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The requirement for improving greenhouse gases flux estimates for peatlands in the UK

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1 Introduction

Under new climate change legislations (Climate Change Act, 2008), action to reduce greenhouse gas (GHG) emissions will be required from all sectors of UK society. The recognition that most of UK soil carbon is held below our feet in carbon-rich soils has led to a need for better quantification of the role of different management practices in UK peatlands on reducing GHG emissions.

Peatland ecosystems are unique, specialist habitats recognised under international and national legislation, acting as key stores of terrestrial carbon. Peatlands contain over half the estimated 10 billion tonnes of carbon stored in UK soil, and a loss of only 5% of UK peatland carbon would equate to the total annual UK anthropogenic GHG (IUCN peatland inquiry, in press). Damaged peatlands can be restored to reduce these emissions, but there is a need for better empirical emissions data to improve understanding and appropriate use of such management practices.

To improve available understanding of the role played by peatland in UK GHG emissions, a consortium of governments and agencies[1]commissioned a review published by JNCC to establish the emission factors which could be derived from research so far, the level of completeness and uncertainty, and the degree to which currently deployed research effort will address the key deficiencies (Worral *et al,* 2011). A second report (Evans *et al,* 2011) presents the research needs required to improve quantification of the C / GHG fluxes to and from UK peatlands.

This paper provides an overview of that review, targeted to specific UK policy needs and compiled by the project steering group and JNCC. It is aimed at UK policy makers and research providers, and outlines a framework for prioritisation of research needs.

[1] Countryside Council for Wales, Defra, DECC, Forestry Commission, Joint Nature Conservation Committee, Natural England and Scottish Natural Heritage; with additional input contributed by Scottish Government, Scottish Environment Protection Agency, and Welsh Government.

2 Peatland evidence-based information

Natural peatlands accumulate organic carbon in the form of partially decomposed plant and animal remains, laid down where the decay-limiting effects of the waterlogged conditions mean that the input rate of material from the surface exceeds the rate of decomposition. Carbon loss from unmodified peatlands occurs only slowly as carbon dioxide (CO_2), anaerobically as methane (CH_4), and also as dissolved and particulate organic carbon (DOC / POC, respectively).

Over the past 10,000 years UK peatlands have sequestered significant amounts (5.5 billion tonnes) of carbon from the atmosphere, representing over half the ~10 billion tonnes of carbon stored in UK soil. However, these peatlands have been extensively degraded in more recent times through drainage, cultivation, agricultural improvement, peat cutting, afforestation, burning, and atmospheric nutrient deposition. Many of these processes cause the water level to drop and the peat to dry, promoting aerobic conditions that encourage decomposition of the organic material and subsequent vegetation succession to non-peat-forming systems. The rapid release of GHGs to the atmosphere, and DOC to adjacent streams and water bodies, represent significant environmental concerns, potentially converting peatlands from a net carbon sink to a source.

There has been some significant effort to restore damaged UK peatlands for biodiversity, archaeological and hydrological reasons. Restoration actions are typically focused on rewetting, to restore the waterlogged conditions required for peat formation. Conserving or enhancing C stocks and mitigating climate change have, until very recently, been secondary or low priority aims.

With an increasing recognition of the effects of climate change, and the UK about to enter its second carbon budget period (DECC, 2011), understanding the role played by peatlands in regulating carbon stocks has become increasingly important. Of the major organic C fluxes, the CO_2 flux between surface photosynthesis and respiration, and the DOC flux, are the best studied. POC, dissolved gaseous flux, and CH_4 from anoxic decay have received considerably less attention, even though CH_4 is a much more potent greenhouse gas than CO_2. The water-borne fluxes of C from peatlands, where the destination of C is unknown, are often not included in peatland GHG and C budgets, and very few studies include fluxes of nitrous oxide (N_2O), which is also a major GHG.

The GHG flux from peatlands is thus not as simple as just the release and retention of CO_2, when all gases and losses are compared in terms of their global warming potential and over different time periods. There is also considerable uncertainty as to when different management states (Annex 1) of restored peatlands become sinks or sources of GHGs. These rates of GHG flux related to particular management states and activities are represented in carbon budget calculations by Emission Factors (EFs).

