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Afforested peatland restoration

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1. Key Points

- The effects on the net greenhouse gas (GHG) balance when the trees are removed from forests that have been established on deep peat in the UK are examined in this report and summarised in Table 1.
- Bogs that are actively increasing in peat depth are accumulating organic carbon making them net CO_2 sinks. Rates of accumulation vary with the type of peat bog, but recent reviews suggest uptake rates ranging between 0.1 and 1.0 t C ha^{-1} y^{-1} (approx. 0.4-4 tCO_2 ha^{-1} y^{-1}).
- High methane (CH_4) emissions from peatlands, when expressed as CO_2 equivalent rates may exceed the net rate of CO_2 uptake. There is high uncertainty over the magnitude of the CH_4 flux, which varies across peatland types, and consequently it is not clear whether temperate peat bogs in disturbed or restored states are net GHG sinks or sources. The few remaining near-natural ombrotrophic bogs (raised and blanket bogs) are generally accepted as net GHG sinks.
- Rates of C loss from peat soils after afforestation are difficult to quantify, and there is a lack of robust data, particularly for UK conditions.
- While the trees on afforested peatland are growing there is C accumulation in the trees both above and below ground, and CH_4 emissions will be substantially less than before afforestation. Therefore afforested peatland sites are expected to act as GHG sinks - although the size of the sink will vary with tree growth rate, stand maturity and management, site fertility, the degree of drainage and thus CO_2 soil emissions. There is, however, no study of the full GHG budget of an afforested peatland to date.
- Similarly, there is no study of the effect of tree removal for peatland restoration on complete C and GHG balances for UK conditions.
- If trees are removed during peatland restoration, and water tables rise seasonally or permanently due to the reduction in transpiration and due to drain or grip blocking, there are several likely positive and negative consequences for the GHG balance. The key likely consequences are:
    - Reduction in soil CO_2 emissions due to increased water table and reduced aeration.
    - Uptake of CO_2 due to increase of C stock in ground vegetation.
    - Resumption of net C sequestration in peat (if peat formation takes place over the longer term).
    - Increase in CH_4 emissions, particularly over the short-term.

  - Loss of significant C stock held in the above ground tree fraction that is removed, (although not necessarily a rapid or complete C loss if tree biomass is retained off-site in e.g. long-lived harvested wood products, or is used for fossil fuel substitution).
  - Increased CO_2 and possibly N_2O emissions in the short-term due to decomposition of forest harvest residues left on site.
- Two key factors will determine the net GHG balance change for restoration of specific peatland areas: the change in water table depth and the fertility of the site.
- If afforested peatland restoration is targeted at sites with poorest tree growth and with most potential for successful and early restoration of peatland to a net C sink, the GHG balance is likely to be a net reduction in GHG emissions in the long term, although the effect per unit area will not be large.
- The net GHG balance of afforested peatland restoration will be improved if harvested wood products (HWP) are used to gain ‘substitution benefits’ and if tree removal occurs close to maturity or normal rotation length.
- However, the LULUCF accounting rules under international GHG agreements are changing. In particular changes are proposed for rules covering emissions accounting for wetland re-wetting and restoration, use of HWP, and arrangements for plantation removal and ‘compensatory planting’, which may influence the reporting of the GHG effects of tree removal from peatland.

2. Introduction

This note is a rapidly-prepared response to two questions that were received by ClimateXChange and passed to Forest Research in early October 2012 from RESAS, about the greenhouse gas (GHG) balance consequences of tree removal from deep peat areas. It should be noted that the management of forestry on peatland is under active discussion and research in Forestry Commission Scotland and Forest Research, particularly examining the possible GHG balance consequences of different site management options for stands at the end of their rotation. Forestry Commission Scotland is presently developing guidance for managers of the national forest estate on deciding the best options taking into account climate, peat-type, carbon balance, hydrological factors, biodiversity, landscape and restoration potential.

3. Question 1: Where forests have been established on deep peat, what effects are there on the net GHG balance when the trees are removed?

