NRW Carbon Positive Project

Condition based estimate of greenhouse gas emissions and carbon sequestration for NRW peatland habitats

J. Williamson, A. Burden, C. Evans

Report No 276

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About this report

This report was commissioned by the NRW Carbon Positive Project to better understand the greenhouse gas emissions and carbon sequestration of deep peat habitats on the NRW-managed estate.

The information within this report has been used to inform the calculation of NRW's net carbon status and the evaluation of potential measures NRW may take forward to deliver decarbonisation in the future as part of the Carbon Positive Enabling Plan and its supporting Action Plan.

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1 Introduction

The Wales wide unified peat map (Evans et al., 2015) was developed as part of the Welsh Government funded GMEP (Glastir Monitoring and Evaluation Programme) project to quantify deep peat stocks in Wales. The unified peat map is based on BGS 1:10,000 mapping of surface deposits and the NRW Phase 1 habitat mapping of Wales. Cranfield's 1:250,000 soils mapping was not included in the Welsh peat map because of the coarse spatial scale used. The areal coverage of forested peat in Wales given in the unified peat map differs from the totals given in Vanguelova et al., (2012) because this was based on the 1:250,000 soils map, along with ground surveys. The peat map covers deep peat deposits and does not include organo-mineral soils.

The aim of this work is to use the data on peat coverage and condition compiled for the Welsh peat map to develop an understanding of carbon stocks, emissions and sequestration on NRW owned and managed landholdings. Additionally, NRW data on peatland restoration to date, areas of bare peat, and modelled outputs of the effects of drainage ditches on the hydrology of peat were incorporated into the updated mapping of peat on NRW land. Since the publication of the Welsh peat map a new report (Artz et al., 2016) for the Department for Energy and Climate Change (now the Department for Business, Energy and Industrial Strategy - BEIS) has been developed updating the emission factors for peatlands, specifically focussed on data available from UK, but augmented by data from other temperate oceanic peatlands (e.g. from Ireland) that were considered sufficiently representative for UK ecosystems. These emission factors have been incorporated into the emissions mapping for NRW peatlands in this report.

This document provides an outline and interpretation of the results given in the Excel tables supplied with the report in fulfilment of the contract reference CPPCEH001. The tables are as follows:

Final emission factors by Phase 1 habitat.xlsx – The areas under each habitat type and the most recent emission factors for each habitat type as derived from Artz et al., (2016). This also incorporates the potential reduction in emissions following peatland restoration for three scenarios.

Above and below ground carbon stocks by Phase 1 habitat.xlsx – The modelled above and below ground carbon stocks for each habitat type.

2 Habitat mapping and emissions estimates

2.1 Land use on peat

The NRW land holding information was used to extract the relevant data from the Welsh peat map (Evans et al., 2015) and the Phase 1 habitat mapping to calculate the total peatland area on NRW land holdings (Figure 1), creating the GIS layer NRW_Peat.shp.