3 Why we need to know about Emission Factors

The Inter-Governmental Panel on Climate Change (IPCC) recognises three tiers of EF, reflecting the level of detail and scope used (IPCC, 2006):

Tier 1: Default international emissions.
Tier 2: Specific to countries or regions.
Tier 3: Emissions at individual sites.

The UK GHG inventory currently uses Tier 1 factors for N_2O in agricultural peatlands, and Tier 2 factors relating to CO_2 from cultivated fenland peat, and from peat extracted for horticulture. There are currently no IPCC Tier 1 factors for most UK peatland management practices, therefore the majority of UK peatland GHG flux goes unreported. The EFs that do exist are not necessarily based upon information from the UK and are focused on steady management states.

Transitional management states (such as the deforestation of a previously afforested peatland) may have very different GHG fluxes than the final steady-state outcome. Quantifying the effect of transitions is important in more accurately determining carbon budgets, as the action taken may produce different effects depending on the timescale considered, and the intended final outcome. For example, restoration rewetting of a drained peatland could result in a net loss of carbon sequestration in the short term – through the transitional release of N_2O and CH_4 – whereas the long-term restoration of a peat-forming environment may be a C sink.

A more comprehensive evaluation of the UK's contributions to GHG emissions through management of peatland soils would provide IPCC Tier 2 or 3 emission factors for much of UK peatlands, and is likely to have a substantial effect on the UK GHG inventory. More accurate and specific emission factors would aid management decision-making, improving understanding of trade-offs between peat and biodiversity, hydrology and carbon services by quantifying the EF of the intended final state and the GHG flux change likely to occur in the process.

4 New perception on evidence

The meta-analysis and evidence review papers (Worral *et al,* 2011; Evans *et al,* 2011) identified 15 major peatland management states, and 9 transitional states that occur as the result of human intervention. Given the variety of management states and transitions identified there is unlikely to be a 'one size' ideal management strategy that can be applied to optimise carbon sequestration. In contrast, the data that is required from all peatlands to characterise the existing flux is very similar, and will likely lend itself well to a standard recording structure.

4.1 Meta- analysis and evidence review

Modified peatlands were shown not to all be C or GHG sources, just as not all "pristine" peatlands are net sinks of C or GHG. Similarly, peatland restoration may not necessarily lead to a peatland becoming a net sink of C or GHG. Changes to the peatland management regime, including the effect of restoration actions, may not provide a GHG benefit if the CH_4 flux is increased as a result of the intervention. CH_4 is 23 times more a potent GHG than CO_2, thus while CH_4 losses are only a few percent (3-5%) of the net GHG exchange between peatlands and the atmosphere, this may be enough to counteract any increased CO_2 sequestration (in the shorter-term). Recognition of long time-scales is very important when considering change in response to management and restoration.

Fluvial C fluxes also represent a significant part of the overall peatland C budget. In all systems the fluvial C flux will reduce the C sink associated with CO_2 sequestration, and in some systems these fluxes may be sufficient to change the peatland from an (apparent) C sink to a net C source. Their role in GHG terms is dependent on their ultimate fate, which remains poorly understood.

Certain steady peatland management states were found to be notably more widespread than others. Undamaged peatlands are rare, with the majority of UK peatlands classified as 'semi-natural', 'wasted' or 'cultivated'. The estimated emissions from different peatland states showed far greater emissions from modified peatlands – particularly from cultivated peat - but throughout the review there was a noted lack of evidence on the major GHG fluxes from UK peatlands.

4.2 Evidence gaps

Some distinct gaps were highlighted in the available evidence base. For some steady management states of concern (e.g. undamaged peat, cultivated peatlands), there was not even one study found that could provide a complete GHG budget, and in most cases there are only one or two appropriate studies to be found. Where work was available, studies had very specific focuses; few projects have been set up expressly to monitor a full GHG budget of the peatlands and are therefore of limited use to the development of UK-wide emission factors.

