PART 1

EXECUTIVE SUMMARY AND KEY FINDINGS

Executive Summary

1) Reviews of peat carbon science have presented often contradictory lines of evidence, in part due to the complexity of the subject but largely as a result of differences in methodology and definition of the peatland under study.

2) An understanding of peatland environments including their different functional, structural and vegetation characteristics is essential in interpreting the findings of peat carbon studies. The main peatland types and forms are described, including the various hydromorphological forms.

3) Estimates of the extent of UK peat vary considerably, from 1.5 million ha to an upper level of 5 million ha if shallower peats <1m are included. From the perspective of an interest in peatlands capable of supporting active peat-forming habitat, the larger estimates may be the most relevant.

4) Peat thickness in blanket bog is usually between 0.3 m and 6 m and can vary considerably even over short distances. Published average national figures, ranging between 1.5 m and 2.4 m for peat thickness are very generalised and have generally not been determined from any systematic measurement across Britain, although significant progress has been made in Scotland.

5) In order to determine the quantity of carbon stored in peat resources of the UK, it is necessary to know how much carbon is stored per unit volume of peat. This largely depends on how densely packed the material is within the peat matrix (bulk density). The bulk density of peat varies according to the management history of the peat habitat and the microtopography but also varies considerably between the two structural layers of the peat (acrotelm and catotelm). One 'standard model' suggests bulk densities of 0.03 g cm^{-3} in the uppermost parts of the acrotelm increasing to 0.12 g cm^{-3} in the lower catotelm. Bulk density may also vary unpredictably down the column of the catotelm where there are weak layers in the peat.

6) In contrast with this standard model, bulk density studies in Britain often show high bulk-density levels in the topmost layer of peat. It is suggested that extensive human influence on peatlands has disrupted or destroyed the acrotelm, creating a dense layer of damaged peat at the surface through compaction and oxidative wastage. The concept of a 'haplotelmic' bog is used to describe sites where these conditions prevail. Such sites, where the peatland has been modified by management, no longer support a functioning *Sphagnum*-dominated acrotelm layer that lays down peat and protects the catotelm peat store. Theoretical values are provided for the carbon content of a "standard cubic metre of peat" under both natural and haplotelmic conditions.

7) When considering the carbon contained within peatlands it is important to recognise the carbon content of the biomass layer as well as the peat soil. It is suggested that a 15 cm *Sphagnum* layer can be considered as living biomass with a carbon content of up to 50 t C per hectare (equivalent, for example, to the total above- and below-ground biomass of some 50-year conifer plantations). On damaged bogs lacking a *Sphagnum* layer and dominated by vascular plants, the total biomass of the bog is lower, at around 10 t C per hectare (including aerial parts and below-ground roots). At present, the UK national greenhouse gas inventory assumes biomass values for bogs that are substantially lower than either of these figures.

8) Information about the carbon content of peatlands at a national level must be regarded with caution in view of the limited measurements of peat thickness and bulk density which have so far been obtained. An estimate of 3,121 Mt C is regarded as the likely minimum for peat soils in the UK.

9) Peatlands are dynamic stores of carbon with interchange between the peat and the atmosphere for most of the year in the predominantly oceanic UK, whereas in boreal regions (*e.g.* Scandinavia, Canada) these exchanges may be frozen during the winter months. Caution must therefore be exercised when using values for peatland carbon-exchange obtained from boreal peatlands.

10) In an active peat bog, the acrotelm takes up carbon dioxide from the atmosphere and converts it into plant material. Much of this is then subsequently lost again through decay as carbon dioxide, methane or as carbon in solution. A small amount of undecayed material is passed to the anaerobic conditions of the catotelm where the rate of decomposition is so slow that material accumulates as peat. The preponderance of *Sphagnum* in such remains reflects the greater resistance of *Sphagnum* to decay compared to vascular-plant tissues. Any decomposition which occurs in the catotelm will tend to produce methane, carbon dioxide, or carbon in solution. It is

the overall balance of accumulation and loss, over time, that determines the carbon dynamics for any particular peatland. Figures for the different components of this system are presented and discussed.

11) Evidence suggests that methane arising from the action of bacterial decomposition in the catotelm may remain largely locked up in the peat under natural conditions, contributing to the low conductivity of this lower peat. In the acrotelm, methane is both produced and oxidised by different microbial populations. Different microtopographical surface features (*e.g.* hummocks, pools) and different vegetation types all show differing methane emissions.

12) *Sphagnum*-dominated swards can suppress methane through oxidation. In contrast, some vascular plants growing in bog pools and hollows can act as routes for direct methane release, transferring methane from lower levels to the atmosphere directly, thus by-passing the oxidising layer in the acrotelm[1]. There have been relatively few long term methane studies on undamaged natural UK peatlands. There have been even fewer studies which take explicit account of the relationship between emission levels, vegetation, and associated hydromorphological structures (*e.g.* pools, carpets, hummocks).