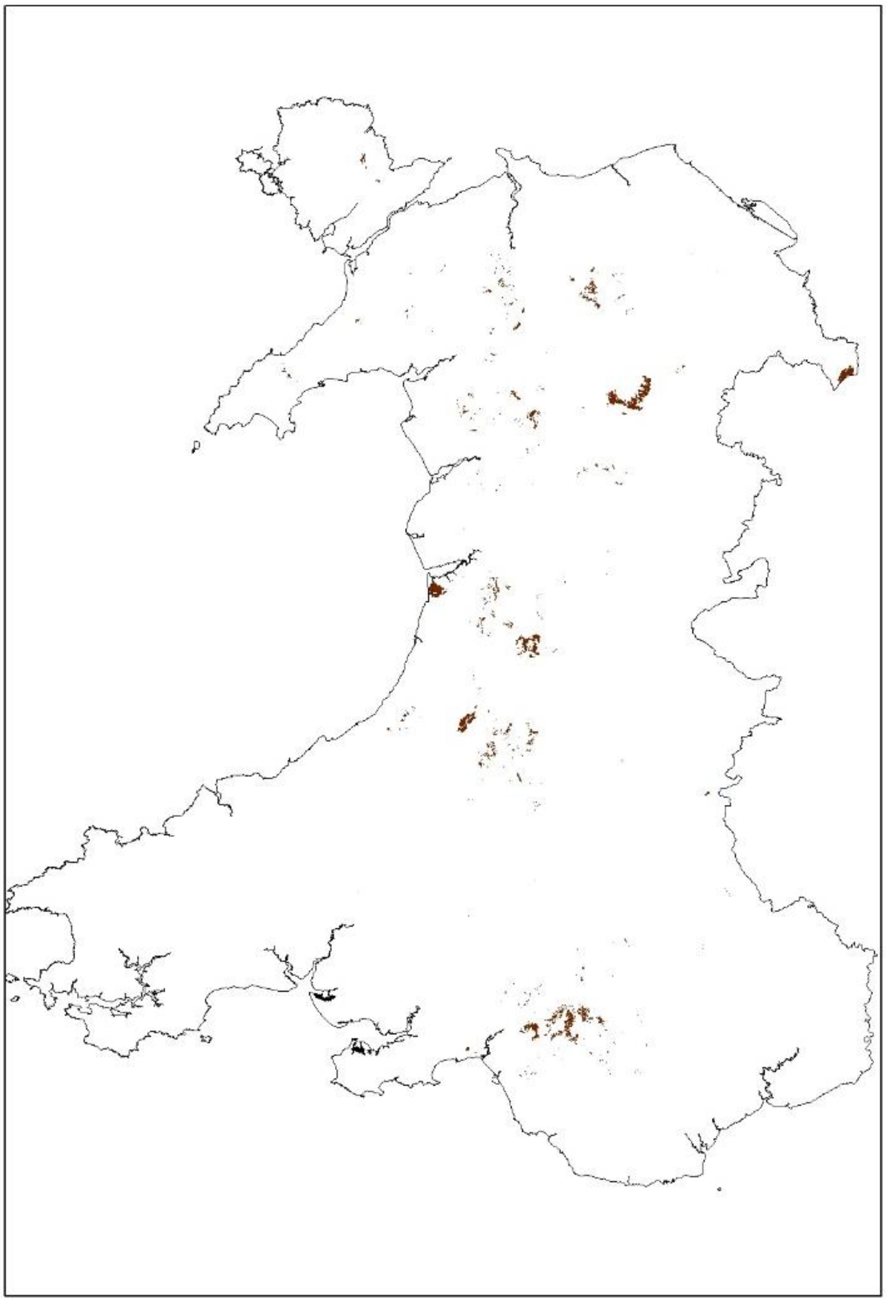

Figure 1: peat on NRW land. Derived from the Welsh peat map (Evans et al 2015). GIS layer = NRW_Peat.shp

The total peat coverage on NRW land, excluding the Phase 1 habitats that sit within larger peatland areas such as rock outcrops and open water, is 11,345 ha. Of this, the largest area is covered by conifer plantation (5,743 ha), and the second largest area is blanket bog (1,037 ha).

The percentage cover of each Phase 1 habitat type is shown in Figure 2. Although some of the labels are unclear, due to the small percentage of peatland occupied by many of the Phase 1 categories, it shows that approximately 50% of NRW land on peat is conifer plantation and that blanket bog (both near-natural and modified), raised bog and 'habitat mosaic' areas make up a further 27% of the land cover types.

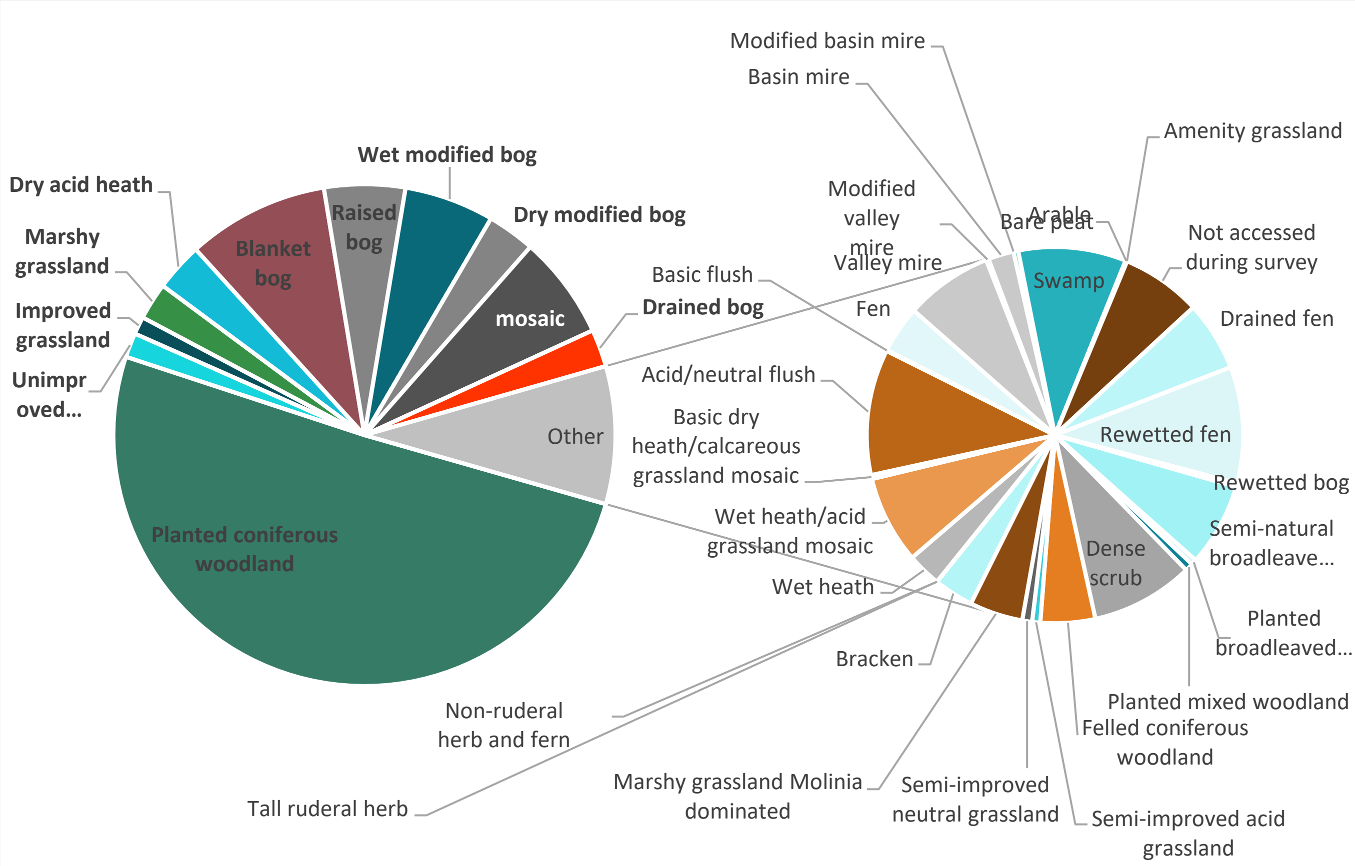

Figure 2: Land use categories on peat on NRW land. The values in the right hand chart show those areas each contributing less than 1% of the peatland area on the NRW estate.