In terms of transitions, there is a general lack of comparability across existing work, with little standardisation used between experimental and monitoring techniques, making it difficult to compare and up-scale existing evidence. Few studies include significant monitoring of the experimental sites before an intervention occurred, or include a long-term follow-up. The interaction of landscape or climate factors with management regimes is also poorly considered, restricting comparisons between areas in different countries with similar strategies, and there are few controls, or work comparing the effects of different management regime interactions within the same site.

Fluxes associated with transitional management states are considered to be more difficult to determine, due to the changing effect on the peatland, but are important for informed decision-making for peat management and restoration effects. It is difficult to assess whether a study describes a position at steady management state, or in transitional state due to a management intervention such as drain-blocking. Thus, while the review attempted to consider management transitions separately to the steady management states, the boundary is not always clear.

As a result, EFs that do currently exist, or were able to be derived / modelled in the review, are mostly from single sites not set up for that purpose, or are primarily based on data not from the UK. Taking into account the drawbacks of the existing evidence base, the collated evidence was used to revise the GHG flux from UK peatlands from a net source of 5.7 Mtonnes CO_2 eq yr^{-1} to a net source of 3.72 Mtonnes CO_2 eq yr-1.

The potential importance of this uncertainty is illustrated by the 2009 statistics for greenhouse gas removals (DECC, 2011b). Peatlands are poorly represented in current LULUCF (Land Use Land Use Change and Forestry) calculations, which is currently dominated by forestry-based emission factors (Hallsworth & Thomson, 2010). The 2009 estimate for carbon removals was 4.1 $MtCO_2e$ (DECC, 2011b), and the provisional data for 2010 anticipate removals of 5 $MtCO_2e$ (DECC, 2011c). While UK peatlands are thought currently to act as a net source of C, even with the current evidence base the review as able to alter the estimate by 2Mt, strongly suggesting that this is an important area to clarify. More accurate EFs for both steady management states and transitions between them would allow for better prediction of the short-to-medium term impacts of management change, where the peatland may act as a net source, as well as the predicted flux on the intended final state, where it may have become a net sink.

4.3 Policy prioritisation of research needs

The UK priority areas for additional experimental studies and monitoring were considered in light of the major peat management states and transitions identified. Five criteria were used for identification of the priorities for future UK peatlands research, with acknowledgement that priorities may differ at country levels due to varying environmental and political pressures. The criteria considered are:

1. The extent of each peatland management state in the UK.

2. The impact (likely / predicted) of the current management *steady state* emissions.

3. Impact (likely / predicted) of any current / expected change in management state (the *transitional state*).

4. The existing level of uncertainty in current data.

5. The perceived opportunity to affect a change / improvement to carbon budgets with improved knowledge / subsequent advice.

The highest priorities for further work on UK peatland management states are listed in Table 1 (for steady management states) and Table 2 (for transitional management states). Further detail on these priorities, and all of the states considered, can be found in Annex 1.

Table 1: Highest priorities for further research into UK peatland steady management states

Steady management state	Description of state
Cultivated	Peatlands currently used for agricultural production.
Eroded	Areas of peatland (predominantly upland) where the peat mass integrity has been affected by past hagging or gullying.
Gripped	Peatlands subject to drainage by shallow open moorland drains normally parallel to each other at up to 50m (more commonly 20m) spacing.
Managed burning	Areas of peatland (mainly blanket bog) subject to rotational burning management to encourage heather for rearing grouse.
Restored / near-pristine peatlands	Functional peatland, either in a near-pristine condition or that were formerly affected by unfavourable land management, and will be subject to restoration management to restore hydrological function and allow new peat to form.
Wasted	Areas formerly dominated by deep peat deposits, but where peat is now less than 40cm thick over most of the area, due to oxidative and erosional loss through drainage and/or cultivation.