13) Despite the higher global warming potential of methane (25x that of CO_2), *Sphagnum*-rich natural peatlands are on balance likely to be climate-change beneficial, apparently sometimes strongly so. Peatlands currently in a less-than natural state may, depending on their current condition, either be contributing to climate warming or to climate cooling on a 100-year time frame.

14) Following cessation of active damage, most bogs tend naturally towards a state of recovery and this may (or may not) stimulate increased greenhouse gas (GHG) emissions compared to the drained state This is because they may still be releasing CO_2 through oxidation of dry peat and at the same time releasing CH_4 from re-wetting areas (although the CH_4 emissions associated with recovery will not generally exceed emission-levels typical of the original natural state). Depending on their natural or assisted rate of recovery, any climate-warming sites are likely to become climate-cooling on a 100-year timeframe because they will tend towards the natural condition of net CO_2 sequestration and relatively low CH_4 emissions.

15) It must be emphasised that the marked increases in CH_4 emissions from recovering bogs appear still to be generally lower than background emissions from natural bog systems, although blanket bogs in England and Wales may experience a period of CH_4 emissions higher than levels in the natural state because large numbers of blocked drains create more open water than would naturally occur in such regions. However, colonisation of this open water by *Sphagnum* will tend to reduce CH_4 emissions to natural background levels. Furthermore, the emissions from a recovering site should be balanced against the carbon losses that would have continued to occur if the site had not been brought into a recovering state so rapidly – usually through active conservation management.

16) It is proposed in this report that many of the dynamic processes associated with carbon cycling in the peat bog system seem to be most closely linked to vascular-plant tissues. In contrast, the *Sphagnum* sward is largely involved with carbon sequestration and transfer of this into long-term storage within the catotelm. As such, it is perhaps helpful to think of two distinct, though linked, cycles within the surface layer of a bog. On the one hand there is the vascular-plant cycle, which processes the majority of CO_2, CH_4 and DOC but ultimately contributes relatively little to the carbon store, and there is the *Sphagnum* cycle, which processes CO_2 and creates the bulk of the long-term peat store. Although this is undoubtedly a simplistic model, it is presented as a means of clarifying the key components of the bog system-processes and their possible relationship with each other.

Several topics of particular concern in relation to peat bog systems are then considered in more detail. These are summarised below.

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[1] This transfer process is often referred to as a 'methane shunt', although a range a different mechanisms may be involved. Prof. Andy Baird (pers. comm.) has suggested that the term 'methane shunt' should be confined to cases where methane is transported through hollow stems such as in common reed (*Phragmites australis*), whereas diffusion through the gas-transport system of plants such as bog bean (*Menyanthes trifoliata*) could more accurately be referred to as 'methane transport'. This suggested approach has been adopted in the present report, but readers may find 'methane shunt' used in the more general sense in other literature.

Discussion Topic 1a: Drainage on peat

17) Drainage removes water from a bog system more rapidly than would occur naturally by infiltration through, and over, the peat surface. In many soils, water removal is readily achieved throughout the soil profile. This is not the case in peat bogs. Rapid water removal is restricted almost entirely to the thin uppermost layer of a bog – the acrotelm. Thus the acrotelm may be readily emptied of its water while the lower catotelm peat remains largely saturated. This has led to the general belief that drainage is ineffective on bogs – which indeed it is from the perspective of a soil-drainage engineer.

18) However, complete water removal from the acrotelm is of major ecological significance. Though it may involve a fall in the water table of only 10-20 cm (or even less) , the lowering produced by drainage can have a substantial impact on the living vegetation, particularly the balance between *Sphagnum* species and vascular plants, because a natural bog water table rarely varies by more than 4-5 cm. Furthermore, because water transmission in this narrow acrotelm layer is so relatively rapid, drainage effects can be felt over considerable distances.

19) Peatland vegetation has the capacity to respond to and alter hydrological conditions within the peat under changing circumstances such as drainage or climate change. Unlike other soils, peatlands can respond to drainage in a number of ways, some of which are physical while other responses are under biological control.

20) Physical responses are most obvious in the form of subsidence due to consolidation as water escapes from the peat, and by compression as the drained material presses down on the peat below. The peat is also oxidised and thus decomposes, leading to further shrinkage of the peat mass. The combined effect is that subsidence can extend many metres beyond a drain in a peat bog depending on the slope, water content of the peat, bulk density of the peat, depth of the drain, and climate.

21) Studies looking at water table levels only in relation to the peat surface rather than to a fixed datum point will tend to under-estimate the water table draw-down effect because they do not take account of surface subsidence, which means that the peat surface follows the water table down to the new lower water table. The picture generally presented is that the water table is drawn down within 2-5 m of a drain. This is often incorrectly considered to be, and generally described as, the prime hydrological impact of drainage.

22) Such a view does not recognise the impacts on the acrotelm, neither does it take into account the existence, and impacts, of subsidence. Subsidence can mean, for example, that the effective width of a drain may be increased substantially over time. However, the main ecological effects of drainage are generally found in the acrotelm.