2.2 Categorising emissions factors

The Phase 1 habitat categories were mapped to the broad habitat classification used in the development of new emissions factors (Artz et al., 2016) and are shown in Table 1. Examples of the varying broad habitat land uses on peat are shown in Figure 3. The broad habitat classifications were limited by the available data for emission factors, for example there is currently no emissions category corresponding to degraded or modified fen. Such habitats may be expected to have differing emissions factors but at the present time there is no available evidence to separate these into different categories. The Phase 1 data represents the most recent country-wide vegetation survey but dates from the early 1990s. More recent spatial data on the coverage of bare peat on the NRW estate were used to update the Phase 1 data where appropriate. In most cases these sites corresponded to bare peat in the Phase 1 survey, but there were a small number of locations where peatlands were reclassified from semi-natural blanket bog to eroding peat. This resulted in the file NRW_Phase1_Peat_BP.shp, with BP referring to the addition of the NRW bare peat information.

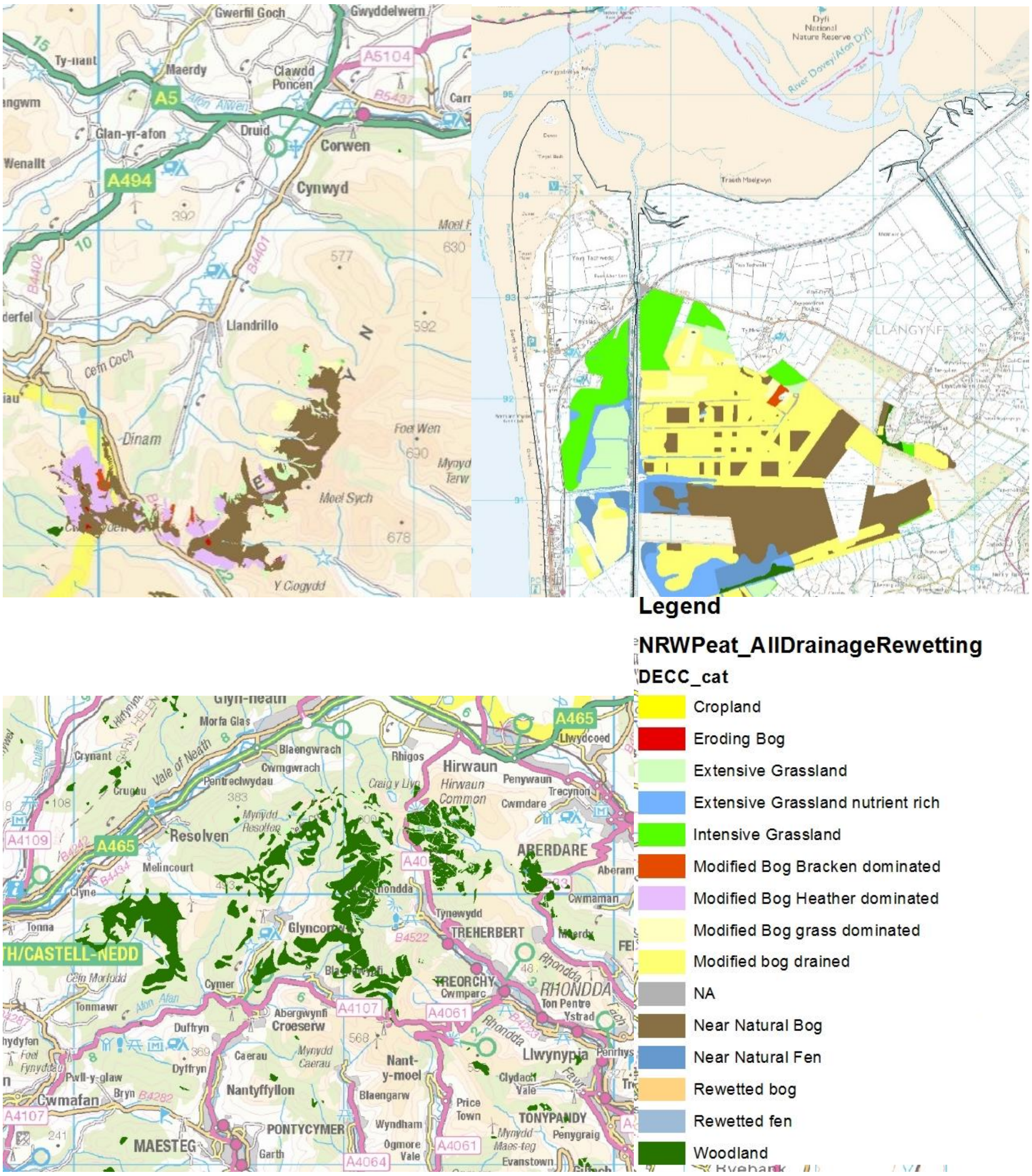

Figure 3: Examples of peatland mapped by Phase 1 habitat category inclusive of mapped drainage and rewetting effects: top left, Berwyn; top right, Borth Bog; bottom left, Afan Forest. Note the maps are different scales.

Emission factors as listed in Artz et al., (2016) were assigned to each broad habitat category for carbon dioxide (CO_2) and methane (CH_4) as well as an overall emissions estimate (t CO_2-e ha^{-1} yr^{-1}), based on IPCC AR4 100 year global warming potentials and including N_2O and fluvial carbon flux estimates. CO_2 and CH_4 emission factors were also assigned upper and lower confidence intervals but these were not available for the overall emissions estimate. Artz et al., (2016) utilised evidence from UK peatlands where available, and evidence from comparable European, oceanic peatlands where UK evidence was lacking, to ensure that emissions factors were UK relevant. It should be noted that due to a lack of evidence to date, modified bog landscapes, including wet and dry heath, are represented by a single emissions estimate, despite the likelihood that emissions will vary. The emissions from fen landscapes should also be considered as having a high level of uncertainty; a recent study (Evans et al., 2016) showed that near natural fens show net carbon uptake, meaning that we may be over-estimating carbon emissions from fens. These emission factors differ slightly from those used in the Welsh peat map and can be considered an update based on the latest evidence.