Table 2: Highest priorities for further research into UK peatland transitional management states

Transitional management state	Description of transition state
Cultivated peat to grassland	Cultivated converted to improved grassland. Represents the first stage of restoration in several cases.
Cultivated peat to other farming systems	Cultivated converted to alternative agricultural systems that lock in soil carbon.
Grassland to bog	Improved grassland converted to restored.
Managed burning	As part of managed burning rotation, relatively undamaged or Semi-natural peat may be impacted.
Rewetting	A common practice of many general restoration schemes, including e.g. Gripped to restored; deforestation to restored..

The category of **Semi-natural** used in the review was considered to be a difficult steady state to define, as peatlands were classified as ‘semi-natural’ when they could not be adequately identified as any of the other states. Given the large extent of ‘semi-natural’ peat in the UK, there is a priority to unpick what other states are represented under this broad category, but this need may be best achieved by a general improvement in survey and characterisation of UK peatlands.

The main focus of further study would be the quantification of EFs for peats under steady management states (which can be also considered the ‘end point’ of any intervention on a site) and the effects of transitions between these states. The requirements for further work are therefore twofold: measurement activities to reliably characterise C and GHG fluxes from steady state situations; and field-based research activities to allow for a direct comparison between fluxes from peat in either different management states at the same location, and from transitional states following intervention actions.

The wide range of C/GHG flux pathways and forms requires an integrated approach to their measurement. Figure 1 describes the main fluxes and their measurement strategies:

Carbon and GHG flux

Gaseous flux measurement
- Eddy covariance methods
- Chamber methods

Fluvial flux measurement
- Water flux measurement
- Dissolved Organic Carbon flux measurement
- Inorganic C flux measurement
- Particulate Organic Carbon flux measurement
- Dissolved CH_4

Biomass transfers

Peat carbon stock and condition

Carbon stock
Vegetation and peat condition
Remote sensing methods
Site history and peat accumulation rate

Figure 1: Carbon flux measurement methods (Worral *et al,* 2011) (described in Annex 2 for tiered measurements).

4.4 Blue print for a research programme

The research programme (Evans *et al,* 2011) presented here proposes a structure for further work, in the development of a tiered measurement programme, including both the direct monitoring of GHG / C fluxes, and also supporting measurements (e.g. vegetation structure, etc). Each level of the tiers should be complementary and interchangeable, so that sites in Level 2 for example will also include all the measurements that would be made at a Level 3 site; this would allow for sites to be up- and down-graded in level as required or as priorities change, while still retaining the required baseline of data to allow for comparability and up-scaling. The levels are detailed in Annex 2, summarised in Table 3.

Table 3: The levels proposed by Evans *et al* (2011) for tiered monitoring standards for GHG/C flux from UK peatlands

Level	Summary	Strengths
LI	All components of the C and GHG balance are measured according to current best practice, focused on high-priority peatland and management types.	Will have the greatest power to detect management impacts and / or the different responses of different peatland types, and would provide high-quality 'platforms' for further research.
LII	Less intensive, lower-cost monitoring methods are used to provide minimum acceptable estimates of fluxes.	The minimum standard of measurements from which a reasonable set of annual C flux estimates could be obtained.
LIII	Periodic survey-based approaches are used to monitor peat condition, and to provide some information on rates of carbon accumulation or loss; annual C fluxes not measured.	To establish lower-cost, long-term monitoring of carbon stock, vegetation status and site condition based on infrequent site surveys; to undertake assessment at a wider range of sites, thereby supporting the extrapolation of data from intensive flux measurement sites to the wider UK peatland area.

Both LI and LII measurements can be incorporated into experimental studies. LIII measures can be co-located in experimental sites with existing LI and LII sites to build cost-effectively on current research activity. Also emphasised are the use of appropriate controls (as sites or as on-site areas), collection of adequate baseline and supporting data pre-manipulation, and the importance of adequate replication, robust study design (e.g. replication, catchments scale) and extended duration past the typical 3-year timescale for the development of times series of change. This would require good coordination and harmonisation between the LI / LII 'steady state' measurements, and the 'transitional' measurements from the experiments (summary guidelines for the design of field experiments is replicated in Annex 3).

