, but not the more gradual (but potentially more significant) changes associated with shifts in vegetation cover and composition.

Ideally, experimental studies should extend over the full period of transition from one management 'steady state' to another, although this may be difficult to achieve where transition periods are long. The risk of misinterpreting short-term responses as long-term changes can be minimised by extending study periods beyond the standard three years, and comparing results to measurements from systems in a stable condition within the Level I and II measurement programme. For assessing very long-term changes, chronosequence studies may provide a useful alternative, or addition, to shorter-term experiments.

Guidance:

- *Experiments should, wherever possible, aim to run for at least five years (including the pre-treatment measurement period)*

**Table 3.** Summary guidelines on the design of field experiments

| | | |
|---|---|---|
| **Measurements** | 1 | The Level II monitoring design described in section 2.4 should be used as a template for measurements to be made at an experimental site. |
| | 2 | Where possible, experimental sites should be co-located with existing Level I or Level II monitoring sites. |
| **Control sites** | 3 | The use of control sites in experimental manipulation studies is essential. |
| **Baseline data** | 4 | All studies should collect pre-manipulation baseline data, and wherever possible for at least a year. Experiments without baseline data may still be acceptable if well replicated, but unreplicated studies without baseline measurements should not be used. |
| **Replication and experimental design** | 5 | Replication of plot-scale experiments is essential. Three replicates is of each treatment type (or level) represents a minimum requirement; four or more replicates is desirable. |
| | 6 | Plots should be randomly allocated to treatments. Full randomisation may be possible within homogeneous study areas. Elsewhere, blocked randomisation can be used to account for pre-existing heterogeneity. |
| ***Plot-scale*** | 7 | As a general rule, plot-scale experiments must be |

| | | |
|---|---|---|
| ***experiments*** | | undertaken at a scale sufficient to encompass both the complexity of the peatland landscape, and the actions of management within it. This scale will vary according to peatland and management type. |
| ***Catchment-scale experiments*** | 8 | The paired catchment approach provides an alternative to replicated plot-scale studies, but requires a) careful selection of comparable catchments, and b) long pre-manipulation baseline and post-manipulation measurement periods, to enable divergence between sites to be reliably attributed management change, rather than pre-existing differences. |
| ***Hillslope-scale experiments*** | 9 | Hillslope-scale experiments provide some of the benefits of catchment studies in terms of scale, and of plot studies in terms of potential for replication. However, the requirement for hydrologically independent experimental units for hillslope studies can only be met for some peat and management types. |
| **Duration** | 10 | Experiments should, wherever possible, aim to run for at least five years (1+ year pre- and 4+ years post-manipulation). |

## 3.3 Current field experimental studies, and priorities for further research

As for the flux measurement activities considered in section 2, it is useful to evaluate:

- the extent to which current experimental studies could be expanded in order to deliver full C and GHG flux assessments of management impacts, rather than partial measurements; and
- where additional experiments may be required to capture key management transitions which have the greatest significance for UK peatland C/GHG budgets, and/or those which are least well quantified at present.

The Evidence Review has identified a range of existing experimental studies, but includes studies that measure only one or two components of the C balance, studies based on stock assessments, studies that have ended, and studies from outside the UK. The number of currently (or recently) operational field experiments at which most elements of the peat C balance are included is substantially smaller. Table 4 lists a number of such studies, the issues that they address, and information on the experimental design and duration. It is worth noting that over a third of the studies included are focused on the effects of external drivers (climate and deposition) rather than management. Data from these studies may nevertheless be relevant to understanding management impacts, either indirectly (i.e. by indicating how climate or deposition change may 'move the goalposts' for peatland C/GHG balances) or directly (e.g. rainfall or water table manipulation experiments may provide insight into the effects of drainage). Of the experiments focused specifically on management, the greatest number address the impacts of drainage and drain-blocking, with a smaller number addressing burning, erosion, grazing, bare peat restoration and deforestation. There are no current studies on afforestation impacts (a reflection of the current trend for reducing rather than increasing forest cover on peats) and only one study of any type on a fen site (the flux tower study on a restored ex-arable site at Wicken Fen).

Although full measurements at each site have not been collated, we believe that only a minority of these studies include sufficient measurements to construct a full C and GHG balance.  However, most sites are either co-located with, or close to, proposed Level I study sites.  This provides clear potential synergies and potential cost-savings if Level I and Level II measurement data can be used to support the experiments, or if control plot or auxiliary data collected from experiments can contribute to our understanding of fluxes associated with steady state land management.  This would, however, require good coordination and harmonisation between the Level I-II 'steady state' measurements, and the 'transitional' measurements from the experiments.

**Table 4.** Field experiments in which peatland carbon fluxes are currently being measured. Experiments are classified according to those examining management transitions, those comparing management steady states, and those evaluating the effects of external drivers of change.

| | | Management transitions | | | | | | 'Steady state' comparisons | | | | External drivers | | | | Details of experiments | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Experimental site | Closest identified measurement site | Drain-blocking | Forest removal | Cutover peatland restoration | Grazing change/ biomass removal | Re-vegetation | Cultivated pest restoration | Drained vs undrained | Bare vs vegetated | Burnt vs unburnt | Grazed vs ungrazed | Temperature manipulation | Water table/rainfall manipulation | Vegetation manipulation | Deposition manipulation | Plot/hillslope/catchment | Controlled | Replicated | Pre-manipulation data | Duration (years to date) | Duration (future planned) |
| Forsinard | Forsinard | • | • | | | | | • | | | | | | | | **C** | √ | x | X | 2 | 3+ |
| Flanders Moss | Flanders Moss | • | • | | | | | • | | | | | | | | **P** | √ | √ | √ | 2 | 2+ |
| Middlemuir Moss | | | | • | | • | | | | | | | | | | **P** | X | √ | X | 6 | 1+ |
| Whim Bog | Auchencorth | | | | | | | | | | | | | • | • | **P** | √ | √ | √ | 8 | 3+ |
| Hard Hills | Moor House | | | | | | | | | • | • | | | | | **P** | √ | √ | X | 7[2] | 3+ |
| Moor House | Moor House | | | | | | | | | | | • | | • | | **P** | √ | √ | √ | 3 | 1+ |
| Cronkley Fell | Moor House | • | | | | | | • | | | | | | | | **C** | √ | √ | √ | 2 | 1 |
| Byershope | Moor House | • | | | | | | • | | | | | | | | **C** | √ | √ | √ | 3 | 0 |
| Thorne Moor | Thorne Moor | | | • | | | | | | | | | | | • | **P** | √ | √ | √ | 2 | 0 |
| Bleaklow | Bleaklow | | | | • | • | | | • | | | | | | | **P** | √ | √ | X | 4 | 1 |
| Peaknaze | Bleaklow | | | | | | | | | | | • | • | • | • | **P** | √ | √ | √ | 5 | 3+ |
| Goyt Valley | Bleaklow | | | | • | | | | | | | | | | | **P** | √ | √ | X | 2 | 1 |
| Holme Moss | Bleaklow | | | | | • | | | | | | | | | | **P** | √ | √ | X | 4 | 1+ |
| Migneint | Migneint | | | | | | | | | | | | | | • | **P** | √ | √ | √ | 3 | 1+ |
| Flynnon Eidda | Migneint | • | | | | | | • | | | | | | | | **H** | √ | √ | √ | 0 | 5 |
| Vyrnwy | Vyrnwy | • | | | | | | • | | | | | | | | **C** | √ | √ | X | 3 | 1+ |
| Wicken Fen | Wicken Fen | | | | | | • | | | | | | | | | **P**[2] | √ | X | X | 1 | 2+ |
| Cors Fochno | Cors Fochno | | | | | | | | | | | • | • | • | • | **P** | √ | √ | √ | 0 | 3 |
| Whixall Moss | Whixall Moss | | | | | | | | | | | • | • | • | • | **P** | √ | √ | √ | 0 | 3 |
| Dartmoor/ Exmoor[1] | Darmoor/ Exmoor[1] | • | | | | • | | • | • | | | | | | | | | | | 0 | 3+ |

*[1]Experiment(s) to be established as part of Mires on the Moors project; [2]Hard Hills experimental burning and grazing manipulations started in 1954, flux measurements started in 2003. Grey circles indicate management transitions that are occurring on site, but are not being studied experimentally.*

Since the current experiments have evolved on an essentially ad hoc basis, they do not fully reflect the range of key management transitions, or the range of peat types, identified as priorities in the Evidence Review. It is therefore anticipated that new experiments will need to be established to effectively assess the impacts of the full range of important current and future land-management options across the range of different peatland types in the UK. The following sections consider what is currently available, and what additional research studies might be needed, for each of the peatland management classes considered in the Evidence Review.