Table 1: Classification of Phase 1 habitats into the broad categories used in the development of new emissions factors by Artz et al, 2016.

Broad habitat category	Phase 1 categories included	CO_2-e emission factor (t/ha/yr)
near natural bog	Blanket bog	-0.2
	Raised bog	
	Acid/neutral flush	
modified bog - bracken dominated	Bracken	5.6
	Scattered bracken	
modified bog - grass dominated	Marshy grassland *Molinia* dominated	5.6
	Wet modified bog	
	Dry modified bog	
	Flush and spring	
	Marshy grassland *Juncus* dominated	
modified bog - heather dominated	Dry acid heath	5.6
	Dry basic heath	
	Scattered dry heath	
	Wet heath	
	Lichen/bryophyte heath	
	Dry heath/acid grassland mosaic	
	Wet heath/acid grassland mosaic	
	Basic dry heath/calcareous grassland mosaic	
	Coastal heath	
	mosaic	
bog eroding	Bare peat	5.6
near natural fen	Basic flush	3.9
	Bryophyte-dominated spring	
	Fen	
	Valley mire	
	Modified valley mire	
	Basin mire	

	Modified basin mire	
	Flood-plain mire	
	Modified flood plain mire	
extensive grassland	Acid grassland	16.5
	Unimproved acid grassland	
	Semi-improved acid grassland	
	Unimproved neutral grassland	
	Unimproved calcareous grassland	
	Marshy grassland	
	Tall ruderal herb	
	Non-ruderal herb and fern	
	Coastal grassland	
	Coastal heath/coastal grassland mosaic	
extensive grassland - nutrient rich	Semi-improved neutral grassland	25.2
	Semi-improved calcareous grassland	
	Swamp	
	Scattered swamp	
	Inundation vegetation	
intensive grassland	Improved grassland	31.9
	Amenity grassland	
	Ephemeral/short perennial	
	Gardens	
woodland	Semi-natural broadleaved woodland	11.4
	Planted broadleaved woodland	
	Semi-natural coniferous woodland	
	Planted coniferous woodland	
	Semi-natural mixed woodland	
	Planted mixed woodland	
	Dense scrub	
	Scattered scrub	
	Scattered broadleaved trees	
	Scattered coniferous trees	
	Scattered mixed trees	
	Felled broadleaved woodland	
	Felled coniferous woodland	
	Felled mixed woodland	
	Introduced scrub	
Cropland	Arable	36.6
NA	Upland species rich ledges	NA
	Standing water	
	Running water	
	Intertidal mud/sand	
	Intertidal cobbles/shingle	
	Intertidal rocks/boulders	

	Scattered salt marsh plants	
	Salt marsh	
	Mud/sand above mhw	
	Shingle/gravel above mhw	
	Rocks/boulders above mhw	
	Dune slack	
	Dune grassland	
	Dune heath	
	Dune scrub	
	Open dune	
	Hard cliff	
	Soft cliff	
	Natural rock exposure	
	Inland cliff	
	Acid/neutral inland cliff	
	Basic inland cliff	
	Scree	
	Acid/neutral scree	
	Basic scree	
	Limestone pavement	
	Other rock exposure	
	Acid/neutral rock	
	Basic rock	
	Cave	
	Quarry	
	Spoil	
	Mine	
	Refuse-tip	
	Caravan site	
	Sea-wall	
	Buildings	
	Track (not comprehensively digitised)	
	Bare ground	
	Not accessed land	
	Habitat code illegible on the original vegetation map	

2.3 Drainage and rewetting

The spatial extent of drainage on NRW land was based on the mapping of peatland drains carried out by Evans et al., (2015). A bespoke software package, PCI Geomatica, was parameterised and used to extract linear features corresponding to drainage ditches from aerial photography. This assessment covered 73% of the upland peat areas in Wales and 29% of the lowland peat areas.

To distinguish between drains that have now been blocked, or those that are still open, the most recently available mapping of blocked drainage ditches from NRW was used to cut the Wales wide ditch layer from the Welsh peat map, thus providing an estimate of open and blocked drainage ditches. To estimate the effect of drainage ditches on surrounding peat, modelling outputs from Low and Baird (2014) were closely examined and, in conjunction with a previous review of hydraulic conductivity measurements on peatlands (Evans et al., 2014), it was concluded that the mid-range hydraulic conductivity model inputs used by Low and Baird provided the most realistic estimate of blanket bog hydraulic conductivity. The model outputs suggest that the presence of drainage ditches running parallel to the contour results in a water table drawdown area extending 5 m upslope of the ditch and 15 m downslope of the ditch. This gives essentially the same estimate of overall drained area as the fixed 10 m buffer either side of drainage ditches applied by Evans et al., (2014). Due to the limitations of the elevation data available to this project (50 m resolution) it was not considered realistic to use these data to make the effects of up- and down-slope drainage spatially explicit, therefore the 10 m radius for upland peat was retained as the most pragmatic solution given the data and evidence available. As lowland raised bog and fen peats typically have hydraulic conductivity values orders of magnitude higher than blanket peats (Evans et al., 2014) the higher drainage radius of 50 m as used in the Wales wide mapping was also retained for this study for this habitat type. Refined drainage extents could be applied to either upland or lowland peat areas if improved empirical or modelling data become available in future, particularly in relation to changes in peat morphology in response to drainage such as cracking or the development of peat pipes, which has not been accounted for in this work because of a lack of available data.