LII monitoring is conceived as the development of 'good practice' standards rather than a prescriptive guideline, for both steady management state monitoring and field manipulations. It is envisioned that adjustments to existing studies could be more easily – and cost-effectively – made to provide the proposed core measurements (detailed in Annex 2) at replicated, representative locations. LIII is suggested to provide a data baseline, which could also be set up across a range of sites as lower-cost, lower-intensity measurements to quantify variations in peat accumulations and loss over a wider range of peatlands and timescales.

It is not considered to be economically efficient or scientifically desirable to develop an entirely new monitoring network. A list of candidate sites for LI monitoring are suggested, including an 'optimal' flux monitoring programme to be used at those sites. The 14 shortlisted sites cover a wide geographical range across the UK, and have some measurement activity already occurring (e.g. the majority already have a weather station and static chamber). Specific sites are not identified for Level II or III work; instead there is discussion of the development and promotion of Level II and III standards for existing peatland work.

5 Framework for actions

The partners who commissioned the Worral *et al,* (2011) review study have subsequently evaluated its findings; it is considered to be an exhaustive examination of the available evidence and the current knowledge of emission factors. The results have highlighted areas of further work that require research input, to allow peatlands to contribute effectively to carbon audits, and where additional information is needed for accurate valuation of peatland ecosystem services to inform management decisions.

Uncertainty around peatland GHG / C fluxes is high, with variation of 2Mt shown even with the inadequacies in robustness of the data, which may represent a significant contribution to UK carbon budgeting. Peatlands currently represent an overall source of C, but an improved understanding of the transitional effects of management regime changes would allow for more appropriate actions to be taken, which could convert this net source to a sink. There is thus a substantial need for improved data on peatland C fluxes, as current information is not sufficient for management decision-making, or production of IPCC Tier 2 or 3 EFs.

5.1 Options for specific activities

The proposed blue print programme described above can be used to explore the following issues:

5.1.1 Improved quantification of UK peatland emission factors

There is a need to produce robust, accurately-quantified EFs for peatlands under both existing steady management states and transitions. Direct monitoring of GHG / C fluxes and supporting measurements are needed to reliably characterise fluxes, with targeted field-based research activities needed to improve comparisons and fill evidence gaps. There is a need for additional measurements, improved robustness and repetition in data collection, and the establishment of standards of comparable evidence.

5.1.2 Adoption of appropriate evidence standards

There is a need for the establishment of consistent tiers of measurement, including both the direct monitoring of GHG / C fluxes, and also supporting measurements (e.g. vegetation structure, etc). Each level of the tiers would be complementary and interchangeable, allowing for the required comparability and up-scaling potential. The suggested levels are:

LI All components of the C and GHG balance measured, according to best practice, focused on high-priority peatland and management types.

LII Less intensive, lower-cost monitoring methods used to provide minimum acceptable estimates of fluxes.

LIII Periodic survey-based approaches used to monitor baseline peat condition. These levels would function as non-prescriptive guidance standards and best practise to be promoted across current and future peatland work.

5.1.3 Targeted development of emission factors

A set of peatland states were identified as priorities – those with a large spatial area, of particular importance to carbon accounting, or with the largest uncertainty – to benefit most from targeted research. For priority steady- and transitional- management states, there is a need for the broader levels of information standards (LII and LIII) be developed further, with new LI sites on priority areas. Research could benefit from building on the base of 14 proposed sites suggested in the review, as these sites are already located in priority areas with some appropriate existing infrastructure to undertake these detailed measurements.

5.1.4 Fate of DOC in peat systems

The loss of Dissolved Organic Carbon from peatland systems has been well studied, but the fate of this carbon remains poorly understood; it is unknown if sequestration occurs further down the line or whether this carbon becomes a later component of the atmospheric flux. It is important to quantify the magnitude of this potential atmospheric flux, and this represents a discrete research priority.

5.2 Stakeholder involvement

This project was developed from an engagement with stakeholders in peatland management and carbon auditing – UK statutory conservation agencies, DEFRA, DECC, and the devolved governments.