3.1 Introduction to peat bog GHG balance

Peatland areas are large carbon stocks because of the large amount of soil organic material (SOM) that has accumulated over time, largely a result of low decomposition rates because of water logging and low temperatures. Deep peat soils[1] can contain over 550 tC ha^{-1} in the first 1m of depth, (Morison et al., 2010, 2012 p. 30, see note[2] on units). This is much more than C stocks in shallower peaty-gley soils

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[1] In this document we use the Forestry Commission soil definition of deep peat soils as those with organic matter depth > 45 cm (Kennedy, 2002).

[2] It is usual to refer to carbon stocks in mass C per unit area; to convert to CO_2 multiply by ratio of molecular weights, i.e. 44/12 or 3.67. Rates are usually referred to as mass per area per unit time, and usually as a gas equivalent, i.e. $tCO_2\ ha^{-1}\ y^{-1}$. If different GHGs are considered and summed, they are expressed as $tCO_2e\ ha^{-1}\ y^{-1}$.

(average C stock to 1 m = 362 tC ha^{-1}, Morison et al., 2012 p.30) or in the trees[3] (in the range 30 - 200 tC ha^{-1}, Morison et al., 2012, p. 15). Furthermore, peat can extend to several metres depth (Smith et al., 2007). When bogs are actively increasing in peat depth they are accumulating organic carbon, thus they are net CO_2 sinks. Rates of accumulation vary with the type of peat bog, but recent reviews[4] suggest uptake rates ranging between 0.1 and 1.0 t C ha^{-1} y^{-1} (approx. 0.4-4 tCO_2 ha^{-1} y^{-1}).

Most measurements have shown that fluxes of N_2O in peatlands are usually very small (e.g. Drewer et al., 2010), in part because of the low N status essential to maintain peat bog environments, so this component of the GHG balance can be largely ignored, although if there is high N deposition, it can increase (e.g. Sheppard et al., 2013).

However, wet peat bogs also release methane (CH_4), which although at much lower concentrations than CO_2, has a 25-fold higher global warming potential on the 100 year time period considered in the Kyoto Protocol. High but variable CH_4 emissions from peat bogs have been measured and the CO_2-equivalent emission rates (mean values range from 0.5 to 7 tCO_2e ha^{-1} y^{-1}, Morison et al., 2012, p. 48) can exceed the net rate of CO_2 uptake, which can result in bogs being net GHG sources (e.g. Byrne et al., 2004; Couwenberg et al., 2011). This has considerable implications for peatland restoration projects, as the recent comprehensive review by Worrall et al. (2011) concluded: “many restoration or management interventions may not provide a benefit in terms of GHG […] because the flux of CH_4 is often a more important component of the C balance of restored peatlands when considered in terms of global warming potential [than the] net exchange of CO_2”.

There is high uncertainty and much variability in the magnitude of the CH_4 flux, which differs between peatland types and environmental conditions, and consequently it is not clear whether particular peat bogs will be net GHG sinks or sources[5]. A wide variety of net GHG emission rates have been quoted in recent reviews, including both positive and negative values (Worrall et al., 2011, Couwenberg et al., 2011, Artz et al., 2012), and the appropriateness of such values for Scottish peatlands is uncertain. The latest review of a large data set of CH_4 emission measurements from UK soils (Levy et al., 2012) shows that the upland deep peat sites studied all have positive and substantial mean CH_4 emission rates (see Appendix 1 for values for deep peat taken from that review, range from 0.69-3.46 tCO_2e ha^{-1} y^{-1}) and emissions are highest with shallow water tables. Many of these sites are disturbed peatlands. If only measurements from undisturbed temperate, ombrotrophic[6] peat bogs are considered, where full GHG balances are available, they indicate that these bogs are small net GHG sinks (Koehler et al., 2011; Yu et al., 2012; Artz et al. 2012). However, only a small proportion of the UK peatland resource can be regarded as in such a near-natural condition.