Table 2: Modification of Phase 1 categories to allow for the effects of drainage and rewetting.

Initial Phase 1 category	Post drainage DECC category	Post rewetting DECC category
Blanket Bog	Modified bog – heather dominated	Rewetted bog
Raised Bog	Modified bog – heather dominated	Rewetted bog
Acid/neutral Flush	Modified bog – heather dominated	Rewetted bog
Grass Dominated Bog	Modified bog – heather dominated	Rewetted bog
Basic flush	Extensive grassland – nutrient rich	Rewetted bog
Bryophyte-dominated spring	Extensive grassland – nutrient rich	Rewetted bog
Fen	Extensive grassland – nutrient rich	Rewetted fen
Valley mire	Extensive grassland – nutrient rich	Rewetted fen
Modified valley mire	Extensive grassland – nutrient rich	Rewetted fen
Basin mire	Extensive grassland – nutrient rich	Rewetted fen
Modified basin mire	Extensive grassland – nutrient rich	Rewetted fen
Flood-plain mire	Extensive grassland – nutrient rich	Rewetted fen
Modified flood plain mire	Extensive grassland – nutrient rich	Rewetted fen
Improved grassland	NA - habitat considered drained	Rewetted fen
Marshy grassland	NA - habitat considered drained	Rewetted fen
Dry heath	NA - habitat considered drained	Rewetted bog
Amenity grassland	NA - habitat considered drained	Rewetted fen
Gardens	NA - habitat considered drained	Rewetted fen

Within the modelled areas of drainage around the ditches, the Phase 1 habitats were modified to a drained bog category (see Table 2) if the initial Phase 1 category was blanket bog, raised bog, acid/neutral flush or grass dominated bog. If the initial Phase 1 category was any of those categorised as near-natural fen, it was modified to a drained fen category. The drained modified bog areas were given the emission factor corresponding to modified heather dominated bog, and drained fen areas were given the emission factor corresponding to extensive grassland – nutrient rich (note that 'nutrient rich' and 'nutrient poor' refer to fen and bog peat respectively, according to the IPCC's terminology, rather than levels of artificial nutrient enrichment). The decision to modify these areas to these specific categories was led by the lack of published research on GHG emissions from drained fens supporting semi-natural vegetation. All other habitats (woodland, grassland etc.) were considered to be drainage modified in some way already. This does not take into account areas of naturally wet woodland. If more detailed surveying of such areas becomes available and studies of greenhouse gas emissions from wet woodland on peat allow specific emission factors to be developed then this should be revisited to address this limitation.

The peat area that has been rewetted to date was calculated using the same radii of influence as for the drainage affected peat. Peat on all habitats except woodlands in the area subject to rewetting was given emission factors for rewetted fen or bog depending on the starting habitat – nutrient rich grasslands were considered to revert to rewetted fen, while all modified bog habitats were considered to revert to rewetted bog.

Table 3: Drained and rewetted peat by Phase 1 category.

	Phase 1 category	Area (ha)
Drained Bog	E.1.6.1	19
	E.1.6.2	198
	E.1.7	40
	E.1.8	1.8
	E.2.1	5.2
	mosaic	9.4
Drained Fen	E.3	2.2
	E.3.1	20.6
	E.3.2	0.1
	F.1	37.5
Rewetted Bog	B.5	2.9
	D.1.1	<0.01
	E.1.6.1	0.2
	E.1.8	0.1
Rewetted Fen	B.4	8.4
	E.3.1	92
	E.3.2	0.01

Using the default drainage estimates, as explained above, gives a total area of unrestored drainage-affected bog of 274 ha (based on the drainage buffer widths described above) and unrestored drainage-affected fen of 60 ha (recoded from Phase 1 habitat to DR_BOG and DR_FEN respectively in the shapefile NRWPeat_AllDrainageRewetting.shp.). This value is subject to the caveats raised in

Evans et al (2015) regarding the accuracy of ditch mapping, for example ground truthing of areas suggests that mapping from aerial photography is approximately 75% accurate (Jones pers. comm.). Using the currently available digitised data from NRW, restoration efforts to date are estimated to have rewetted 100 ha of drainage-affected fen and 3 ha of drainage-affected bog on NRW land. This does not include any ditch blocking work undertaken in woodland habitats, as there is not the information available currently to ascertain whether the ditch blocking has resulted in a change from woodland towards blanket bog or fenland vegetation. This figure is known to be an under-estimate of the true extent of rewetting on peatlands on the NRW estate, as a number of projects have not had the spatial extent of ditch blocking centrally digitised and made available to wider projects. This value can be refined in future as further information becomes available on the extent of restoration projects. The area of peatland recategorised as drained or rewetted is shown by Phase 1 habitat in Table 3.

Mapping of drainage ditches, as carried out in Evans et al., (2015), covered 73% of the Welsh upland peat and 29% of Welsh lowland peat. As a result of this, the estimate above of drainage affected area is based on the mapped areas only, meaning that the total peatland area affected by drainage will be greater. When the total area of peatland on NRW land inside and outside the area of mapped drains was compared, 70% of NRW's peatland fell within the mapped area. The split by habitat coverage was not equal between all habitat types, for example all cropland on NRW land was outside the area mapped for drainage ditches (although this does only cover 1.2 ha). 75% of non-forested NRW land on peat was within the area mapped for drainage, meaning that the majority of NRW land has drainage estimates spatially included in this study. The assumptions were made that the peatland that had not been mapped had a similar concentration of drainage ditches to the mapped areas and that all modified habitat had been affected by drainage to some extent already. Estimates of the additional areas of near natural bog and fen habitat affected by drainage beyond the current spatial extent of mapping were carried out as described below.