This document was prepared for wider engagement with UK policy and research provider communities, to expand the initial network of stakeholders. Establishment of common data collection standards requires UK-wide cooperation, and improved quantification of GHG / C fluxes would allow for the devolved administrations to take management decisions appropriate to the state of the different country peatlands and carbon balances.

The document has been widely circulated and its impact will be discussed in a planned stakeholder meeting to be held in late 2011.

We will welcome comments from interested parties.

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Annex 1

Peatland management state priorities - details

Table A1(i): Steady management state priorities - detail

Peatland management state	Priority (high – low)	Description of state	Reason for priority, based on criteria
Afforested	Medium	Land planted with non-native coniferous trees. This steady state should be seen as a very long term rotational management – assuming replanting every 40-50 years.	Relatively well studied, with additional ongoing work. Differing priorities in the countries – e.g. a relatively small areas in England, more prevalent in Scotland. May be important for understanding impact of deforestation and restoration to bog.
Bare soil	Medium	Peat surface without vegetative cover, easily eroded by wind, water and livestock, and subject to extensive drying. Eroded peat is usually washed into watercourses, hugely increasing the water fluxes.	Large potential loss from erosion, but difficult to quantify ultimate impact on GHG. Evidence of high fluxes, but limited areas affected.
Cultivated	**High**	Peatlands currently used for agricultural production, with land subject to inversion tillage at least every 5 years. Water table typically 60cm or lower beneath peat surface as yearly average.	Very little information available for GHG / C fluxes, although this is a widespread peatland type, particularly in England. Estimated emissions are very large, so this is a very high priority for further work (although most of this now on “wasted” peat soils). Large political motivation relating to food production and security, and to costs of drainage.
Developed	N/A	Areas where peat has been removed for eg. quarrying, landfill etc, or where it has been predominantly built over with infrastructure, or development. Includes most urban areas on peaty soils e.g. York.	Considered to be too late to restore; the peat resource is lost.
Eroded	**High**	Areas of peatland (predominantly upland) where the peat mass integrity has been affected by past hagging or gullying. This may	Covers around a seventh of English blanket peatlands, and is also likely to be common in other UK countries (e.g. Monadliath mountains in Scotland, moorland near Ysbyty Ystwyth in

		be exacerbated by natural as well as anthropogenic erosion features. Peat may be bare or vegetated (often bare on sides of features, but vegetated on flatter surfaces), but erosion features will be likely to have severe hydrological impacts on peat masses, with gullies and space between haggs representing effective drainage features for adjacent peat.	Wales). There are likely to have severe effects on peat hydrology and therefore GHG and C flux. This may be amenable to hydrological restoration such as gully blocking and trapping of redeposited peat.
Extracted	Medium	Areas that continue to be affected by current or recent (last 10 years) peat extraction. May include areas of adjacent undisturbed peatland affected hydrologically by peat cutting.	Restoration of extracted sites is already occurring, and a baseline for comparison is needed. Extraction is ongoing Relatively well studied abroad (Canada), so if comparability of effects can be shown the available data pool is increased. Restoration is often amenable for carbon credits.
Grazed	Low	Difficult to define a particular steady state as most blanket bog is grazed to some extent, and grazing occurs on a continuum from no grazing to overgrazing.	The level of grazing is likely to be indicated by relatively predictable vegetation changes in peatlands, thus it may be more effective to characterise EFs of vegetation cover states rather than grazing intensity (vegetation cover information is already available, e.g. from LCM2007).
Gripped	**High**	Peatlands subject to drainage by shallow open moorland drains normally parallel to each other at up to 50m (more commonly 20m) spacing.	A fifth of all English blanket bog affected. Some emission data available and work is underway – research is needed to characterise and develop EFs. Restoration activity will require baseline to establish overall GHG benefits of actions.
Improved grassland	Medium	Peatlands dominated by agriculturally managed-vegetation, dominated by productive grasses (e.g. Perennial ryegrass) and clover, but not cultivated in last 5 years. Usually drained so water table is around 40cm below peat surface as annual average, but not wasted.	Represents a potential option for reducing GHG flux from cultivated peatlands, with potential impacts on surrounding habitats. Emissions are likely to be high, although lower than actively-cultivated peat.
Managed burning	**High**	Areas of peatland (mainly blanket bog) subject to rotational burning management to encourage heather for rearing grouse. May also coincide with gripped/eroded areas.	Widespread management (30% of English Blanket bog), with much debate about biodiversity and carbon benefits. Growth of heather lowers the water table due to transpiration.