### 3.3.1 Peat drainage and re-wetting

At a UK scale, peatland drainage has been one of the most extensive forms of management, in both upland and lowland systems. Increasing areas of drained peat are now being restored via drain-blocking. The Evidence Review (section 2.3.1) highlights the large uncertainties in GHG budgets for both drained and drain-blocked peatlands, suggesting that this should be a priority for additional research. However, there are a large number of experimental studies now taking place in drain-blocked peatlands, including some which have recently been established. Further data from these studies should help to significantly reduce current uncertainties, and support the calculation of more accurate emissions factors for drain-blocked peatlands. The inclusion of unblocked control areas in these studies should also provide information on the steady-state GHG balance of drained systems. There are no experimental studies of the transition from undrained to drained peatlands. However, since further peatland drainage is not expected to occur on a large scale, this is not considered a priority for future work.

### 3.3.2 Burnt/unburnt peatland

Although managed peat burning is extensive in areas such as Northern England, there is very little published information on GHG budgets for rotationally burnt peats (Evidence Review section 2.3.2). That which is available only covers a small area subject to a single (low) intensity of burning and is insufficient to calculate an emissions factor. This study is for a site under stable long-term burn management, and thus provides no information on transitions to or from a rotational burning regime.

There are also no complete studies of more intensively burnt areas, or of the effects of wildfire. In terms of management transitions, experiments to address the effects of shifting between no-burn and high-frequency burn are considered to be a priority. Due to the nature of rotational burning, it should be noted that the impacts of burning on C/GHG flux need to be quantified over the full fire rotation period, rather than just the period of burning itself, which implies the need for either sustained experimental studies, or their augmentation by other information, for example from chronosequence studies. Studies which examine the effects of differing intensities of burn management would also be beneficial.

### 3.3.3 Grazed/ungrazed peatland

The impacts of variable grazing levels, or of cessation of grazing, on peat C and GHG balances is not well quantified, with only one current study at a lightly grazed site (Evidence Review section 2.3.3).

While the available evidence suggests a relatively small GHG impact, the potential for changes in grazing to lead to long-term vegetation change, and the likelihood of future changes in the agricultural use of peatland areas, suggest that additional field studies would be beneficial. Such studies would need to take account of variable grazing levels as well as presence/absence, and of the biomass transfers and GHG emissions associated with livestock. It is noted that lowland (particularly fen) peats can be subject to more intensive grazing, as in the Somerset Levels, and that grazing can form a component of the management of re-wetted lowland peats. The Tadham Moor study provided some information on the C budget of these systems, but only for a site under steady state management. Further experimental work targeted on the transitions between high- and low-intensity grazing on fen peats is recommended, given the large, but uncertain, potential changes in GHG fluxes that could occur.

### 3.3.4 Peat afforestation and deforestation

Section 2.3.4 of the Evidence Review notes that the process of peatland afforestation has been relatively well studied, but that little information is currently available on the C/GHG impacts of deforestation (i.e. restoration to bog vegetation). However, this situation is now being addressed via GHG budget studies of restoration sites at Forsinard and Flanders Moss, which should generate improved information within the next few years for both recently deforested areas, and for areas under continued forest cover. Changes in flux are likely over the forest rotation period, and over an extended period following deforestation. As for burnt peatlands, chronosequence studies may therefore be needed to augment field experiments. Because new peatland afforestation is decreasing sharply, and is now discouraged in current forest guidelines, studies of the transition from unforested to afforested peatland are not a high priority.

### 3.3.5 Revegetation of degraded peats

The estimated emissions factors for bare, eroded and wasted peats peat are high (Evidence Review section 2.3.5), suggesting that significant gains in GHG budgets can be obtained through active re-vegetation of these areas. This is highly uncertain, however, given the very limited number of studies and the sometimes drastic interventions (e.g. lime, fertiliser and grass seed application) required to re-vegetate degraded peats. Much of the most severe peat degradation occurs in the Southern Pennines, an area in which a number of studies are ongoing. In other regions, the significance of emissions from degraded peatlands may be proportionally smaller, despite large fluxes per unit area. It is therefore suggested that maintenance of existing restoration studies in the South Pennines, augmented where necessary to provide full C and GHG budgets, may be the most effective means by which to provide the necessary evidence base.

### 3.3.6 Cutover and restored peatland

Cutover peatlands are associated with severe rates of C loss, but as noted in the Evidence Review (section 2.3.6) most of the available evidence has been obtained from studies outside the UK. The only current UK experimental study on a restored cutover peatland is at Middlemuir Moss, although other research is also taking place on formerly cutover areas of Thorne Moor, which have now been re-wetted. Conversion of peatlands to and from active peat extraction is an issue of high policy relevance, e.g. within the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, and further studies specific to UK ecosystems would therefore be beneficial to improve emission factor estimates. In particular, it is important to distinguish the transitional and subsequent steady-state fluxes associated with the re-wetting of cutover peatlands with and without active re-vegetation (e.g. with *Sphagnum* species), and to different final water tables (e.g. above and below the surface), since these factors can result in very different outcomes for GHG fluxes. Since similar studies exist for cutover raised bogs in Canada and continental Europe, one or two well-constructed, comprehensive studies on UK cutover peatlands may be sufficient to determine whether results from these studies are applicable to the UK situation.

### 3.3.7 Cut or mowed peatland

Peat management by cutting or mowing has been used as an alternative to managed burning in some areas, such as in Wales where burning of blanket bogs is now discouraged. The Evidence Review (section 2.3.7) notes that no studies of the effects of cutting or mowing on C/GHG budgets currently exist, but that the effects of infrequent biomass removal may more closely resemble those of managed burning than of continuous grazing. Some studies in the Peak District are now examining the effects of this form of management; if its use is to become more widespread, then additional field experiments in other areas may be required.

### 3.3.8 Peatlands converted to or from agriculture

The Evidence Review (section 2.3.7) notes a ‘complete lack of information’ on C and GHG fluxes associated with peatland conversion to arable land or improved pasture. However, the evidence of severe and ongoing wastage of agricultural peatlands in areas such as the East Anglian Fens demonstrates the critical significance of these areas in terms of GHG emissions from UK peatlands. The $CO_2$ flux studies in intact fen and former agricultural land at Wicken Fen, and the former study at Tadham Moor, provide the only C budget information for any type of UK fen peat. The Wicken study includes measurements on a site in transition from cultivation to conservation management, but at present there are no ‘control’ measurements from areas under continuing agricultural use. The Tadham study only provided data for a site under ‘steady state’ management. New targeted field experiments in agricultural fen peats, which compare sites in transition from intensive to extensive agriculture or conservation management with areas subject to ongoing intensive agriculture, are perhaps the highest priority for additional research work of all the issues considered in this review.

# 4 Design of a large-scale peat carbon stock and condition assessment

This task was outside the core scope of the project, and has not therefore been developed in detail. However, the capacity to scale up understanding from site-based studies to the wider landscape remains crucial. The following short section briefly comments on the role of survey-based approaches for measurement of C stock, in support of intensive site-based measurement and experimental studies of C flux, and considers the issues and approaches that might be relevant for developing a large-scale peatland survey.