23) Drainage impacts on the acrotelm are much less frequently measured than the more obvious, if limited, water-table draw-down effects in the catotelm. In the acrotelm, although drainage can lead to extended and even permanent dewatering over substantial distances, in many drainage studies this is described merely as 'removal of surface water'.

24) Drainage causes the acrotelm vegetation to experience drought conditions more often and for longer periods. Topography can also have a major influence on the impact of drainage in blanket bog areas, particularly downslope from drains. Some studies indicate a potential effect on acrotelm hydrology as far downslope as 400m from a drain. The ecological response to even small changes (4-5 cm) in average water levels in the acrotelm can be sufficient to bring about changes in vegetation, although communities exhibit a degree of adaptive resilience to varying water regime, changing species composition according to prevailing conditions.

25) The key stages of topographical change and biological response are presented, from *Sphagnum*-dominated vegetation to dwarf shrubs and grasses, with increasing loss of the acrotelm. Natural conditions with a mixture of drier and wetter *Sphagnum* communities are replaced by *Sphagnum* communities typical only of drier conditions. With continued drainage the vegetation of the acrotelm steadily loses its *Sphagnum* cover and thus ceases to be peat forming. The normally-functional acrotelm is therefore lost and the surface becomes a haplotelmic surface (unprotected catotelm surface) dominated by vascular plants such as dwarf shrubs and grasses, rather than *Sphagnum*.

26) Many drainage studies have either looked only at draw-down in the catotelm and not measured acrotelm effects, or have looked at sites with existing drains and attempted to make assessments of drainage impacts based on what is now visible. Uniquely in peatlands it is possible, when undertaking studies of already-drained ground, to look at the nature of the bog vegetation prior to

drainage (provided the approximate date of drainage is known). This is because the peat archive will hold a record of the pre-drainage condition. Such an approach to assessment of drainage impacts is only now beginning to attract research interest.

27) The carbon impact of drainage essentially consists of increased oxidation of the peat matrix leading to carbon dioxide release to the atmosphere and to dissolved organic carbon in water outflows. Peat is only formed in the acrotelm, largely by *Sphagnum*. As drainage tends to result in loss of *Sphagnum* and a functioning acrotelm, the system increasingly becomes dominated by vascular plants and steadily loses its ability to sequester carbon as peat. There are reductions in methane emissions due to oxidation as air penetrates more deeply into the peat, but cracking can release methane from deeper in the peat even under conditions of drainage. The net effect of drainage is thus a variety of carbon losses and few gains. However, the extent to which different degrees of drainage may halt carbon sequestration and lead instead to carbon losses is not well understood, particularly in relation to UK blanket bogs.

28) Drainage-induced changes to the carbon budget may be significant and can occur even when the water table shows only a limited draw-down relative to the ground surface. Vascular plants are more easily decomposed and therefore provide less net long-term carbon sequestration. Vascular-plant tissues may dominate the carbon store of the surface layer but little of this survives to be passed down into the long-term store of the catotelm because vascular-plant tissues are not as resistant as *Sphagnum* to decay.

29) Vascular plants may, however, therefore contribute significantly to increased dissolved organic carbon (DOC). This increased DOC appears to be derived from elevated quantities of breakdown products generated by the increased biomass of vascular plants resulting from drainage. Furthermore, in the absence of *Sphagnum*, the root systems of vascular plants may increase the loss of carbon from the deeper peat by stimulating decomposer microbial populations with supplies of fresh organic carbon in the form of root tissues, root exudates and oxygen.

30) Drainage also leads to cracking and piping within the peat catotelm. Piping and drainage have been shown to be interlinked through mechanisms which are not yet understood. Such cracking and piping results in greater oxidation and decomposition of the peat, and may make the bog system more susceptible to slope-failure and consequent peatslides. Carbon losses from peatslides can be substantial.

31) Methane emissions on drained peatlands fluctuate considerably over a year, with annual totals often much smaller than indicated by peak rates. Results from short-term studies must therefore be treated with caution. There are few long-term studies of methane and drains in UK peatbogs.

Discussion Topic 1b - Restoration of drained peat bog systems: the carbon balance

32) Restoration of peat bog systems aims to restore high, stable water-table conditions *within* the peat. Large areas of open water are not conducive to habitat recovery.

33) Restoration of drained peatlands through ditch blocking has been shown to raise water levels and stabilise the water table. The vegetation response is different in the ditch and on the bog surface. Growth of aquatic *Sphagnum* species in the open water of the ditches leads to 'terrestrialisation' of the ditch water, and although peat accumulation in such aquatic systems is slow, the presence of *Sphagnum* carpets helps to stabilise the water table in the ditch and reduce CH_4 emissions.

34) Raised water levels in blocked drainage ditches also result in elevated water levels within adjacent areas of the bog surface. This rewetting of the dry bog surface is termed 'paludification', and across the bog surface can result in a switch from vascular-plant dominance to a *Sphagnum*-dominated vegetation characterised by terrestrial *Sphagnum* species. These terrestrial species are more vigorous formers of peat than the aquatic *Sphagnum* species colonising the standing water in the ditch.