Overgrazed	Low	See “Grazed”	Overgrazing of peat is less of a problem since headage payments stopped. May be indicated by vegetation status, although overgrazing cross compliance cases could be mapped.
Restored / near-pristine peatlands	**High**	Functional peatland, either in near pristine condition or formerly affected by unfavourable land management, normally including drainage, will have been subject to restoration management to raise the water table and restore hydrological function, to enable peat-forming vegetation to develop and new peat to form.	This represents the desired endpoint for many peatland restoration schemes / transitional states. The GHG / C flux from these ecologically-functional peats is poorly understood whether approached from pristine or restored. Should not be confused with revegetation of bare peat – if this does not result in near-surface water tables, peatland cannot be considered restored.
Semi-natural	**High**	A catch-all term for peatlands which we know will support semi-natural vegetation, but about which we know little else. Commonly defined as NOT being in any of the above states,. **Difficult to consider in the same way as the more defined steady states**.	Large areas are classified as in this ‘state’. Probably represents a mixture of different vegetation types, affected by a range of different managements, best characterised by vegetation type using data from e.g. LCM 2007. Almost all areas subject to damaging levels of ammonia deposition – should not be ignored. **Difficult to consider in the same way as the more defined steady states.**
Undamaged	Low	Peatlands that have never been artificially drained, and which retain mire vegetation.	Very few sites exist. Restored / pristine category should provide information on endpoint of restoration schemes.
Wasted	**High**	Areas formerly dominated by deep peat deposits, but where peat is now less than 40cm thick over most of the area, due to oxidative and erosional loss through drainage, cultivation and planning activities.	Extensive problem, particularly in England; also may be an analogue for natural soil type with shallower organic deposit (organo-mineral soil) accounting for 1/3 of soil carbon stores in Scotland. A better understanding of associated emissions is needed, as there may be the potential to restore this peat to a wetland use, or to grassland. Also, declining agricultural productivity in these areas likely to mean these are prioritised for wetland restoration.

Table A1(ii): Transitional management state priorities

Peatland managemen t state	**Priority (high – low etc)**	**Description of transition**	**Reason for priority, based on criteria**
Afforestation	Low	From Undamaged to Afforested	UK FC standard preclude afforestation on peat unit >25ha + FC definition of peat not always aligned with other UK classifications. Current position precludes planting on peat more than 50cm deep
Cultivated peat converted to grassland	**High**	Cultivated to improved grassland	Represents the first stage of restoration in several cases, and also is the state that non-profitable agricultural peats may be converted into for e.g. biodiversity benefits. The EFs of this are unknown, but will need to be compared to cultivated peat EFs and restored peat EFs to help determine priority actions. Particularly important for England and Scotland.
Cultivated peat converted to other wetland farming systems	**High**	Cultivated to agricultural systems that lock in soil carbon.	A number of new production techniques using a wet agriculture (“paludiculture”) could be developed to generate production benefits from peatlands without diminishing their ability to store carbon. The different cultivated techniques would need to be assessed for how affective they are.
Cut or Mowed peatlands	Med	Like burning this is a rotational practice but with a shorter cycle (and thus not consider a steady state) – cutting or mowing could be an ongoing management for semi-natural peatlands.	No studies exist; may resemble burning. Possibly a spreading management. Potential to use as bio-fuel system in future. Unlikely to be sustainable in long term.
Grassland converted to bog	**High**	Improved grassland to restored	Improved grasslands, resulting from restoration activities on cultivated peatlands or more general management, converted to functioning peat-bog. Longer-terms EFs, particularly with regard to CH4 flux (and potentially N20, due to improved nature) are needed for management decisions of such sites.