While the focus of the study has been on developing an effective field-based monitoring and experimental programme, larger-scale surveys can provide important, and complementary, information on the impact of management on peatland C and GHG budgets. Surveys have the advantage (compared to experiments) of avoiding the need to instigate land-management change at particular locations, since sites can be selected on the basis of pre-existing management activities. Surveys can be undertaken over relatively short periods, and at a relatively low cost per site, enabling measurements to be made at a large number of locations, and for results obtained and reported on within a short timeframe. A recent example of a survey-based study is the assessment by Armstrong *et al* (2010) of DOC concentrations in waters draining gripped and grip-blocked peats across Northern England and Northern Scotland and Southwest England, in which measurements were obtained from 320 blocked and open drains at 32 sites within one year.

Inevitably, it is not possible to undertake the breadth and intensity of measurements at a large number of survey sites that can be made at a smaller set of experimental sites; specifically, it is generally only possible to measure C stocks (or changes in C stocks based on repeat surveys) rather than fluxes. Additionally, as the aim is to provide a representative national-scale assessment rather than simply to improve process understanding, large-scale surveys must, as noted earlier, be carefully designed to provide a valid basis for statistical analysis. A review of soil carbon monitoring for Wales (Evans *et al* 2009) recommended following the stratified random sampling methodology utilised by the Countryside Survey. In the specific case of peatlands and management impacts, such a survey would need to stratify sites according to both peatland type and (where this is possible based on prior information) management. Peatlands with a small spatial extent but high importance for GHG fluxes (such as cultivated or degraded peats) and/or greater heterogeneity (fens) would require more intensive sampling. Analysis of survey-based data must avoid confounding the driver under consideration (in this case management) with other environmental gradients such as temperature, rainfall and atmospheric deposition, which vary significantly across the UK peatland area.

Finally, it is generally difficult to characterise all relevant aspects of each site, such as their past land-use history, which may be important determinants of current conditions. Nevertheless, the low cost and high spatial representation provided by survey-based approaches make their use in support of a more intensive, site-oriented research programme appealing. Were this approach to be incorporated in an overall research programme, it is recommended that this should incorporate a subset of the measurements outlined for Level III monitoring described in section 2.4. Specifically, it should be possible to include basic C stock change measurements (i.e. %C, bulk density and depth measurements above an identifiable horizon (as described in Annex 1)) into surveys of a larger number of sites. Near-surface bulk density measurements would also provide information on peat condition, as would vegetation or microtopographic observations. A one-off set of full-profile peat core measurements would provide valuable new information on peatland C stores (which remain incompletely quantified), including the extent of residual peat stocks in degraded areas. By collecting a limited set of measurements compatible with

Level III monitoring at an appropriately selected set of sites, this could also provide a potential baseline for an expanded large-scale peatland monitoring programme in future, should this be considered necessary. There is clear potential for any such programme to be integrated within existing national-scale assessments such as the CS.

# 5 Network operation

## 5.1 Coordination and funding

As the preceding sections illustrate, a substantial number of field monitoring and experimental studies on peatland carbon cycling already exist. However, to a great extent these are operated individually, by different institutions. The range of funders for this research includes Defra, NERC (via individual research grants and through funding of research centres such as CEH), conservation and environment agencies, the devolved administrations, the Forestry Commission, utility companies and the EU. This remarkable range of funding sources highlights the widespread interest and relevance of research on peatland carbon cycling. However, the challenges involved in coordinating and integrating such a diverse range of research in order to provide a coherent evidence base at a national scale should not be underestimated. Developing a formalised, unified long-term measurement programme at a UK scale is likely to require the coordinated involvement and support of multiple funding agencies, and also greater level of coordination within the research community. If this can be achieved, there is the clear opportunity to achieve an integration of peatland research programme which generates consistent and comparable data from multiple sites, links experimental and monitoring activities, provides improved representation of UK peatlands as a whole, and delivers outputs that feed directly into policy development.

A suggested mechanism for achieving an integrated network would be through the pooling of resources from different funding agencies into a network with centralised management. An alternative, given the issues noted above, would be for individual funders to support different experimental or monitoring studies, although this would still require some (funded) central coordination, to ensure that these studies will, in combination, provide comparable output data and meet overall policy requirements at a national scale. The role of any coordinating body would be expected to include the following:

i To coordinate and integrate current and new measurement and experimental sites to provide a common set of measurements, which meet generally agreed standards of data collection, analysis and experimental design, and provide the necessary evidence base for decision-making;

ii To maximise the efficiency of measurement activities by better linking research into steady-state land uses and experimental studies examining transitions, and avoiding unnecessary duplication and repetition (for example through the use of experimental controls to provide Level II measurement data);

iii To identify requirements for (and potentially direct funding to support) the collection of additional key measurements at existing experimental studies, to provide complete information on peatland C/GHG responses to management and restoration;

iv To provide an ongoing review of the remaining evidence gaps, and to prioritise further field measurements and experiments accordingly;

v To collate, update and review the evidence base to ensure that the full range of available information is utilised appropriately and effectively by policy-makers and land-managers;

vi To support key follow-up activities such as modelling and provision of emissions data to inform GHG inventories, and assessment of environmental trends across the network.

Recent reviews, collaborations and workshops, including the workshop organised within this project, suggest that the goodwill exists to make such a cooperative approach successful. It is likely that substantive progress could be made simply by facilitating further engagement. Inevitably, however, the capacity of such a coordinating body to pro-actively influence research is likely to depend on its capacity to direct financial support. This will need to be considered if a coordinated and effective programme of research is to be achieved.

## 5.2 Network management

Regardless of the funding model used, any integrated peatland network will require some central coordination in order to ensure consistency of measurements, methods, data analysis and storage across different institutions and site managers. Two somewhat contrasting templates for environmental monitoring network coordination are provided by the Acid Waters Monitoring Network (AWMN) and Environmental Change Network (ECN). Although both are centrally managed, the AWMN has a relatively centralised structure involving a small number of institutions, sample analysis at central laboratories, and biological surveyors visiting all sites on a campaign basis. The ECN has a more diffuse, multi-partner structure, with measurement protocols and database management provided by a central coordination centre, and different institutions operating each site. While the AWMN structure offers significant advantages in terms of ensuring consistency, continuity and quality control, the ECN structure appears more appropriate for a peatland monitoring network likely to involve a large consortium of scientific and stakeholder organisations.

If the ECN structure is followed, this would require the establishment a central coordination unit. This would have responsibility for liaising with site operators, developing measurement protocols and quality assurance procedures to ensure consistency and reliability of field measurements, sampling handling and laboratory analytical methods across sites and organisations. Potentially, a central coordination unit could also maintain a programme database and website facility. Whether such a central database is considered appropriate would depend on the willingness of participants (many of whom would likely be making many of their measurements with funding from other sources) to submit data, and/or to make it available. In addition, some of the instruments used to measure C fluxes (notable eddy flux systems) produce very large volumes (terabytes) of data which are challenging to handle and expensive to store. CEH is currently establishing a central data storage facility for eddy flux data, which might be expanded to provide a wider community facility. However, it may be more appropriate for a central coordination unit to store and make available summary data from each site, rather than to hold the full raw monitoring data.

Oversight of the network (again following the ECN example) could be provided by a scientific management group comprising site managers and other appropriate experts, and a steering committee comprised of network sponsors and stakeholders.

## 5.3 Data analysis, modelling and reporting

For a measurement network to be effective in delivering relevant policy outputs, a formalised structure for analysis of data and reporting should be established. This should incorporate results from both the monitoring and experimental elements of the programme. It is proposed that the following should be undertaken on an annual basis:

i Quantification of annual fluxes and overall C and GHG budgets for each Level I and Level II site;

ii Statistical analysis of annual results in order to assess differences between treatments and sites; we would propose that power analysis is also included in this annual assessment in order to provide a statistical quality assurance to the programme;

iii Reporting on results of experimental studies showing effects of management on C and GHG budgets, and calculation of updated emission factors for peatland under steady-state management and during management transitions, including estimation of uncertainties in estimates;

iv Updating of the meta-analysis described in the review based on both sites included in the programme, and any additional studies in the literature.