35) A decrease in the rate of carbon dioxide released from the peat can be expected as vascular plants are replaced by *Sphagnum*. This is because there are fewer vascular-plant root systems to oxidise the underlying peat. Indeed there may be increased CO_2 uptake and sequestration as

vigorous terrestrial *Sphagnum* species re-establish the peat-forming process. Examples are given of sites which are recovering naturally and where the current rate of carbon sequestration is very high.

36) Methane emissions are known to increase with rising water tables on peatlands but there have been few direct studies of restored UK blanket bogs. Indeed a naturally-recovering site has been found to release extremely low levels of methane. The age of the carbon in methane emissions associated with rewetting suggests that such emissions arise from the decomposition of newly-flooded vascular-plant vegetation in ditches rather than decomposition of catotelm carbon store. If this is the case, then once the vascular-plant material has decomposed, methane emissions can be expected to fall.

37) Methane emissions associated with restoration may thus be relatively short lived (perhaps less than 5-10 years) and of course they are localised within the ditches. There is evidence to suggest that in both ditches and the wider bog surface, re-establishment of *Sphagnum* can suppress methane emissions arising from the peat. *Sphagnum* dominance in the ditches also reduces the vigour and abundance of vascular plants responsible for methane transport.

38) The amounts of methane released from re-wetting are likely to be low in relation to the overall carbon and global warming benefits of restoration. Indeed the limited amount of existing evidence from re-flooded peat bog systems suggests that methane emissions, though showing an increase compared to the drained state, are still lower than those found on natural peatbog systems. In addition, such emissions must be balanced against the long-term losses of carbon dioxide which would have occurred had the site not been brought into restoration management.

39) Dissolved organic carbon has been shown to increase in blocked drains for some years after restoration. A delay in the restarting of certain enzyme reactions following flooding has been suggested as a possible cause. However, this observed increase in DOC might be more simply explained by the death and decomposition, due to rewetting, of the substantial quantities of vascular-plant biomass previously encouraged by the original drainage. The young age of the carbon in DOC suggests that the latter may be the more important factor. After longer periods of restoration, studies show that DOC levels fall substantially in blocked drains. This may be explained by increases in *Sphagnum* and consequent reduced vigour in vascular-plant cover, thereby reducing the source of DOC production.

Discussion Topic 2 - Windfarms on peat

40) The main physical impacts of windfarms on blanket mire arise from the construction and ongoing presence of service roadways running between the turbine towers. Where these roads must cross deep peat (typically ‘deep’ is defined as 1 m), the approach presented in many recent EIA proposals for windfarm developments is to ‘float’ the road on the peat using a geotextile. This is a relatively new technology and there have so far been few, if any, published studies on which to draw conclusions about the likely long-term ecological impacts of these roads.

41) Floating roads cause compression of the peat and therefore subside where the peat is softest and wettest, causing hydrological disruption through changes to both surface-water movement and sub-surface seepage. Disruption to surface flows may give rise to hydrological impacts extending 400 m downslope or more depending on the landform, as described in Discussion Topic 1.

42) Drainage proposals for such roads generally involve the installation of culverts. These can cause further erosion by focusing what was originally a diffuse surface seepage into channelled flow, at least over limited distances downslope. An alternative increasingly being proposed in EIA proposals is that the road be engineered to permit diffuse flow through the road to match the seepage of water through peat. This has not yet been demonstrated or tested in practice.

43) Excavated roads in effect operate as ditches or barriers, depending on whether they are infilled to the bog surface or not, and depending on the material used for the infilling. In either case, excavated roads cut down through the peat to the subsoil. This has significant hydrological implications for the bog not merely at the small-scale local level of the immediately-adjacent peat, but also potentially for the hydrological pattern of the bog system as a whole (*i.e.* the mire unit, or ‘mesotope’). The hydrological implications include oxidation, subsidence and vegetation responses as covered in Discussion Topic 1.

44) A recently-produced model for estimating the carbon savings of windfarms on peat is examined and considered to be a useful tool. Much of the model provides a valuable quantification of potential carbon-effects, but certain in-built parameter values may merit further review, and there is evident scope for exploring a range of example input-values to reflect the varying conditions generally found in blanket mire environments.

Discussion Topic 3a - Forestry on peat: the carbon balance

45) Forestry plantations on peat require drainage for successful growth. Some tree species themselves further dry out the peat. Forest drains and shallow furrows result in lowering of the water table to an extent that causes subsidence of the peat and, ultimately, oxidative wastage. Determining the relative proportions of oxidative loss and compression responsible for the subsidence below a plantation requires more study for UK blanket bogs.

46) The amount of subsidence depends on, amongst other things, the bulk density of the peatland. For relatively natural blanket bog, bulk density can be relatively low, resulting in up to 100 cm subsidence in 35 years. Trends indicate that this slumping may extend horizontally beyond the forest edge by distances of 50-60 m over time. Ecological drainage effects as described in Discussion Topic 1 could then significantly extend this zone of impact.