11% of near-natural blanket bog and 22% of near-natural fen is outside the ditch-mapped area. Using the estimate that 1.6% of the near-natural bog within the tiles is drainage-affected (based on the estimated of drainage extent around ditches, as described above), this gives an additional 3.7 ha of near-natural bog subject to drainage that is not accounted for in the emissions totals. An estimated 18% of the near-natural fen within the tiles has been drainage-affected, which gives an extra 11.6 ha of near-natural fen that is actually subject to drainage. If the bog peat has higher hydraulic conductivity than the values used in the modelling work by Low and Baird, the extent of drainage effects on near natural blanket bog will also be higher. The potential under-estimation of the spatial extent of near natural fen and bog affected by drainage also means that the estimation of greenhouse gas emissions from peat on the NRW estate may be an under-estimate. If future funding becomes available to extend the mapping of drainage ditches to the full extent of peat in Wales then these under-estimates can be rectified. The final file of peat coverage on NRW land that accounts for the presence of mapped drainage ditches and mapped rewetting projects is NRWPeat_AllDrainageRewetting.shp.

2.4 Greenhouse gas emissions

When CO_2 and CH_4 are considered separately, blanket bogs on NRW land sequester 718 t CO_2-C yr^{-1}, with lowland raised bogs sequestering a further 414 t CO_2-C yr^{-1}. The largest emission of CO_2 comes from forestry plantation, which is estimated to emit 11,500 t CO_2-C yr^{-1}. Over all of the peatlands on NRW land there is a net CO_2-C emission of 13,000 t CO_2-C yr^{-1}, which is driven by the large area of land under conifer plantation. If the land area under conifer plantation is excluded NRW land holdings emit approximately 1500 t CO_2-C yr^{-1}, although this may be an over-estimate based on emissions from near natural fens.

Methane emissions, in contrast, are highest from blanket bogs with almost 97 t CH_4-C emitted per year. Raised bogs contributed the second largest emissions of methane at 55 t CH_4-C yr^{-1}, and due to the large area of conifer methane emissions from conifer plantation were 24 t CH_4-C yr^{-1}. Total methane emissions from NRW peatlands were calculated at 369 t CH_4-C yr^{-1}.

Excluding potential emissions from open water environments mapped as peat, the present day estimated GHG emissions, based on IPCC AR4 100 year global warming potentials, from peat on NRW land is 100 kt CO_2-e yr^{-1} with 65 kt CO_2-e yr^{-1} emitted from conifer plantations, and 34 kt CO_2-e yr^{-1} from all other habitats.

When considering the GHG emissions from peat soils on NRW landholdings it should be taken into account that CO_2-e emission factors developed by Artz et al., (2016) include nitrous oxide (N_2O) emissions, fluvial fluxes of dissolved organic carbon (DOC) and fluxes of CH_4 from drainage ditches.

Within the results tabulation of GHG fluxes from NRW peatlands columns N:S show the upper and lower confidence intervals of the total CH_4 and CO_2 fluxes from NRW landholdings on peat. These are calculated based on the upper and lower intervals of the emissions factors and the land area in each habitat type.

2.5 Mitigation potential

Three potential scenarios were chosen as examples of the mitigation potential of NRW's peatlands. The first scenario was that all peatland areas would be restored to rewetted fen or bog (scenario 1), the second was that all peatland areas except those currently under woodland, cropland or intensive grassland would be restored to rewetted fen or bog (scenario 2) and the third, least wide-ranging scenario was that all drained fen and bog would be restored to rewetted (scenario 3).

If scenario 1 was achieved and all peatland on the NRW estate was to be rewetted and converted to fen or bog as appropriate for the site, GHG emissions are estimated to fall by 79 kt CO_2-e yr^{-1} to 21 kt CO_2-e yr^{-1}. If all areas were to eventually revert to emissions similar to near natural bog and fen then GHG emissions would fall further, to 1.5 kt CO_2-e yr^{-1}, which can be considered the natural baseline. This baseline flux is positive due to the natural emission of methane from wetland ecosystems. The further large decrease is a result of the difference between rewetted and near-natural emission factors. This baseline should be considered a hypothetical minimum given current emission factors rather than a scenario that will occur after a certain number of years because there isn't a fixed timescale of restoration (for example it is dependent on interventions carried out and the degree of habitat degradation) and it isn't known whether rewetted peat habitats will return to baseline emissions. Table 4 shows the maximum potential emissions reductions by Phase 1 habitat under scenario 1.

If scenario 2 was achieved then GHG emissions from NRW peat would be an estimated 82 kt CO_2-e yr^{-1}, a reduction of 18 kt CO_2-e yr^{-1}. This is largely due to the emissions from conifer plantation on peat, which would remain at 65.5 kt CO_2-e yr^{-1}. If scenario 3 was achieved it would result in the smallest estimated emissions reduction, with annual emissions of 98 kt CO_2-e yr^{-1}, a reduction of approximately 2 kt CO_2-e yr^{-1} from present day emissions. It should be noted that these estimates are reliant on the accuracy of ditch extent and restoration mapping, and as such may under- or over-estimate current emissions.

Table 4: Maximum potential emissions reduction under scenario 1 – restoration to rewetted fen or bog.