In addition, we suggest that C/GHG models are parameterised (set up to run based on available data) for each site at the start of the project, with upscaling supported by Level III stock and condition measurements, and by available national-scale peat mapping data. Model parameterisation should be updated periodically as new data from the measurement programme become available. The inclusion of an integrated modelling component will permit results from the measurement programme to be upscaled to the wider UK peatland area, with simulations based on current management and condition, and scenario assessments for different management options, utilising the information gained from monitoring and experimental studies. Data obtained from the network will also be used to improve the process descriptions in the models (e.g. using detailed Level I and experimental data) and for model testing (e.g. using Level II and III data).

Finally, we recommend that a comprehensive assessment of results from the programme be made on at the end of the five year period. This should include: a full analysis of measured C/GHG budgets; analysis of trends across the measurement network; collated evidence of the effects of management (and other environmental drivers) on the C/GHG balance from experimental sites; assessment of changes in peat C stock and condition; revised estimation of emission factors for each peatland and management type; updated meta-analysis and national-scale model application; and requirements for further research. The results of this assessment should be disseminated via publications, workshops, web pages and other media.

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# Annex 1 - Overview of current methods for measurement of peat C/GHG budgets

## Methods for carbon and GHG flux measurement

To develop a practicable measurement programme, it is necessary to identify the current range of measurement techniques available, and their advantages and limitations. This section aims to build on (rather than repeat) the detailed methodological descriptions of peatland monitoring techniques provided in a number of recent reviews (e.g. Holden and Armstrong, 2007; Bonnett *et al* 2009; Baird *et al* 2009), with a specific focus on the key measurements required to quantify C/GHG balances, either directly via flux measurement or indirectly via measured C stock changes.

### Gaseous flux measurement

- ***Eddy covariance methods***

The most comprehensive method for estimating $CO_2$ fluxes is via eddy covariance measurement. These provide a high-resolution record of land-atmosphere $CO_2$ exchange for a 'footprint' of surrounding land, typically a few hundred metres surrounding the flux tower. This method combines high-frequency (> 10Hz) measurement of $CO_2$ concentration above the ground surface (typically 1-3m) with 3-dimensional wind measurements using a sonic anemometer. Differences in the concentration of $CO_2$ in air masses moving upwards and downwards are used to calculate the vertical gradient of $CO_2$ concentrations between the land surface and the atmosphere, and therefore the net flux of $CO_2$ from or to the land surface, referred to as net ecosystem exchange (NEE). Measured instantaneous fluxes are integrated over time to calculate annual NEE.

Flux towers have been operated at a number of peatland sites internationally for some years, including Mer Bleue in Canada (Roulet *et al* 2007), Degerö Stormyr in Sweden (Nilsson *et al* 2008) and Glencar in Southwest Ireland (Koehler *et al* 2010). In the UK, the longest-running record available for a peatland is for Auchencorth Moss in Southeast Scotland, which has been collecting full flux data for the last five years, with earlier measurements of a subset of fluxes in the mid 1990s (Billett *et al* 2004; Dinsmore *et al* 2010). In addition to Auchencorth Moss, flux towers measuring $CO_2$ are currently operating on UK peatland sites at Moor House (North Pennines, England), Forsinard (Flow Country, Northern Scotland), the Migneint (Snowdonia, North Wales) and Wicken Fen (East Anglian Fens, England) (Figure 1). A further tower is planned at Flanders Moss (Stirlingshire, Scotland). Previously, fluxes were also measured at Tadham Moor in the Somerset Levels (Lloyd, 2006) although this site is not currently active.

Importantly for peatland systems, recent sensor developments (such as the Li-COR LI 7700) mean that the eddy covariance methods can now also be used to measure $CH_4$ fluxes reliably in remote locations. Continuous $CH_4$ measurements are currently made at Auchencorth Moss, and are planned for Forsinard and the Migneint (based on current funding), providing a test of these systems for UK peatlands. The high temporal resolution of eddy covariance measurements represents an important advantage of this approach, although some degree of gap-filling (based on established correlations with meteorological variables such as solar radiation and temperature) is required for periods when measurements are unreliable or unavailable, e.g. due to poor weather conditions or power failures. Disadvantages include variability of the source footprint for measured fluxes, which varies according to wind conditions. This is a particular problem in relation to experimental studies of restoration impacts, since it is difficult to relate measurements to areas under particular management or condition unless these extend across large areas (i.e. over the entire footprint). The larger and variable footprint of eddy flux systems also means that care is required in order to relate the fluxes to key drivers within the footprint, such as relationship to water table. To obtain sufficient experimental control and replication using eddy covariance methods, the extent over which manipulations would need to occur, and the number of flux towers that would need to be deployed, is likely to be prohibitive in most instances. Although they can have low running costs, eddy flux towers have a high initial cost relative to chamber methods and have a high data-processing requirement. However, overall eddy covariance methods are considered more appropriate for the purpose of long-term monitoring.

- ***Chamber methods***

The second main method used to measure GHG fluxes is via the use of flux chambers. Although methods vary, the basic principle is to create a sealed enclosure above an area of intact vegetation, in which accumulation of trace gases can be measured. The more widely used (and lower cost) static chamber method is considered most appropriate for peatland systems. In this method, changes in gas concentrations within the enclosure are measured over time, to estimate the net release of uptake of gas by the ecosystem. Changes in $CO_2$ concentration are commonly measured over a few minutes (to minimise measurement artefacts associated with warming, pressure changes, or $CO_2$ build up/depletion within the chamber) using an infra-red gas analyser (IRGA). Parallel use of dark and light chambers can (by stopping photosynthesis with dark chambers) be used to disaggregate the measured net $CO_2$ flux into gross photosynthesis and ecosystem respiration fluxes, whilst measurements on areas of bare soil may be used to separately estimate soil respiration. For measuring $CH_4$ and $N_2O$ fluxes, chambers are generally left in place for longer periods (20 minutes to one hour) to permit measurable concentration changes to take place, with artefacts associated with the chamber minimised through use of pressure equilibration balloons and fans. Air within the chamber is periodically sampled via syringes, and samples analysed in the laboratory using a gas chromatograph (GC), or for a faster turnaround using bench-top laser systems. In general, it is necessary to install 'collars' within the ground surface, in order to attain an air-tight seal with the chamber.

Methods for chamber gas flux measurement have been described and evaluated in detail by Denmead (2008), and in the recent review of peatland restoration monitoring methods by Bonnet *et al* (2009). The key benefits of this approach are the relatively low cost, and the defined location at which measurements take place. The latter is of particular importance in relation to monitoring management and restoration impacts, as it means that measurements can be made within specific vegetation types, in areas of contrasting condition or management, such as adjacent to open and blocked grips, and also that these measurements can more readily be associated with key drivers such as water table. Key disadvantages are the potential for artefacts associated with the measurement (for example, disturbance associated with the installation of collars), the limited area over which measurements are made (commonly < $1m^2$), and the relative infrequency of measurements, since these require considerable manual input on site (although this is counterbalanced in part by a lower subsequent data processing requirement). The infrequency of measurement makes annual flux estimation difficult, although where empirical relationships with key meteorological or hydrological variables can be derived (e.g. with temperature or moisture levels) it may be possible to scale up in time based on Automatic Weather Station (AWS) measurements (established at many potential study sites). However, the accurate estimation of fluxes remains challenging for $CH_4$ and $N_2O$, fluxes of which may be highly heterogeneous in both space and time. For example, McNamara *et al* (2008) found that 95% of the $CH_4$ flux at Moor House occurred within gullies, which comprised less than 10% of the surface area. Baird *et al* (2009) highlight the importance of ebullition (gas bubble) fluxes to the total $CH_4$ flux; static chambers are effective at capturing the steady diffusive flux of $CH_4$ through the soil or plants, but have a low probability of capturing highly episodic ebullition events as they can only be operated for short periods (Coulthard *et al* 2009). To address this issue, ebullition funnels (which capture the cumulative flux over longer periods) have been used at locations including Cors Fochno (Dyfi Estuary, mid Wales) and Vyrnwy (Berwyn Mountains, Northeast Wales) to capture the cumulative emission of $CH_4$ via ebullition from saturated areas such as bog pools. They are, however, unsuitable for use in unsaturated areas.