47) Based on the limited field research and modelling work available, existing figures suggest that, in the carbon-budget for a full forest rotation (which also takes onto account the trees, timber, other forest products, forest litter and contributions to soil carbon), the overall loss of carbon from an afforested peatbog may exceed the carbon gains made by the plantation forest within a 100-year time-frame and the tipping-point may be as little as 30 years. Recent efforts to model the relative losses and gains of carbon when conifers are planted on peat have used figures which may not be truly representative. The latest data from one of the sites involved are very different from those used in earlier studies.

Discussion Topic 3b - Restoration of afforested peat: the carbon balance

48) In principle, the carbon contained in all conifer plantations on deep peat in Britain could be matched by restoring a *Sphagnum* carpet 3 cm deep across 700,000 ha of peatland. This area is less than the restoration target set out in the UK Habitat Acton Plan for blanket bog and may therefore represent an achievable goal.

49) The full carbon balance of peatlands restored from formerly-afforested areas in the UK has been the subject of little published research. One model, based on conifer plantations on deep peat in the Flow Country, and taking account of both methane and carbon dioxide losses from the decomposition of trees felled to waste, suggests that under the most rapid rates of peat growth likely under the prevailing conditions, the system would be in carbon credit immediately restoration begins. Lower rates of peat growth could put the system in carbon credit within 50 years. If methane outputs decline as the flooded ditches become covered with *Sphagnum*, then even lower rates of carbon sequestration could be in carbon-credit quite quickly. Furthermore, for a forest felled at 15 years it would take the establishment of a *Sphagnum* carpet of only 1.5 cm thick to replace the lost biomass carbon from the trees.

50) In addition, it seems reasonable to expect that a substantial proportion of the below-ground carbon provided by the former forest would remain in place once the above-ground tree biomass had been removed and the ground re-wetted. This preserved, below-ground forest carbon may therefore contribute additionally and positively to the net carbon balance of the peatbog restoration budget.

51) Furthermore, the overall carbon budget should take into account the carbon losses which would have occurred had the trees not been felled when they were. A further 30-40 years' worth of forest growth could have seen carbon emissions from the system of 4-5 t C ha^{-1} yr^{-1} which will not now happen. This would mean that all but the slowest peat accumulation rate would exceed the total GWP emissions within 10 years or so.

Discussion Topic 4 - Hydro-electric schemes in peat-covered catchments

52) When reservoirs are constructed on, or expanded across, peatland habitat or remnant peat soils for the purposes of hydro-electric developments, this can lead to carbon losses from peatlands through flooding of the peat soil and vegetation. The most immediate loss arises from decomposition of the drowned vegetation. Studies show that carbon dioxide and methane emissions rise significantly in the flooded peatland as the inundated bog vegetation decomposes. The loss of carbon-sequestering capability from this vegetation is also relevant. In addition, the waters of such reservoirs have been found to remain super-saturated with carbon dioxide long afterwards.

53) Within peat-covered catchments where the peat is eroding, the supply of peat soil washed down into reservoirs from the catchment is likely to provide an even more significant long-term source of carbon dioxide and methane emissions. The constant input of organic material from the catchment can lead to additional chronic levels of emission from such reservoirs post-construction, particularly of methane, because the bottom sediments of reservoirs generally experience anaerobic conditions.

Discussion Topic 5 – Peatbogs and climate change

54) Natural peatbogs have demonstrated an ability to grow at fairly constant rates over several millennia despite dramatic climate shifts. This can be explained in terms of the capacity of peat bogs to respond biologically to such shifts. Vegetation composition changes in response to changing climate, thereby maintaining waterlogged conditions across the bog surface and enabling peat formation to continue.

55) Damaged peatbogs have less biological capacity to respond to such changes because the primary architects of the biological response are *Sphagnum* mosses. Restoration of peat bog systems to an active condition should re-establish a more robust and resilient habitat capable of responding more successfully to climate change.

56) The most recent climate-change predictions suggest that conditions may become somewhat drier for at least part of the blanket bog resource, but factors such as cloud cover and increased oceanicity may compensate for such changes. In addition, warmer conditions offer the potential for greater dew fall and mists, as well as continued low-lying cloud cover in the hill districts, all of which offer the potential for uptake by *Sphagnum* of ‘occult’ precipitation – *i.e.* precipitation which does not appear in rain gauges. Lacking a cuticle, *Sphagnum* is much more able than vascular plants to take up such moisture.

57) Construction of ‘climate envelopes’ for species, particularly the major peat-forming species *Sphagnum papillosum*, suggest that even under worst-case climate scenarios of 2050, conditions would still allow *S. papillosum* to grow throughout its current range. As one of the main architects of the bog environment, it would appear that *S. papillosum* will continue to act as a keystone species for the blanket bog habitat even under predicted conditions.

58) Moreover the evidence from the peat archive for the past 7-8,000 years suggests that terrestrial *Sphagnum* species such as *S. papillosum* may grow rather more vigorously and lay down peat at a faster rate than the species which predominate during wetter climate phases. It is therefore possible that the scenarios set out for 2020, 2050 and 2080 may even lead to more rapid peat accumulation than at present. This scenario is, however, predicated on the widespread presence of an active, *Sphagnum*-rich bog surface across blanket mire areas. Unfortunately this is not currently the case because the majority of blanket mires in Britain are haplotelmic, lacking a *Sphagnum*-rich acrotelm.