Levy et al. (2012) derived an empirical relationship between water table depth and soil CH_4 emissions across their range of sites[7]. The authors noted that this CH_4 emission rate change per cm depth of water table implies that an increase in CO_2 sequestration after restoration of 0.1 ± 0.04 t CO_2 ha^{-1} y^{-1} for every cm of water table height increase would be required to maintain the GHG balance. Thus, extrapolating

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[3] C stocks in trees: e.g. average tree C stocks in Sitka spruce forests in the UK of 83 tC ha^{-1} [calculated from NFI conifer report, 2012], or average tree stocks across the UK of 57 tC ha^{-1}, Morison et al., 2012, p.15 .

[4] This spans the ranges of 0.1 and 0.4 t C ha^{-1} y^{-1} for temperate bogs in general (Parish et al., 2008) and 0.3-0.8 t C ha^{-1} y^{-1} for *Sphagnum* dominated bogs (Lindsay, 2010).

[5] Note that the net GHG balance calculated depends on the time period considered for the calculation of equivalent global warming potential for CH_4 relative to CO_2. Here we use the Kyoto Protocol value of 100 years.

[6] Ombrotrophic bogs are those that are ‘cloud-fed’, receiving water and nutrients from precipitation only; such as blanket or raised bogs. They are nutrient poor in contrast to mineratrophic fens and other bogs which may derive nutrients from runoff or groundwater.

[7] an increase in CH_4 emission of 0.4 g (± 0.14 s.e.) CH_4 m^{-2} y^{-1} per cm of water table increase

linearly[8] for e.g. a 20 cm increase in water table height in a restored bog, an increase in net CO_2 uptake of approximately 2 t CO_2 ha^{-1} y^{-1} would be required to “offset” the expected increase in CH_4 emissions, (when expressed in CO_2 equivalents) . While such a rate is at the high end of the range of CO_2 sequestration rates reported for near-natural peatbogs (see earlier), re-wetting will reduce the enhanced CO_2 loss from decomposition in drained peat so that a net improvement in the CO_2 balance is likely. The time course of net GHG emission rates following restoration is poorly quantified, and obviously will be affected by the extent and nature of the disturbance. Methane emission rates can be high initially as the presence and cover of species which can enhance CH_4 emissions increase on re-wetting, and subsequently emissions may decline over decades. Net CO_2 uptake rates may also be high during the early phases of re-vegetation (e.g. Tuittila et al., 1999), but increasing the longer term C sink depends on re-establishing peat-forming species, which may have lower CO_2 uptake rates (e.g. Yli-Petäys et al., 2007). Thus re-establishing a net carbon sink can take decades (e.g. Samaritani et al., 2011).

3.2 Effect of afforestation on peatland GHG balance

Drainage and soil disturbance of peatland areas carried out in order to establish trees may result in increased rates of SOM decomposition, increasing CO_2 efflux, primarily because of the lowering of the water table, resulting in more aeration and possibly warmer soil temperatures. This may change the peat soil from a C sink into a C source. At the same time, the reduction in water table effectively stops CH_4 loss, because an aerated zone causes microbial methane oxidation, even if CH_4 is produced in deeper saturated areas. However, if the bottom of drains and ditches remain saturated, there may still be some CH_4 emission.

Artificial drainage is also likely to lead to increased loss of dissolved and particulate organic carbon (DOC & POC), which in some very disturbed peatlands might be sufficient to turn the bog from net C sink to net source. However, the net consequence for the GHG balance is unclear, as DOC & POC fluxes from the peatland may not result in subsequent CO_2 release into the atmosphere (Worrall et al., 2011). The depth to the water table is therefore a key factor in understanding peatland GHG balance, and it is also an important determinant of tree growth rates and tree stability, which also has implications for the net GHG balance.