## Fluvial flux measurement

Many studies have now demonstrated the significance of the fluvial pathway for carbon losses from peatlands (e.g. Billett *et al* 2004; Dinsmore *et al* 2010; Worrall *et al* 2009). In general, Dissolved Organic Carbon (DOC) forms the largest part of the fluvial C flux from intact peatlands, although Particulate Organic Carbon (POC) may be as or more important in eroding systems. Inorganic carbon fluxes (comprising gaseous $CO_2$, and dissolved inorganic carbon species in more alkaline systems) may also be significant, although (as discussed below) a part of this C flux may derive from mineral weathering rather than from the peat itself.

- ***Water flux measurement***

A fundamental requirement for fluvial C flux measurement is a reliable measurement of the water flux. This is best obtained by monitoring at the catchment scale, within a natural stream draining the study area, although artificial drainage networks may also be used if the contributing area can be reliably defined. It is important that the catchment draining to the monitoring point should (to a reasonable extent) be dominated by peats, and that the scale over which gaseous flux monitoring (as described in the preceding section) is taking place should be representative of the catchment as a whole. A smaller catchment area is thus preferable. Methods of discharge measurement generally involve installation of a pressure transducer to record water level, either in a gauged stream section or together with control structures such as v-notch weirs or flumes. Holden and Armstrong (2007) provide a description of methods for hydrological monitoring of peat catchments, including a range of additional instrumentation for the measurement of water table height using dipwells, overland flow using crest-stage tubes, and hydraulic conductivity using piezometers. While not absolutely necessary for flux estimation, the contextual information provided by a well-designed hydrological monitoring infrastructure will add greatly to the interpretation and understanding of both fluvial and gaseous flux measurements, and (given the relatively modest associated costs) should be a considered an important component of a long-term monitoring infrastructure.

The approach described above is applicable to rain-fed peatlands in headwater positions, and having sufficient spatial extent to generate discharge via natural or artificial drainage channels. In other peatland types, robust quantification of water fluxes may be more problematic. For fen peats, much of the water input is derived via lateral flows from adjacent soils or groundwater, and in areas subject to agricultural or conservation management water levels may be maintained by pumping. This additional hydrological complexity presents a significant challenge for fluvial C flux measurement; in pumped systems, for example, it will be necessary to quantify fluvial C fluxes both into and out of the peat ‘catchment’ by monitoring water fluxes in both directions, as well as C concentrations in inflows and outflows. On the other hand, actively managed systems may have good existing hydrometric information, such as the amount of water pumped into the system, to support these calculations. Measurement of fluvial fluxes from systems lacking natural drainage (e.g. small raised bogs) is also problematic. While water fluxes can be measured simply within artificial drainage channels using the same methods applicable for natural streams, there is potential for under-estimation of the water flux if a significant proportion of the water leaving the system occurs in subsurface lateral flow rather than within the artificial channel. Blanket peats in which a significant component of water flow occurs within peat pipes may also give underestimates of water (and hence fluvial C) fluxes if pipeflow bypasses the gauging point. These issues may be minimised by careful site selection and hydrological characterisation (e.g. piezometers to estimate lateral water movement) during to the establishment of monitoring.

- ***Dissolved Organic Carbon (DOC) flux measurement***

DOC fluxes generally represent the largest component of the fluvial C flux, in the order of 10-30g C $m^{-2}$ $yr^{-1}$ (Billett *et al* 2010). DOC largely comprises humic substances, complex and recalcitrant high molecular weight compounds which are formed via the incomplete decomposition of vegetation and soil organic matter. It is generally defined as the proportion of total organic carbon which passes through a 0.45 $\mu$m filter (the larger material retained on the filter paper thus being defined as POC). It can be measured using oxidation-based methods to measure total carbon in the sample after acidifying and purging samples to remove Dissolved Inorganic Carbon (DIC). Alternatively, it can be measured as the difference between total C and DIC although this method is subject to error in more alkaline waters (Findlay *et al* 2010). The simplest approach for estimating DOC fluxes combines spot-sampled DOC concentrations with continuous discharge measurements to calculate a flow-weighted annual mean DOC concentration, which is multiplied by the annual water flux to give an annual DOC flux. This method is prone to error in waters where DOC varies strongly as a function of discharge, as in organo-mineral soils. On the other hand, true peat catchments often show less flow-dependence of DOC concentrations, with constant or even slightly decreasing DOC concentrations over the course of high flow events (e.g. Clark *et al* 2007), such that the majority of concentration variation is seasonal rather than episodic. As a consequence, Koehler *et al* (2009) found that DOC flux estimates for an Irish blanket bog catchment based on regular (weekly to monthly) spot-sampled DOC concentrations compared well with those based on more intensive measurements and Worrall *et al* (2007) found that reducing the frequency of DOC measurements from a daily to a monthly frequency resulted in only 8% error.

Because DOC is coloured, it is possible to infer DOC concentrations from measurements of absorbance (or fluorescence) in particular wavelengths. This has the advantage that optical sensors may be operated *in situ* in order to provide a continuous proxy measure of DOC concentrations. While this is clearly advantageous for capturing short-term concentration variations, care is required in the use of optical methods for DOC estimation, since the absorbance/DOC relationship has been found to vary seasonally and spatially (e.g. as a function of drainage status; Wallage *et al* 2006) and may also be changing over the longer term as DOC concentrations in upland waters increase (e.g. Dawson *et al* 2009). As a result, it is essential to develop and maintain absorbance/DOC calibrations for all sites where these methods are applied, through comparison with spot-sampled measurements. Recent automated spectrophotometric techniques on recording the full range of absorbance characteristics across the spectrum may provide advances in this area (Grayson and Holden, in review; Koehler *et al* 2009).

It should be noted that DOC flux, as measured above, is a measure of C flow from a peatland but that this does not necessarily equate to a GHG flux. However, DOC may be microbially, physically or chemically transformed in the fluvial network. For example, Worrall *et al* (2006) estimated that 32% of the DOC flux was lost (presumably as $CO_2$) during fluvial transport within the Moor House catchment. Because this flux is localised, it may not be captured by dissolved $CO_2$ or eddy flux tower measurements if it occurs outside of their measurement footprint. It should also be noted that DOC can be produced in-stream by a number of mechanisms. Thus, a valuable addition to current monitoring would be the in-situ measurement of DOC degradation. A proposed simple option is to measure DOC concentration change in spot samples taken upon every visit to a monitored site, which are left in uv-transparent quartz tubes at the site to be recovered on the next visit. This, combined with estimates of water residence time in the stream, can provide some indication of the proportion of DOC converted to $CO_2$ in the stream channel, although it will not account for processes occurring remote from the site, such as DOC degradation or sedimentary burial in estuarine or marine systems. It is noted that current uncertainties regarding the fate of DOC (and other fluvial C) fluxes from peatlands will be addressed in the Defra-funded project on the GHG emissions associated with non-gaseous losses of carbon from peatlands (Defra project SP1205).