Discussion Topic 6a – Commercial peat extraction and the carbon balance

59) Commercial peat extraction involves considerable loss of the carbon store and carbon-fixing potential because peat is physically removed for use in horticulture and energy production. The extraction process also results in a range of indirect gaseous and particulate carbon losses from the cut-over surface, as well as from adjacent uncut areas of the bog through drainage processes described in Discussion Topic 1. The gaseous emissions can be up to ten times greater than in a natural bog.

60) Peat milling and extraction, together with processing methods, can result in significant loss of windblown peat. As much as 2.9 t C may be lost from a 100ha site in a single harvesting season.

61) There is considerable loss of particulate and dissolved carbon in the runoff water from extraction sites.

62) Commercially exhausted peatbogs which are then afforested are likely to result in further loss of carbon, at rates which may not be compensated for by the trees.

Discussion Topic 6b – Carbon balance and the restoration of commercial peat extraction sites

63) Rewetting of former peat workings has taken place in a number of areas. The carbon implications of these restoration attempts depends on the type of extraction methods previously used and the nature of the restoration methods employed. Techniques which encourage terrestrial *Sphagnum* species rather than extensive development of aquatic *Sphagnum* species may provide lower methane emissions and re-establish peat-forming conditions more rapidly. Re-shaping and flooding of large areas as part of a restoration programme may thus be less beneficial than methods which encourage raised water tables within, and consequent *Sphagnum* colonisation across, the surviving peat surfaces.

64) Methane emissions from restoration sites do increase following restoration, but are reported to remain lower than in natural, undisturbed sites. This may be due to the loss of methane producing-bacteria from the catotelm when the catotelm is exposed to oxidative conditions during extraction. Such methanogenic microbial populations take time to become re-established following cessation of extraction. If conservation management can produce extensive *Sphagnum* swards before these microbial populations can become established, a significant proportion of the methane pulse associated with re-wetting may be avoided.

65) Restoration of old-style cut over-bogs characterised by abundant trenches and hollows can result in a net carbon sink, but the extensive flooded trenches may also be a significant source of methane. Such systems may require longer periods after restoration for the carbon balance to return to that of a natural mire, although management for rapid *Sphagnum* establishment may significantly reduce this period.

66) On former milled areas, there is clearer evidence that restoration can result in the development of a large carbon sink. This is because there are no deep trenches to flood and in-fill, only relatively shallow slit-drains. Recovery on milled surfaces occurs largely through terrestrial *Sphagnum* species rather than those typical of aquatic areas, and restoration techniques are becoming steadily more successful at restoring such *Sphagnum* swards.

Discussion Topic 7 – Burning and peat bog systems

67) Human-induced burning of peatlands as a form of management for game and livestock appears to have been most intensive in the last 200 years, although there is evidence for burning throughout the peat archive going back to Mesolithic times. In Britain the majority of blanket mire areas show evidence of having been burned, often many times over several millennia.

68) Deep peat dominated by vigorous heather is usually a sign that land management is causing the peat to dry out. Burning of tall heather makes growth more vigorous, leading to further drying out and oxidation of the catotelm peat by healthy vascular-plant root systems. Tall heather can

additionally encourage hot fires which further damage or destroy the ground layer of *Sphagnum* mosses.

69) In contrast, heather which grows within a vigorous *Sphagnum* carpet does not enter the classic 'growth and collapse' cycle which drives the demand for a cycle of burning management. Heather shoots growing in a *Sphagnum* carpet are continually engulfed by the vigorously-growing *Sphagnum*, causing the heather to send out fresh shoots and roots within the *Sphagnum* layer (heather 'layering') and thereby heather growth remains relatively young and vigorous.

70) The carbon balance of burned peatlands generally involves a loss of carbon from the peat store as well as loss of the peat-forming capability. Natural fire frequencies on *Sphagnum* peat bogs in boreal Canada have been found to average 1,150 years. It has been shown that if the fire frequency is 5x to 7x greater than this average (*i.e.* between 164-230 years), then the resulting long-term losses from the carbon store mean that the bog achieves zero carbon sequestration. If the fire frequency is more than this, then the bog goes into long-term carbon deficit. The average fire frequency in the past 100 years or so on British blanket mires has been approximately 30 years.

71) Several studies undertaken using the long-term burning-and-grazing monitoring plots established at Moor House, north Pennines, in 1954, indicate that burning cycles tend to reduce or remove the bryophyte (moss) layer, including *Sphagnum*. Overall photosynthesis may increase because vascular-plant cover is increased by burning, but vascular-plant material is a poor former of peat because it decomposes relatively readily within the acrotelm. Loss of *Sphagnum* by repeated burning (on cycles shorter than 200 years or so) means that the long-term carbon inputs do not match losses, as indicated by the study of Canadian bog systems.