Rates of C loss from peat soils after afforestation are difficult to quantify, and there is a lack of robust data, particularly for UK conditions (Morison et al., 2010, Worrall et al., 2011). This is because of differences between peatland types and fertility; the variety of drainage and ground preparation practices and their effectiveness; lack of sufficiently deep measurements and reliable soil bulk densities; other measurement problems because of the small scale spatial heterogeneity; the difficulties in establishing reference depths or comparison ‘control’ sites; and uncertainty in other changing environmental drivers. The peat soil CO_2 emission[9] measurements that do exist for British conditions suggest a wide range from 4 to 17 tCO_2 ha^{-1} y^{-1} (lowland raised bog, Flanders Moss, Stirling, Yamulki et al., 2013; blanket bog, Galway, Byrne & Farrell, 2005). In addition, there may be DOC and POC losses, as well as dissolved CH_4 and CO_2 losses as emphasised by Worrall et al. (2011). Also during afforestation the existing ground vegetation will be reduced or completely lost as the tree canopy grows, but this represents a considerably smaller C stock than in mature tree crops[10]. Finally, if N fertiliser is applied to assist in tree establishment, some N_2O emission is likely to occur, although as amounts used are small,

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[8] Note, however, that the relationship between CH_4 emission and water table depth is not linear, and emissions increase substantially the closer the water table is to the surface.

[9] Note that ‘soil CO_2 emissions’ measurements are combined measurements of two main components that cannot be easily separated in practice: SOM decomposition by microbial action and respiration of plant roots.

[10] for heathland and moorland measured C stock in vegetation varies from about 0.8 to 20 t C ha^{-1}, with a typical value of 11 tC ha^{-1}, Morison et al., 2012, p. 71

the emission rates are likely to be small, and could be partially compensated for by higher growth and CO_2 sequestration rates.

However, and most importantly, while the trees are growing there is C accumulation in the trees both above and below-ground, usually accompanied by leaf and stem litter accumulation on the ground. Therefore afforested peatland sites are expected to show a positive overall C and GHG balance (i.e. sinks for both, Worrall et al., 2011), although the sizes of the sink will vary with tree growth rate, stand maturity and management, the site fertility, the degree of drainage and thus CO_2 soil emissions. Furthermore, if the GHG balance benefits of the use of harvested wood products (HWP) are considered[11], forested peat can have significant net GHG emissions reduction benefits. It has to be stressed that there is no complete C and GHG balance study of peatland afforestation in British conditions.

3.3 Tree removal from afforested peatlands

Similarly, there is no study of the effect of tree removal for peatland restoration on C and GHG balances for UK conditions. However, if trees are removed during peatland restoration, and water tables rise seasonally or permanently due to the reduction in transpiration and due to drain or grip blocking there are several likely consequences for the GHG balance:

<u>Positive</u> (improving the net GHG balance, i.e. more uptake)

- Reduction in soil CO_2 emissions due to increased water table and reduced aeration.
- Reductions in DOC & POC losses (but see comment above about uncertain impact on GHG balance).
- Uptake of CO_2 due to increase of C stock in ground vegetation.
- Resumption of net C sequestration in peat (<u>if</u> peat formation takes place), over the longer term.

<u>Negative</u> (worsening the net GHG balance, i.e. more emission)

- Increase in CH_4 emissions from enlarged water logged areas in the blocked drains, and from higher water tables that will reduce the aeration zone, and may result in more methane-emitting plants (sedges, rushes etc.), particularly over the short-term.
- Loss of significant C stock held in the above ground tree fraction that is removed, representing a net C loss <u>from the peatland</u> (although not necessarily a rapid or complete loss when considered at the wider scale if tree biomass is retained in e.g. long-lived harvested wood products (HWP), or is used for fossil fuel substitution).
- Increase of CO_2 emissions and release of DOC in the short-term due to decomposition of forest harvest residues left on site: brash, stumps and roots, although the latter below ground components may be very slow to decay in the water-logged conditions.
- Possible emission of N_2O in the short-term during forest residue decomposition.

One major area of uncertainty is the time-course of changes following tree removal – how quickly does the normal bog vegetation recover, and how quickly does the peat bog function change back to provide peat accumulation and thus net C sequestration, or for methane emissions to return to those of the 'pristine' state, if indeed they do.