- ***Inorganic C flux measurement***

Inorganic carbon fluxes comprise several components, the relative importance of which varies between and within catchments. In acidic, ombrotrophic bogs, the sole form of inorganic C is likely to be free gaseous $CO_2$ (this is not strictly part of the dissolved inorganic carbon (DIC) component), but intimately linked to DIC via carbonate equilibria). Gaseous $CO_2$ in runoff is produced via peat respiration, where a proportion of the $CO_2$ generated is transported laterally in drainage waters rather than released directly to the atmosphere. Peat headwater streams are typically over-saturated with $CO_2$ relative to the atmosphere, resulting in $CO_2$ degassing as water moves downstream. This can occur heterogeneously, from locations of turbulent water movement such as waterfalls. Billett *et al* (2004) and Dinsmore *et al* (2010) have found this 'evasion' flux of $CO_2$ to be quantitatively significant at Auchencorth Moss, in the order of 5-15g C $m^{-2}$ $yr^{-1}$. Although $CH_4$ can also be dissolved and transported in streamflow or evaded to the atmosphere, most data suggest that the flux involved is very small (Dinsmore *et al* 2010). Dissolved $CO_2$ in streamwater can be measured directly on spot samples by direct analysis of headspace $CO_2$ concentrations (Kling *et al* 1991) or indirectly estimated from measured pH, alkalinity and temperature (Neal, 1998). More recently, methods have been developed for direct, continuous measurement of dissolved $CO_2$ using atmospheric $CO_2$ sensors adapted for use in water (Johnson *et al* 2010). These methods all provide estimates of the flux of $CO_2$ leaving the catchment in streamflow. Evasion of $CO_2$ from the stream channel *within* the catchment could arguably be considered a part of the land-atmosphere $CO_2$ flux, but as this flux is heterogeneous within the wider landscape, focused on the stream channel or 'hotspots' within it, it may not be captured by eddy covariance measurements. Floating chambers located over the stream surface have therefore been used to provide estimates of the evasion flux, which (in combination with headspace analyses) have been used to estimate catchment-scale mean annual fluxes (Billett and Moore, 2008; Dinsmore *et al* 2010).

The other major component of the inorganic C flux, DIC, is present in more alkaline drainage waters. Bicarbonate, $HCO_3^-$, is present at significant concentrations above a pH of 5.5. In highly calcareous fens, carbonate ($CO_3^{2-}$) may also be present. $HCO_3^-$ can be formed by the dissolution of gaseous $CO_2$, which as noted above may be derived from respiration within the peat. However, $HCO_3^-$ and $CO_3^{2-}$ can also be derived from mineral weathering, for example from the dissolution of limestone. In this case, the associated C export is not linked to the release of C from the peat and should not be considered part of the peat C budget. While this flux of 'geogenic' DIC may be largest in fens, it has also been shown to form a substantial component of the flux in streams draining blanket bogs overlying calcareous bedrock, where there is connectivity between the bedrock and the stream, as in the Trout Beck at Moor House. Worrall *et al* (2009) applied a correction to their estimate of fluvial peat C export based on the measured net flux of Ca from the catchment, assuming that carbonate weathering produced a molar equivalent flux of $CO_3$-derived C. $HCO_3^-$ concentrations can be estimated by titration, although distinguishing bicarbonate alkalinity from weak organic acidity in highly organic waters is problematic. Direct measurement of total inorganic C concentrations can also be measured by headspace analysis of $CO_2$ on acidified water samples, or inferred from measurements of alkalinity and pH (e.g. Neal, 1988; Worrall and Burt, 2005). Continuously monitored pH has also been used to infer alkalinity (and subsequently DIC and $CO_2$) concentrations on a continuous basis in some studies (e.g. Tetzlaff *et al* 2007), although this method is dependent on empirical relationships, which may be unstable between sites and over time (Johnson *et al* 2010). Direct measurement of total inorganic C is therefore most appropriate.

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- ***Particulate Organic Carbon (POC) flux measurement***

As noted above, 'POC' is normally defined as the organic carbon in stream water which does not pass through a filter paper of 0.45 µm pore size. It is measured by via loss on ignition (LOI) analysis of carbon free filter papers through which a known volume of sample has been passed. A subset of samples should be analysed for %C to establish a robust relationship with LOI. The POC flux from peat catchments is largely comprised of eroded peat particles, and may be dramatically increased in degraded systems with large areas of bare peat, gullying, piping or gripping (Evans *et al* 2006). Because POC fluxes generally have a strong positive correlation with discharge, much of the annual POC flux can (like sediment fluxes in mineral soil catchments) occur during a very short period of time, during extreme flow events (Pawson *et al* 2008). These are difficult to capture based on routine spot-sampling, and therefore require more intensive sampling of high-discharge periods.

While difficult and expensive to undertake on a frequent basis, intensive sampling of a relatively small number of such events (e.g. using autosamplers) may be sufficient to define a POC-discharge rating curve for the site, permitting annual POC fluxes to be estimated from the discharge record. While this should be sufficient to approximately quantify the role of POC export in the C budget of the site, it may be necessary (particularly at degraded sites with large fluxes, or where site condition or management have altered) to carry out intensive event-based sampling on a regular basis to maintain reliable rating curves based upon stage-level triggering of automatic water samplers.

As for water colour, optical sensors exist for the measurement of turbidity, which in peat systems is largely associated with POC. If effective, the use of these sensors for continuous monitoring would overcome the problems of capturing short-duration periods of high POC flux described above. However, because turbidity sensors have generally been developed for monitoring mineral sediment transport, their accuracy for measuring particulate organic matter concentrations in peatlands is currently poor. Furthermore, hysteresis effects in sediment concentration with discharge during storms (i.e. higher sediment concentrations when flow is increasing than at the same discharge rate when flows are decreasing) are common. Hence, no simple sediment discharge/concentration relationships are observed. However, recent work by Marttila *et al* (in press) has shown in the laboratory that there can be a good relationship between peat sediment concentration and turbidity probe readings when calibrated for the particle size class of the peat; and that the probes can be used for both low and high concentrations. Nevertheless this work was carried out in the lab in clear water and much further work is required to establish techniques for continuous POC monitoring.

As noted above for DOC, further work is required to estimate the GHG flux associated with POC export. While POC may be comparatively inert, a proportion may be converted to DOC or mineralised to $CO_2$ within stream channels, or following redeposition on floodplains.

- ***Dissolved $CH_4$***

As for $CO_2$, some $CH_4$ is transported in dissolved form from peats into drainage waters, from which it will subsequently be evaded to the atmosphere. Dinsmore *et al* (2010) estimated fluvial $CH_4$ fluxes at Auchencorth Moss to be around 0.02g C $m^{-2}$ $yr^{-1}$ (mainly from evasion within the catchment). Even allowing for the greenhouse gas warming potential of 23, this would mean that the fluvial $CH_4$ flux is less than the error in the dissolved $CO_2$ flux. We therefore propose that dissolved $CH_4$ be considered negligible within the overall peat GHG budget.

- ***Biomass transfers***

In peatlands with little or no active land-use, off-site carbon transfers in biomass are likely to be negligible, and may be ignored. In more intensively utilised systems, on the other hand, these fluxes may be considerable, and must be included in the C balance. For example at Tadham Moor, a wetland meadow site in the Somerset Levels, Lloyd (2006) found that a measured net ecosystem production of 169g C $m^{-2}$ $yr^{-1}$ was completely cancelled out by an estimated C offtake of 228g C $m^{-2}$ $yr^{-1}$ associated primarily with hay harvesting, and to lesser extent cattle export, resulting in a net loss of carbon from the site. In other managed peat settings, removal and transformation of carbon by grazers (including $CH_4$ production by ruminants) may be more important. Similarly, much of the net carbon gain in afforested peatlands is exported during timber harvesting. Off-site carbon fluxes can be accounted for if management practices and harvest yields are known. It is suggested that a monitoring programme should aim to quantify these C exports where relevant, for inclusion in the overall peat C budget. Determining the subsequent fate of this C is likely to be beyond the scope of such a programme, but may be inferred from other studies and published information.

## Methods for Peat carbon stock and condition assessment

The report by Bonnett *et al* (2009) provides a detailed description and evaluation of methods for monitoring change in peat condition in relation to management and restoration. In the specific context of peatland C/GHG budgets, priorities for measurement are considered to be: 1) repeat measurements of total C stock; 2) monitoring of water table height; 3) recording presence/absence of key peat forming plant species, and species influencing rates of $CH_4$ emission; and 4) recording peat condition, including measurements of peat properties and of changes in management and related factors, such as drainage, gullying and wildfire.