Drainage	Low	From Undamaged to Gripped.	Unlikely to occur at large scale now. May need a separate transition for lowland drainage accompanied by agricultural manipulation of vegetation.
Drain-blocking *Included in 'Rewetting'*	Med / **High**	From Gripped to Restored.	Some data becoming available – need to build on this quickly to understand and improve techniques. Suspected transitional issues with increased CH_4, require longer-term study.
Grazing removal	Low	From Overgrazed to Semi-natural / Restored	Current evidence suggests small GHG impact, but will result in vegetation change, so long term / intensity effects are less certain. Hard to characterise and measure. Transition effects will be gradual and mediated by vegetation cover changes – perhaps more likely to be linear change between initial and end states?
Intensific-ation of managed burning	**High**	From Undamaged or Semi-natural to Managed Burning with a shorter cycle, and accidental fires.	The use of burning as a management regime - including on previously-unburnt areas - is on the increase, especially in England. Accidental fires as a result of weather changes are also increasingly common. Better EFs are needed for the changes in fluxes that this will produce, over full fire rotation period, particularly considering the policy-relevance of these actions.
Reduction in managed burning	Med / **High**	From Managed Burning to Semi-natural or other states	Another part of potential restoration activities, also needed in comparison to the 'new burning' state. Reduction of burning frequency has potential effects on the vegetation build-up on peatlands, and the unintended fire risk, but the flux effects are poorly understood.
Revegetation of degraded peats	Med / **High**	From bare to semi-natural or eroded.	Degraded peats have a high EF, but limited work has been done on revegetation practices and scale of intervention required. Maintenance / augmentation of existing studies may be effective. Most GHG benefits will be one off-capture of carbon into new vegetation, and reduction of the degraded loss. Better information could change restoration options on sites in future.

Rewetting	**High**	Gripped to restored; deforestation to restored; general component to restoration.	Many transitional management states can be included under the overall heading of 'restoration activities', aimed to convert other steady states to the restored state. Rewetting the peat - whether it was e.g. drained, afforested, gullied etc - is an essential part of this, but known EFs are poor, particularly with regard to the CH4 balance over the longer term.
Restoration of cutover peatland	Med / **High**	From extracted to restored.	Cutover peat associated with high C loss, but current data mostly not from UK. Of high policy relevance. A few comprehensive studies needed to allow better UK comparison with existing data.
Peatlands converted to agriculture	Low - med	From undamaged or semi-natural to cultivated Possibly from improved grassland to cultivated.	Very unlikely that undamaged or semi-natural peatlands with potential for cultivation would be drained – most are now designated. It is possible that improved grassland peatlands (e.g. in Somerset levels) could be converted for cultivation – this would require EIA. There is a complete lack of information on conversions, but 'cultivated' endpoint status is widespread management with evidence of severe and ongoing wastage. Transitional effects may occur during dewatering and compression of drained peat. Other farming options (wet farming or paludiculture) need to be explored.

Annex 2

Proposed monitoring for measurement Levels

Level I

LI/1	Automatic weather station (AWS) measuring air temperature, rainfall, humidity, pressure, wind speed and direction, soil temperature and solar radiation.
LI/2	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/3	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/4	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/5	Continuous stream discharge monitoring using a pressure transducer to measure water depth in combination with a v-notch weir, flume or gauged section.
LI/6	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/7	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/8	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/9	Monitoring of ebullition gas fluxes (particularly for CH_4) in wetter areas using ebullition funnels (Baird *et al,* 2009).

Level II

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:

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.

Annex 3: Summary guidelines on the design of field experiments

Measurements	The Level II monitoring design described in section 2.4 of Research Programme (Evans *et al,* 2011) report should be used as a template for measurements to be made at an experimental site.
	Where possible, experimental sites should be co-located with existing Level I or Level II monitoring sites.
Control sites	The use of control sites in experimental manipulation studies is essential.
Baseline data	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	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.
	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 experiments	As a general rule, plot-scale experiments must be 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	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	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	Experiments should, wherever possible, aim to run for at least five years (1+ year pre- and 4+ years post-manipulation).