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[11] Note: that the contribution to net GHG emissions or removals from C stocks in HWP are presently not included in LULUCF accounting in the 1st Commitment Period of the Kyoto Protocol, but the rules agreed at the Durban Conference of the Parties have included them for the 2nd Commitment Period (i.e. from 2013) – see later.

3.4 Key issues assessing net GHG balances of tree removal

The key issues in establishing the net GHG balance of the peatland after tree removal from deep peat soils are (in order of probable importance):

1. What is the net GHG emission of the peatland during and after restoration?
    a. How much will SOM decomposition and thus CO_2 and DOC loss rates decline on re-wetting?
    b. Will the bog re-wet sufficiently to become a CH_4 source, and if so how large?
    c. How quickly will the normal bog vegetation regrow and start to accumulate peat?
2. What is the C stock loss on removing trees?
    a. Are trees removed from site, or felled to waste etc?
    b. How quickly will belowground components decay (stumps, roots) and what fraction will contribute to new peat?
3. What would be the net GHG balance of the afforested peatland if the trees remained?

However, as Worrall et al. (2011) point out: [tree removal] "will always have to be considered in the context of the options for the use of the harvested timber, replanting or restoration to peat bog in order to give an appropriate emissions factor reflecting a life cycle analysis of the site C". Thus, if the wider GHG balance is to be considered, then an important additional question is:

4. The use of any timber extracted when trees are removed
    a. Use for biomass substituting for fossil fuel use
    b. Or use as HWP substituting for fossil-fuel intensive materials

The different C & GHG balance components and how they differ qualitatively between near-natural peatland, afforested peatland, and after restoration are summarised in Table 1.

Table 1. Summary of the changes in peatland C and GHG balance and C stocks after afforestation and after tree removal. + or – indicate rates with respect to peat sink, thus - - indicates moderate source, and +++ large sink.

C & GHG balance component	*Near-natural peatland*	*After afforestation with drainage*	*After tree removal and drain blockage*
CO_2 loss from soil decomposition	-	-- or ---	-
Net CO_2 uptake by vegetation	+	++ or +++	+
DOC, POC and other fluvial losses	-	- or --	-
Net C balance	+ (small sink)	++ (moderate sink)	+ (small sink)
CH_4 emissions	-, -- or ---	- or +	-- or ---
N_2O emissions	Usually very small	If N fertilised, small short-term source	Initial loss, then very small
Net GHG balance	+ or - (small sink or source)	+ or ++ (small or moderate sink)	*uncertain**
C stock changes			
C stock in vegetation & litter	+ or ++	+++	+ (increases over 5-20 years)
C stock in soil	Slowly increasing	Declining	Likely to increase

* The net GHG balance of restored afforested peatlands are shown as '*uncertain*' because the net GHG balance will depend a) on the original degree of peat disturbance when afforested , b) environmental conditions, c) the restoration methods and d) time since restoration; and because of the lack of any complete GHG balances studies over time in UK conditions.

Note: The C & GHG balances are for assumed 'steady state' conditions, and do not include the effects during transition, in particular the loss of C stock during tree removal.

4. Question 2: For climate change mitigation reporting purposes (RPP2), what scale of net emissions abatement might reasonably be estimated to result from this programme in the period up to 2027?

4.1 Planted peat areas being considered for restoration

Advice from FC Scotland is that the future extent of the areas assigned for restoration are not yet decided, partly pending discussions about GHG balance, and about the likelihood of successful peatland restoration. The peat soil types being considered for restoration are types 10, 14 and 11 in the FC Soil classification, because they are identified as ‘very wet’ or ‘very poor’ for tree growth, and areas at higher elevations where tree growth is also likely to be poor, resulting in a less CO_2 uptake. The main tree species involved in these areas are Sitka spruce and lodgepole pine with Scots pine the 3rd largest proportion. Average Yield Classes are 12 m^3 ha^{-1} y^{-1} for Sitka spruce[12], and 6-8 m^3 ha^{-1} y^{-1} for the pine species, and some areas have mixtures of Sitka spruce and lodgepole pine.