### Carbon stock

At present, long-term changes in UK soils and vegetation are recorded through repeated national-scale surveys, notably the Countryside Survey (CS) and, for soils only, repeat surveys for the National Soils Inventory (NSI) for England and Wales and more recently in Scotland. This and other information is used to underpin the land-use, land use change and forestry (LULUCF) estimates in the UK GHG inventory as reported to the UNFCCC. Although both the CS and NSI surveys have reported on changes in soil C stock (Bellamy *et al* 2005; Emmett *et al* 2010), these are based on measurements of C concentration in the top 15cm of the profile in England and Wales, a methodology which is recognised as being ineffective for monitoring change in the C stock of deeper organic soils such as peats (e.g. Smith *et al* 2007) since it will not detect changes in organic layer depth, and may be affected by peat expansion and contraction as a function of moisture content, leading to the sampling of different (effective) depths of peat.

Accurate peat C stock measurement requires measurement of depth, carbon concentration (i.e. %C) and bulk density for the full peat profile, including multiple measurements of %C and bulk density down the profile to allow for vertical changes. Since peat depth and bulk density also vary spatially, often over short distances, a substantial number of measurements are required to provide robust stock estimates at a catchment scale (e.g. Lindsay, 2010; Frogbrook *et al* 2009). Such an intensive survey is important to characterise a site, but repeated full-profile surveys of whole catchments are probably not practicable (or effective) for monitoring C stock change. Two alternative methods for measuring change in peat C stock at multiple locations were considered by Evans *et al* (2009), namely 1) sampling to a dateable horizon, and 2) sampling to a fixed base point. The former method was used by Garnett *et al* (2000) at Moor House, using the ‘take off point’ of Spherical Carbonaceous Particles (SCPs), inert microscopic particles associated with the onset of high-temperature coal and oil combustion, to define a horizon of known date (at 6-12cm depth in this site) above which recent C accumulation rates could be determined. This method was sufficiently sensitive to be able to measure different C accumulation rates in burnt and unburnt plots over a 30 year period, and in principle repeat surveys might be used to quantify recent C gains or losses. Isotopic measurements (such as $^{14}C$ or $^{210}Pb$ dating) may also be used, although the cost of $^{14}C$ dating is relatively high, and more appropriate for measuring longer-term accumulation rates. Sampling to a fixed base point (such as a steel plate), fixed either within the catotelm or to underlying mineral soil or bedrock, would permit repeat sampling of a known depth of peat, although this method requires development and would involve some initial disturbance. Full peat cores can be used to provide basal ages for peat deposits, estimates of long-term carbon accumulation rates, and comparative estimates of recent accumulation rates based on SCP marker points (Billett *et al* in press).

Regardless of method, reliable measurement of peat C stock requires accurate measurements of depth, bulk density and %C (e.g. Frogbrook *et al* 2009). Given the extent of spatial heterogeneity and (generally) small rates of C change relative to the large size of the total peat C pool, it is unrealistic to expect measurable changes to be detectable on an annual basis, and this would in any case result in high levels of disturbance. Therefore, a lower sampling frequency (e.g. five-yearly, as used in the Environmental Change Network (ECN)) is considered more appropriate. To provide catchment or landscape-scale estimates of current C stock, or to measure stock change with sufficient confidence, a substantial number of sampling points would be required. Emmett *et al* (2006) and Black *et al* (2008) evaluated the sampling density required to report soil carbon change for a UK national soil monitoring network, although (since this assessment focused on measuring topsoil C concentration change for all soil types) their conclusions may not be fully transferable to the measurement of peat C stock change. With regard to methods for sample site selection, Black *et al* (2008) found that the stratified random sampling approach used by the Countryside Survey to be the most suitable approach for detecting changes in soil C. Stratification could be based on vegetation type (e.g. NVC class) and/or peat condition (e.g. drained and undrained areas). Upscaling (e.g. to a national level) requires that the same information is available to undertake the same classification at the larger scale, and a stratification based on nationally-available datasets is therefore preferable. Due to the disturbance associated with soil sampling, it is not practicable to make repeated measurements at the same locations; an approach similar to that employed by the ECN is therefore suggested. In the ECN soil sampling protocol (http://www.ecn.ac.uk/protocols/Terrestrial/S.pdf), a set of fixed 20x20m 'blocks' are identified, and subdivided into 16 5x5m cells. Five-yearly sampling is undertaken at one randomly selected 1x1m subcell within each of the cells. Since the aim of a peat C monitoring network would differ somewhat from that of the ECN (where the aim is to quantify changes at a relatively small 'target study site'), it may be more appropriate to distribute 5x5m cells across the entire study area, rather than within a relatively few blocks. The smaller scale of the cells would also permit them to be located within single vegetation/condition units as described.

It should be noted that surveys of C stocks are not a full substitute or proxy for flux-based measurements of C or GHG budgets, as they cannot discern the form in which C is gained or lost (and hence the associated GHG balance), or the short-term dynamics of carbon balance changes in response to management. Nevertheless, the relatively low cost of this approach provides the potential to estimate C accumulation rates and stock changes at many more sites than would be possible using flux measurements, providing valuable information to support upscaling from site-based studies to the wider peatland landscape.

## Vegetation and peat condition

Vegetation surveys provide information on the condition of a site, on its stability over time (or rate of change in sites undergoing transition), and on the likely magnitude and trajectory of C and GHG fluxes that are strongly associated with vegetation cover and composition, including photosynthetic $CO_2$ uptake, $CH_4$ emission and DOC production. The permanent quadrat approach used in the Countryside Survey (Maskell *et al* 2008) provides a template for monitoring vegetation change in peatlands. Plot locations are selected based on a stratified random method as for soils, and may be co-located with soil monitoring sites to permit comparison. A 2x2m quadrat is likely to be sufficient for most peatland areas, although larger quadrat sizes may be required where larger vegetation is present (e.g. 4x4m for tall fen vegetation or 10x10m for the field layer of afforested bogs, as used by Rodwell (1991-2000). The number of quadrats required will depend on the heterogeneity of the vegetation and microtopography and the area over which monitoring takes place. Permanent quadrats should be fixed by a combination of GPS location and installation of marker posts.

For the specific aim of relating vegetation condition to peat carbon balance, it is probably unnecessary to survey all vegetation to species level, although it may be useful to record the presence of specific ecohydrological indicators such as aquatic *Sphagnum* species or *Rhyncospora alba* (e.g. Bonnett *et al* 2009). The key vegetation attributes of interest are considered to be the presence/absence of peat forming species, and of vegetation types known to facilitate the transfer of $CH_4$ to the atmosphere, such as sedges. On this basis, it may largely be sufficient to record changes in the proportional cover of key plant functional types (e.g. bryophytes, ericoid subshrubs, graminoids, forbs). However, some subdivision of these classes is required for specific vegetation types critical to peat formation and GHG fluxes. Specifically, it is necessary to separate *Sphagnum* and other bryophytes, and ideally to distinguish between peat-forming and non peat-forming *Sphagnum* species. Graminoids should be divided into grasses, sedges and rushes, to take account of the importance of sedges (such as *Eriophorum* species) and rushes in transporting $CH_4$ to the atmosphere. Sub-division of ericoid species may also be justified, in order to distinguish between wet and dry heath vegetation. Similarly, subdivision of functionally important or indicator species grass species (such as *Molinia caerulea* in upland bogs) may be required to assess site condition. Cover estimates obtained by visual assessment using 5% increments (0-5%, 5-10%, etc.) are likely to be sufficient, as the extra objectivity provided by labour-intensive pin techniques is not justified. In layered vegetation (e.g. a dwarf shrub canopy over a moss layer) total percentage cover can exceed 100%. Areas of bare peat should also be recorded. Insofar as possible, vegetation survey methods should be compatible with other schemes (such as the NVC) to enable comparison with other monitoring. A five year interval for vegetation surveys, consistent with soil surveys, represents a reasonable minimum frequency, although more frequent surveys would be preferable, particularly for sites undergoing management change.