Phase 1 name	**Peat area (ha)**	**Potential restoration category**	**current emission factor CO2-e (t CO2-e ha^{-1} yr^{-1})**	**restored emission factor CO2-e (t CO2-e ha^{-1} yr^{-1})**	**Potential emissions reduction per ha CO2-e (t CO2-e ha^{-1} yr^{-1})**	**Total potential emissions reduction CO2-e (t CO2-e yr^{-1})**
Semi-natural broadleaved woodland	71.86	rewetted fen	11.4	7.8	3.6	259
Planted broadleaved woodland	4.62	rewetted fen	11.4	7.8	3.6	17
Planted coniferous woodland	5742.66	rewetted bog	11.4	1.7	9.7	55700
Planted mixed woodland	6.98	rewetted bog	11.4	1.7	9.7	68
Dense scrub	88.79	rewetted bog	11.4	1.7	9.7	861
Felled coniferous woodland	47.27	rewetted bog	11.4	1.7	9.7	459
Unimproved acid grassland	178.78	rewetted bog	16.5	1.7	14.8	2650
Semi-improved acid grassland	6.99	rewetted bog	16.5	1.7	14.8	104
Semi-improved neutral grassland	8.50	rewetted bog	25.2	1.7	23.5	200
Improved grassland	129.41	rewetted fen	31.9	7.8	24.1	3120
Marshy grassland	270.20	rewetted fen	16.5	7.8	8.7	2350
Marshy grassland Molinia dominated	46.09	rewetted fen	5.6	7.8	-2.2	-101
Bracken	34.35	rewetted bog	5.6	1.7	3.9	134

Tall ruderal herb	0.03	rewetted fen	16.5	7.8	8.7	0.3
Non-ruderal herb and fern	0.08	rewetted fen	16.5	7.8	8.7	0.7
Dry acid heath	352.20	rewetted bog	5.6	1.7	3.9	1370
Wet heath	29.40	rewetted bog	5.6	1.7	3.9	115
Wet heath/acid grassland mosaic	75.85	rewetted bog	5.6	1.7	3.9	296
Basic dry heath/calcareous grassland mosaic	3.39	rewetted bog	5.6	1.7	3.9	13
Blanket bog	1026.90	NA	-0.2	-0.2	NA	NA
Raised bog	591.67	NA	-0.2	-0.2	NA	NA
Wet modified bog	656.42	rewetted bog	5.6	1.7	3.9	2560
Dry modified bog	350.08	rewetted bog	5.6	1.7	3.9	1370
Acid/neutral flush	108.71	NA	-0.2	-0.2	NA	NA
Basic flush	0.78	NA	3.9	3.9	NA	NA
Fen	40.76	NA	3.9	3.9	NA	NA
Valley mire	75.81	NA	3.9	3.9	NA	NA
Modified valley mire	2.19	NA	3.9	3.9	NA	NA
Basin mire	22.06	NA	3.9	3.9	NA	NA
Modified basin mire	0.11	NA	3.9	3.9	NA	NA
Bare peat	16.20	rewetted bog	5.6	1.7	3.9	63.2
Swamp	93.09	rewetted fen	25.2	7.8	17.4	1620
Arable	1.21	rewetted fen	36.6	7.8	28.8	35
Amenity grassland	0.18	rewetted fen	31.9	7.8	24.1	4.4
mosaic	754.84	rewetted bog	5.6	1.7	3.9	2940
Not accessed during survey	68.18	rewetted bog	5.6	1.7	3.9	266
Drained fen	60.41	rewetted fen	25.2	7.8	17.4	1050
Rewetted fen	100.51	NA	7.8	7.8	NA	NA
Drained bog	273.95	rewetted bog	5.6	1.7	3.9	1070
Rewetted bog	3.21	NA	1.7	1.7	NA	NA

3 Above and below ground carbon stocks

3.1 Below ground

In contrast to the mapping of land use and emissions from peatlands in the above section, the work on below ground carbon stocks uses a 50 m grid Digital Elevation Model of the UK as its base. This raster approach results in some small differences in area because of the relatively coarse scale grid used. The modelling approach used in this report is that developed for the SNPA Peatland Strategy (Burden et al., 2016). In order to estimate peat carbon stocks within the study area, peat depth was modelled using equations taken from Holden and Connolly (2011), based on a study of peat depth in the Wicklow Mountains, Ireland (an area located at the same latitude as Snowdonia, and with a similar range of topography and altitude). Main input parameters in this model are maximum theoretical peat depth at a given elevation and angle of slope:

$$\textit{Equation 1: } Depth = (e^{-a*slope}) * D_{max}$$

Although other peat depth models have been developed which include other explanatory factors such as elevation (e.g. Parry et al., 2012), the relationship between peat depth and elevation appears to be region-specific, and this approach was found to be ineffective for Snowdonia, where deep peats occur in both upland and lowland situations, and the same problems would arise at an all-Wales scale. For this we modified the equation of Holden and Connolly (2011) by constraining the maximum depth (D_{max}) to 300 cm across all altitudes and used a multiplier of -0.189 for slope, based on calibration of the model to Welsh peat-depth data. Measurements of peat depth in semi-natural areas using datasets from both CEH and NRW were used as the base measurements against which the goal seeking approach was applied. Goal seeking using average peat depths in 1 hectare units suggested that these values gave the lowest error estimate (calculated by using the root-mean-square deviation, or RMSE, which is an unbiased estimator of variance) across all sites with available in-situ measurements of peat depth.

To account for disturbance, separate correction factors were then applied for land-use change and drainage. These were both derived from a detailed post-drainage subsidence study by Shotbolt et al., (1998). This study suggested that, over a 30 year period following drainage of a Scottish blanket bog for forestry, subsidence rates within the forest averaged around 20 mm yr^{-1}. In areas outside the forest but still affected by drainage, subsidence rates were lower, in the region of 5 mm yr^{-1}. To model changes in peat depth we assumed that the former subsidence rate (which is similar to - albeit somewhat lower than - those observed in peatlands drained for agriculture elsewhere) would apply to all areas now under forestry or improved grassland. A similar, but lower, rate of subsidence of 10 mm yr^{-1} was applied to areas of semi-improved grassland. For other areas of peat within 10 m of a mapped drain, we applied the lower rate of 5 mm yr^{-1}. As a first assumption, all land-use changes were assumed to date from 1970, giving a total reduction in peat depth (to date) of 90 cm for peat under forest or improved grassland, 45 cm under semi-improved grassland and 20cm for drained semi-natural peat. Both of these correction factors were given a limit so that if the estimated peat depth fell below 5 cm, a 5 cm depth was recorded to avoid negative peat depth estimates. The resulting file is NRW_PeatDpthF.adf.