It is difficult to establish the age of felling and the tree volumes likely to be removed, but it should be noted that lodgepole pine on the wetter sites is prone to windthrow, so may be felled as early as 30 years, resulting in reduced harvest volumes and a lower net C accumulation since planting. At some wet sites more harvested material may be used for brash mats to enable machinery movements, and thus end up on site, reducing any ‘substitution value’ from its use as biomass for energy supply.

4.2 Restoring afforested peatland – the GHG accounting aspects for LULUCF

1. Under the terms of the UNFCCC, GHG emissions and accounting of changes towards achievement of the Kyoto Protocol (KP) targets of emissions reduction are reported at UK level. For the first KP commitment period (CP1, 2008-2012), accounting is mandatory for emissions and removals related to the LULUCF activities of afforestation, reforestation and deforestation (ARD) since 1990. Therefore, removing trees for peatland restoration is counted as deforestation activity and the carbon emitted is considered instantaneous, i.e. within the year of removal. No contributions from the C stocks in harvested wood products (HWP) to GHG emissions or removals under LULUCF are accounted for, although harvested biomass used in energy generation probably would be included in estimating emissions within the energy sector. The UK also elected to account for emissions and removals related to management of forests created before 1990 (see Matthews et al. (2012) for a more detailed discussion).
2. For the 2nd commitment period (CP2, possibly 2013-2020) under the Durban rules accounting for particular contributions towards emissions or removals due to carbon stocks in HWP from pre-1990 forests will be mandatory. Thus countries will have to record wood production and allocated harvested wood to 4 product types, with different life-times.
3. For the CP1 emissions due to deforestation activity for LULUCF reporting are calculated using a simple emissions factor dependent on assumed forest C stocks, that does not take into account species and age. For CP2 the calculation method for UK forestry LULUCF reporting will be based on more detailed methodology developed by Forest Research, which will include more detail on different tree species and allow implementation of forest management activities, and will better account for pre-1990 forests.
4. In the CP1 there is no accounting for peatland GHG emissions; in the CP2 management of organic soils including the drainage and re-wetting of wetlands is proposed to be a voluntary activity. The

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[12] For comparison with other C balance figures, Sitka spruce YC 12 will have a maximum C stock of approx. 110 tC ha^{-1} at age 50 years if thinned according to prescription, and 150 tC ha^{-1} if unthinned (Morison et al. 2012, p. 22).

European Commission and UK Government support this proposed change, although there are EU & UK ambitions for mandatory wetland accounting. An IPCC methodology for the latter is currently under review for release in July 2013. Whether the UK will include wetland drainage and rewetting in its reporting is at present undecided.

5. Currently the UK reports only emissions from peatlands arising from extraction of peat for horticulture and past drainage of lowland peats in England. Under proposed new IPCC Wetlands Guidance (draft for 2013) methane emissions from natural wetland are not considered, as only anthropogenic emissions are considered. Thus the reduction in CH_4 emissions after wetland drainage is not considered, but any emissions of CH_4 after drainage (e.g. from drains) will now be considered, as will CH_4 emissions from drained and subsequently restored peatlands, because they are both anthropogenic. It is also proposed that carbon loss from drained organic soils will be calculated from CO_2 emissions due to on-site SOM decomposition and off-site waterborne losses, particularly DOC. The IPCC draft guidance suggests that depth to water table will be taken into account in estimating CO_2 emissions, and ditch width and spacing will be taken into account for estimating CH_4 emissions from drained wetland.
6. It is likely that if peatland drainage and restoration is reported, it will result in an increase in emissions reported, because of the emissions from past drainage activities, although only those since 1990 are accounted for. In addition, some small reductions will be able to be reported in the future from any re-wetted and restored wetland areas. While generic factors will be available from the IPCC methodology for Tier 1 reporting, there will need to be substantial work in establishing the appropriate emissions factors for 'local' country-specific conditions if Tier 2 accounting is used.
7. Under the Durban agreement, there are special provisions for accounting for 'compensatory planting' where plantation areas are removed and the land converted from forestry, but equivalent areas of new plantations are planted elsewhere. This will be accounted for under forest management, so will not count as deforestation, but the HWP benefits of such forest management could then be included in the LULUCF accounting. The Scottish Government Policy on Control of Woodland Removal (2009) already includes the notion of compensatory planting for particular situations. Therefore, the implications of this proposed LULUCF accounting method if it is introduced should be examined. Adoption of the 'compensatory planting' mechanism under the Durban rules is discretionary. It is not favoured by a number of Parties who consider it to be a complication to accounting and not necessarily a reflection of what is happening in the forest sector. In particular it is not clear that the mechanism will be favoured as part of accounting in the UK. The inclusion of a version of such a mechanism within the draft EU decision on LULUCF is under consideration but may not be supported.