Total biomass estimates may be useful for inferring vegetation productivity and the extent of management impacts such as grazing and burning. However, accurate quantification by destructive harvesting and dry weight measurement may result in unacceptable disturbance to the site, particularly if regularly repeated. Non-destructive methods such as vegetation height measurement (e.g. using a tripod-mounted laser rangefinder) may be calibrated against an initial set of biomass measurements, and used to estimate biomass change in permanent quadrats. Biomass measurement for bryophytes and deciduous grasses is problematic due to the difficulty of accurately separating living from dead material. Annual net primary production (NPP) of *Sphagnum* or other bryophyte species can be estimated using the cranked wire method, which measures annual shoot growth relative to a wire fixed within the moss canopy (Clymo, 1970; Bonnett *et al* 2009).

In addition to recording vegetation cover, direct measurements of peat condition are useful to provide an indication of the current peat-forming capacity of the ecosystem. An intact two-layer (acrotelm-catotelm) peat structure is indicative of a system which is continuing to sequester $CO_2$, whereas the absence of an acrotelm ('haplotelmic' peat) is indicative of a damaged system where net C loss may be occurring (Lindsay, 2010). Lindsay (2010) has noted that bulk density measurements can provide an effective proxy for peat humification (i.e. decomposition) status, with the presence of dense, highly humified peat at the surface suggestive of a haplotelmic system. Peat humification status can also be estimated directly based on visual and textural assessments such as the commonly used von Post Scale. The microtopography of peatlands (hummocks, hollows, ridges, pools etc.) provides further information on the condition and functioning of a site (e.g. Lindsay, 2010) and should be recorded as part of any initial site survey. The quantitative monitoring of microtopographic change can be undertaken using remote sensing methods, discussed in the following section.

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## Remote sensing methods

A range of remote sensing methods are relevant to peatland monitoring. Aerial photography has been widely used to assess peat condition and management impacts, including management burning, wildfire, drainage and gully erosion (e.g. Yallop *et al* 2006; Longden, 2009). More recently this has been augmented by the use of airborne LIDAR surveys to provide high resolution topographic information, including quantification of the extent and severity of carbon losses due to erosion (e.g. Evans and Lindsay, in press) and potentially to identify and assess the impacts of moorland grips if high-resolution measurements are made. Although expensive to undertake, data from Lidar surveys are now available for a number of important peatland areas and, along with air photograph and spectral data, provide detailed site characterisation in support of monitoring. Fixed point ground-based photography provides a lower-cost option for recording landscape-scale change, and has for example been used to record long-term changes in grazer numbers and distribution at the Snowdon ECN site. Hand-held Lidar may also have potential for repeated ground-level scanning, to detect changes in the peat surface, and the evolution and change in microtopographic features. An assessment of the potential role of satellite imagery for mapping peat erosion in Scotland (Keyworth *et al* 2009) suggests that this may be useful for targeting areas where erosion is occurring, and monitoring change over time, but that aircraft- or ground-based methods remain the best approach for delineating smaller erosion features such as gullies.

Airborne GHG measurements can be used to upscale ground-based GHG flux monitoring, and to detect and attribute variations in GHG flux across heterogeneous landscapes. This approach has been tested at the Vyrnwy peat restoration experimental catchments, and could have wider application for a range of key intensive study sites. While this may be beyond the scope of a core monitoring programme, campaign-based airborne GHG measurements would support upscaling of site and catchment-based measurements to the wider peatland landscape, and would thus be a valuable addition to the ground-based measurement programme. The use of satellite monitoring of GHG fluxes associated with the Scottish land-use section was recently evaluated by Capelluti *et al* (2009). They found that the current 60 x 30km resolution of the SCIAMACHY satellite, and reliance on cloud-free conditions, meant that it is not yet possible to detect signals in $CO_2$ concentration related to land-use. While higher-resolution data from new satellites will have greater potential to detect land-use effects on GHG fluxes at the broad scale, we conclude that satellite monitoring is unlikely to provide peatland- and management-specific GHG flux data in the near future.

## Site history and long-term peat accumulation rates

Current functioning of peatland systems is to a substantial extent determined by past management history. This can to some extent be established through the collation of information such as documentary records, aerial photographs, and landowner knowledge, but may be further quantified from ground-based observations. In particular, stratigraphic analysis of peat cores provides long-term (Holocene-era) information on the development of the site, based on preserved vegetation remains (e.g. plant fragments and pollen records), radiocarbon dating and dateable horizons within the profile (e.g. Tallis *et al* 1997; Ellis and Tallis, 2001). Peat accumulation above a dateable horizon has been used to provide both long-term (millennia) and more recent (decades to centuries) estimates of peat C accumulation rates (e.g. Billett *et al* in press) which provide an important context for contemporary flux measurements.

# Annex 2 - Outline cost estimates

| | | Start up costs | | Annual running costs | | Notes on costings |
|---|---|---|---|---|---|---|
| Code | Item | Equipment (£) | Labour (staff days) | Consumables (£) | Labour (staff days) | |
| LI/I | Automatic weather station (AWS) | 7,000-9,000 | 15 | 500 | 5 | |
| LI/2 | Eddy covariance tower ($CO_2$, $CH_4$) | 70,000 | 20 | 2,000 | 10 | |
| LI/3 | Static chamber measurements | 3,200 | 10 | 800 | 24 | Depends on replication/heterogeneity. Estimated costs for 16 chambers monthly |
| L1/4a | Dipwell measurement | 300 | 4 | 0 | 4 | Cost for 12 dipwells |
| L1/4b | Water table loggers | 1,000 | 1 | 100 | 2 | Cost for 4 continuous loggers |
| L1/5 | Discharge measurement | 2,000-7,000 | 5-15 | 100 | 4 | Approximate for one v-notch weir and one pressure transducer (cost depends on size of stream and structure required) |
| L1/6 | Continuous DOC, pH and $CO_2$ monitoring | 15,000 | 20 | 1,000 | 6 | Includes cost of sample analysis for calibration |
| L1/7 | Two-weekly spot-sampling and analysis | - | - | 200 | 15 | 24 samples/year analysed for DOC, POC, CO2, DIC, pH, Alkalinity, Ca |
| L1/8 | Periodic episodic sampling for POC | 2,500 | 1 | 200 | 4 | Two campaigns of 24 samples per year using automatic sampler (note that this could be moved between sites to reduce costs) |
| L1/9 | Monitoring of $CH_4$ ebullition fluxes | 500 | 4 | 400 | 12 | Cost for eight ebullition chambers, sampled monthly |

| | | | | | | |
|---|---|---|---|---|---|---|
| LII/1 | Automatic weather station (AWS) | *As for L1/1* | *As for L1/1* | *As for L1/1* | *As for L1/1* | |
| LII/2 | Discharge measurement | *As for L1/5* | *As for L1/5* | *As for L1/5* | *As for L1/5* | |
| LII/3 | Static chamber measurements | *As for L1/3* | *As for L1/3* | *As for L1/3* | *As for L1/3* | |
| LII/4 | Monthly spot-sampling and analysis | - | - | *50% of L1/7 costs* | *50% of L1/7 costs* | |
| LIII/1 | Vegetation surveys on permanent quadrats | - | - | 100 | 10 | 5-yearly surveys, costs are for a year with survey so less per year overall |
| LIII/2a | Initial carbon stock assessment | - | - | 3,000 | 25 | One-off full profile survey of ~100 points |
| LIII/2b | Five-yearly carbon stock change measurement | - | - | 1,000 | 10 | 5-yearly survey of ~25 points (costs are for a year with survey so less per year overall) |
| LIII/3 | Full peat core analysis | | | | | *Not evaluated - would need to consult outside project group to obtain estimates* |
| LIII/4 | Collation of air photo and other aerial data | | | | | *Not evaluated - likely to be very site-dependent* |
| LIII/5 | Dipwell measurement | *As for L1/4* | *As for L1/4* | *As for L1/4* | *As for L1/4* | |
| LIII/6 | Annual fixed point photographs | - | 1 | - | - | |
| LIII7 | Annual recording of site management/condition | - | 1 | - | - | |

*Note that the above costs include time for initial data processing, but not time for full data management or analysis*