72) Studies indicating that there may be short-term carbon gains from certain types of burning on peatlands in Britain need careful interpretation, particularly in terms of the specific nature of the peatland under study. Such work has not fully addressed the complete carbon balance nor the long-term implications of burning.

73) It is proposed that if burning affects the vascular-plant layer but does not touch the moss layer, then processes such as methane release, CO_2 exchange and DOC release will be affected but long-term carbon sequestration would largely remain intact. If, on the other hand, burning affects the moss layer, then the major contributor to carbon sequestration would also be affected. The precise relationships between methane, DOC, carbon store, vegetation and burning have yet to be clarified.

Discussion Topic 8 – Blanket bog erosion

74) When peat covers the landscape as it does in blanket mire, it protects the underlying sub-soil from erosion. However, blanket mires themselves are currently subject to extensive and often severe erosion in many parts of Britain and Ireland. This is a phenomenon largely unique to British and Irish blanket mire systems.

75) It has been estimated that 16% of the blanket mire resource is eroded, but this figure hides a wide range of regional variation and intensity. The most extensively eroded parts of Britain are probably the Shetlands, the Monadhliaths, the Brecon Beacons, and the Peak District, all of which are estimated to be eroded across 70-80% of the blanket mire area. The majority of severe erosion occurs at high altitudes across broad watershed plateaux.

76) Rates of erosion and carbon loss also vary, with rates of surface lowering ranging from 0.6 mm to as much as 4 or 5 cm per year. Typical values of around 1 cm per year equate to approximately 575 g carbon m^{-2} per year in the form of eroded material. Single storm events can cause losses of 40x the rate at which carbon is normally sequestered.

77) Remarkably, it is still not known whether blanket mire erosion is a natural process, perhaps part of a natural cycle of denudation and regeneration. This leads to problems of both terminology and policy, because eroded bogs are generally described as 'damaged', but if the process is natural this is not a logical term to use. On the other hand, if erosion is indeed a product of human impact, then policy needs to encourage as much restoration as possible.

78) Evidence is accumulating to indicate that erosion is often associated with human activity. In particular, evidence points to early phases of erosion being triggered by Neolithic, Bronze Age, or

even later deforestation around the blanket mire margins. Examples are presented of modern blanket mire landscapes in other parts of the world where deforestation has not occurred and there is little sign of erosion. It is suggested that consideration might therefore be given to the re-establishment of a forest cover on the marginal slopes of blanket bog systems by encouraging natural regeneration, though the current value of this ground as open land would also need to be considered.

79) Internal drainage systems (peat pipes) which cause collapse have also been implicated as triggers of erosion. Examples of these are considered, but so, too, are examples where such peat pipes are constructive features of the bog landscape. The presence of peat pipes is therefore not invariably linked to erosion.

80) A commonly-cited natural trigger of erosion is climate change, either in the past, or in response to the changing climate of the last 100 or so years. In particular the Little Ice Age of 1500 AD to 1850 AD is often cited as a key driver of erosion at this time.

81) Possible anthropogenic triggers of erosion are considered. It is noted that only Britain, Ireland and the Falklands have such eroded blanket mires. Other blanket mires elsewhere in the world (*e.g.* Spain, Tierra del Fuego, Canada) do not possess such dramatic erosion landscapes. It is possibly significant that Britain, Ireland and the Falklands all employ the same land-management systems of hill-sheep grazing linked to burning to improve the vegetation for grazing. In Britain and, to a lesser extent in Ireland, blanket mires are also burnt as part of the management regime for deer and grouse. Grazing has been shown to increase the amount of bare peat, sometimes significantly, but it has not been shown conclusively to *trigger* erosion.

82) Burning is widely acknowledged to have demonstrably initiated erosion, and is generally recognised as being capable of causing very severe damage to blanket bog systems. It is not widely accepted as the prime trigger of erosion because individual fire patches are regarded as local features whereas erosion is widespread and almost ubiquitous on high watershed plateaux. However, evidence of fire in blanket bogs *is* almost universal. Any peat core from any blanket bog is likely to show at least some charcoal bands in the peat archive, and most show an increasing frequency towards the modern era.

83) What is often under-estimated in relation to erosion and the potential link to burning are the necessary recovery times from particular fire events and the time taken for erosion to take hold. In the uplands, recovery times will inevitably be slow. If other factors then intervene, or further fires occur, the nascent erosion complex may develop rapidly. Otherwise, such nascent erosion systems may take many decades or even centuries to develop fully. The link between burning and erosion may not therefore be immediately evident.

84) An example is provided of a study which was originally described as showing that erosion was linked closely to, and driven by, climate change. Closer inspection of the information for the site reveals an alternative explanation whereby burning provides the key trigger for erosion, climate change then merely amplifying certain species responses to the erosion and re-vegetation process.

85) Given the acknowledged evidence that burning can trigger erosion and the absence of any proven alternative cause, it would seem reasonable to regard burning as the default trigger for blanket mire erosion until such time as other causes might be demonstrated as alternative triggers. It would also seem desirable to consider the implications of this in terms of land-use policy in the uplands.