5. Conclusions

a) Given the possible range of net GHG balances (from positive to negative) and the lack of relevant empirical data it is inadvisable at present to derive quantitative estimates of an overall GHG balance change resulting from planned tree removals during peatland restoration in Scotland. Two key factors will determine the net change for specific peatland areas: the change in water table depth and the fertility of the site. These affect the growth rate of the trees, the decomposition rate of the peat, the methane emissions and the likelihood of successful restoration. If planted peatland restoration is targeted to the sites with poorest tree growth, with most potential for successful and early restoration of peatland to a net C sink, in general these are likely to be the wettest sites, presently with lower CO_2 emissions from peat decomposition and with some methane emissions from drains and wetter areas etc. The net GHG balance is likely to be improved (net reduction in GHG emissions) in the long term, although the effect per unit area will not be large. Furthermore, if the area already restored and planned for restoration (about 4,500 ha) is compared with the total area of deep peat planted in Scotland, (approximately 150,000 ha) it is evident that the net effect on the GHG balance of afforested peatlands is likely to be small.

b) The net GHG balance of restoration of afforested peatland will be improved if HWP are used to gain ‘substitution benefits’ and if tree removal occurs close to maturity or normal rotation length (if possible – in the absence of wind throw risks) to maximise overall C accumulation rate and maximise substitution benefits.

c) However, under international agreements on GHG emissions and emissions reduction, the LULUCF accounting rules are changing. In particular changes are proposed for rules covering emissions accounting for wetland re-wetting and restoration, use of HWP, and arrangements for plantation removal and ‘compensatory planting’ (see discussion in Matthews et al., 2012), which may influence the reporting of the effects of tree removal from wetland on GHG emissions.

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Appendix 1

Table 2. Mean soil CH_4 emission rates for upland deep peat sites in GB, taken from Table 2 of Levy et al. (2012). Sites are arranged in approximate order of decreasing water table depth. Means derived from multiple measurements using static chamber methods, approximately monthly over one or more years. Only those sites with > 0.5m peat depth and with data covering all seasons are shown. Mean results from 2 years of measurements in a 'near-natural' raised bog at Flanders Moss are also shown (Yamulki et al., 2013)

Site	*Peat depth*	*Water table depth*	*Mean CH_4 flux*		*Sample size*
	m	*cm*	*nmol m^{-2} s^{-1}*	*t CO_2e ha^{-1} y^{-1}*	
Peaknaze, Peak District	2.3	15.0	5.5	0.69	249
Moor House, N. Pennines	1.5	10.3	11.3	1.43	208
Migneint A, North Wales	2.0	10.1	16.9	2.13	251
Forsinard, Sutherland	2.9	8.7	15.9	2.01	615
Migneint C, North Wales	2.0	5.8	12.7	1.60	160
Loch More, Sutherland	4.0	5.6	27.4	3.46	188
Whim, Scottish Borders	6.0	2.6	22.2	2.80	229
Flanders Moss, Stirling	>4	4.3	44.8	5.65	144

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