Key Findings

Description of study sites

1. Ecological descriptions of locations used in peat-carbon research need to be *substantially* improved if the results obtained are to be understood and interpreted meaningfully.

Estimates of UK carbon stocks

2. Estimates for the amount of carbon stored in UK peat bogs are *highly reliant* on the definitions used for 'peat' and 'peatbog soils', and on the generalised parameters used for both peat thickness and bulk density of peat. *UK national carbon estimates for peatbog soils are based on an extremely small number of actual field measurements*.

3. Given these sources of variability, estimates of peatbog extent in the UK range from 1.47 to 5.24 Mha, with UK carbon stocks amounting to *a minimum of 3,121 Mt*.

Condition of study sites

4. Natural bogs consist of two layers – a thin surface layer of soft conductive peat (the acrotelm) covering the somewhat denser peat beneath (the catotelm). Natural bogs are therefore 'diplotelmic' (two-layered), *but this fact, and the significance of this diplotelmic structure, is often not recognised in the relevant scientific literature.*

5. Where bogs have lost their protective acrotelm (typically through human action) *they are termed 'haplotelmic' (single-layered)*. Haplotelmic bogs represent areas where the long-term carbon store is steadily being lost. *A large proportion of the UK peatbog carbon store is haplotelmic and is thus probably experiencing steady carbon loss as a result of human action*.

6. Many peatbog carbon flux studies have been carried out on damaged, haplotelmic peat bog *but this is not recognised or acknowledged in subsequent published accounts*.

Carbon balance of natural peatbog systems

7. Natural bogs show a clear trend of increasingly abundant hollows and pools towards the north and west of the UK. This *may* mean that these so-called 'patterned bogs' of the north and west release more methane than the bogs of northern England, Wales and southern Scotland, where hollows and pools are much less common. *Nonetheless all natural bogs appear to have an overall carbon balance which, to a greater or lesser degree, is greenhouse cooling.*

Carbon-rich living biomass

8. The carbon stored per unit area in the living biomass of natural *Sphagnum*-rich peat bogs is *very much greater than has previously been realised*. This biomass carbon may be equivalent, for example, to the total carbon stored per unit area in the roots, litter and aerial parts of some 50-year conifer forests.

Carbon and drainage

9. Drainage of peat bogs causes the catotelm layer of a bog to undergo *physical* changes (specifically, subsidence and oxidation of peat carbon) which may extend for significant distances. *The major change to water-table behaviour occurs in the surface acrotelm layer only*, which may become permanently emptied and result in significant ecological changes.

10. *Drained bogs are a substantial carbon source*, losing carbon in the form of gaseous emissions and aquatic carbon losses. Drained bogs subject to restoration management show substantially-reduced aquatic losses. Although methane emissions may temporarily increase at the start of

the restoration process, *these do not exceed the range of methane emission levels observed from natural bogs*.

11. Restoration of drained bog also reduces or halts ongoing losses associated with drainage. *Such 'avoided losses' constitute an important part of the overall carbon budget for bog restoration*. Taking into account all carbon fluxes including avoided losses and increased methane emissions, *restored bogs are substantially more global cooling than drained bogs*.

Plantation forests on peat

12. Studies undertaken to date suggest that, in the short term, conifer forests grown on peat may result in a net carbon gain to the system. In the longer term, however, *plantation forests are acknowledged to result in net carbon losses from the system because eventually the carbon-gains of the forest are outweighed by oxidative losses of carbon from the bog.*

13. Projection of data from studies so far presented suggests that the tipping point, beyond which such conifer forests *appear to cause net carbon losses exceeding the maximum possible long-term carbon gains for the forest and its products, could be as little as 30 years*. This projected estimate *does not include oxidative and particulate carbon losses resulting from site preparation, drainage and felling/re-planting*.

Climate change

14. Current climate-change scenarios indicate that the environmental requirements of the main peat-forming species in the UK *will continue to exist even under worst-case conditions*. Furthermore, peatbogs have shown a robust biological response to climate change in the past, but for this response to be possible under future climate change, *peatbog systems will need to be in as 'active' a state as possible*.

Burning

15. Burning, which is widespread on UK blanket bogs, *occurs 5-10x more frequently in the UK than the threshold at which fire has been shown to result in net long-term losses of carbon from peatbog ecosystems in Canada*. Furthermore, apart from large-scale slope failures, *burning is the only activity which has been observed to initiate erosion in recent times*.

Erosion

16. Widespread erosion of blanket bogs in the UK and Ireland remains an unexplained phenomenon but is a major source of carbon loss from such systems. Some evidence exists to suggest that deforestation of marginal slopes in pre-historic times may have initiated some examples of blanket bog erosion. *Re-establishment of forest cover by natural regeneration on the marginal slopes of blanket bog landscapes may thus be a desirable aim.*

17. Until proven otherwise, it would seem reasonable to assume *that the majority of peatbog erosion in the UK results from human action either now or in the past and thus warrants restoration intervention*.