To calculate peat carbon stocks, peat depth was multiplied by an estimate of its bulk density and its carbon content, using equations in Lindsay (2010) (Equation 2).

Equation 2: $\mathrm{Cstock} = 10 * \mathrm{depth} * \mathrm{bulk\ density} * \mathrm{fraction\ OM} * \mathrm{Proportion\ C}$

The fraction of peat that is organic matter was taken as 0.94, and the proportion of organic matter that is carbon was taken as 0.5, both from Lindsay (2010). The outputs of equations 2 and 3 are NRW_carbon.adf and NRW_BD.adf respectively.

In a previously published study based at Plynlimon in mid Wales and Glensaugh in eastern Scotland Frogbrook et al., (2009) showed that peat bulk density was negatively correlated with peat depth (Figure 4). From soil core measurements taken from both sites a relationship between total peat depth and bulk density was developed (Equation 3). The mean of up to three bulk density measurements for each core was taken as the mean bulk density, with shallower cores only using one or two measurements depending on peat depth. This approach includes the observation that degraded, shallower peats often have higher bulk density as a result of compaction.

Equation 3: $\mathrm{bulk\ density} = 0.7005 * \mathrm{peat\ depth}^{-0.347}$

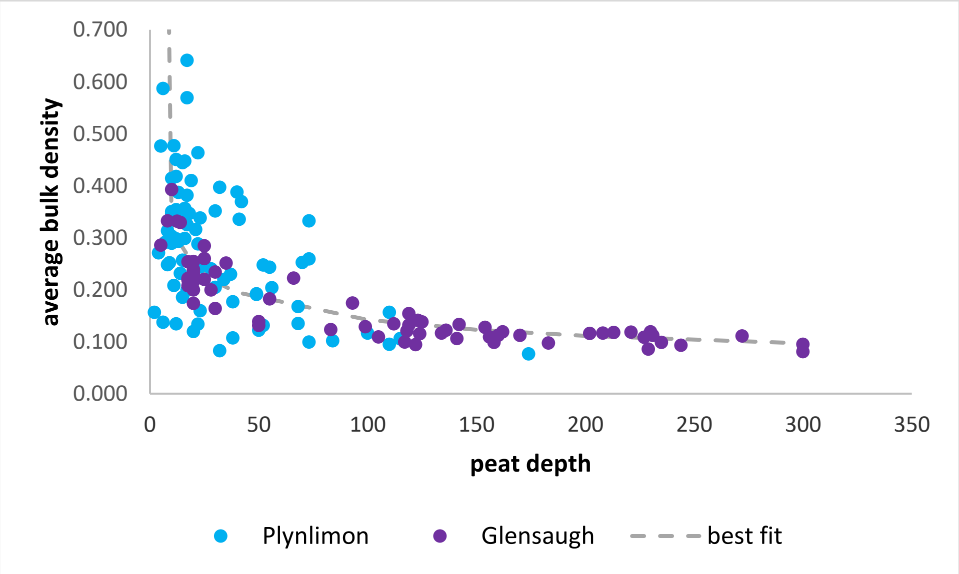

Figure 4: Average bulk density values from peat soils of varying depths at Plynlimon and Glensaugh. Samples were taken from a maximum of three depths: 0-15 cm, 15-30 cm and 50-65 cm per core (see Frogbrook et al 2009 for details). $R^2 = 0.57$

3.2 Above ground

Carbon stocks in vegetation were modelled from biomass data measured during a recent NERC Macronutrients project (Smart et al., pers comm) for all sites except fens. The NERC funded Macronutrients work was developed to progress current understanding of cycling of carbon, nitrogen and phosphorus in natural terrestrial, biological and freshwater systems. Fen biomass estimates were taken from Menichino et al., (2016), which were measured as part of the EU Life funded project on the Anglesey and Llyn fens and part-funded by NRW. Phase 1 habitats were mapped to available data as in Table 5.

Table 5: Habitat types used for the carbon stocks in biomass modelling.

Broad habitat type	Phase 1 categories	Citation for data	Above ground biomass (kg ha^{-1})
Fen	Fen	Menichino et al (2016)	8,640
	Valley mire		
	Modified valley mire		
	Basin mire		
	Modified basin mire		
	Bare peat		
	Swamp		
	Marshy grassland		
Broadleaf woodland	Semi-natural broadleaved woodland	Smart et al (pers comm)	146,593
	Planted broadleaved woodland		
	Dense scrub		
Conifer	Planted coniferous woodland	Smart et al (pers comm)	301,680
	Planted mixed woodland		
	Felled coniferous woodland		
Acid grassland	Unimproved acid grassland	Smart et al (pers comm)	4,367
	Bracken		
	Non-ruderal herb and fern		
	Wet heath/acid grassland mosaic		
Blanket bog heather dominated	Dry acid heath	Smart et al (pers comm)	5,217
	Wet heath		
	Basic dry heath/calcareous grassland mosaic		
	Wet modified bog		
	Dry modified bog		
	Mosaic		
	Not accessed during survey		
	Marshy grassland *Molinia* dominated		
	Blanket bog		

	Raised bog		
Soligenous mire and flush	Acid/neutral flush	Smart et al (pers comm)	1,273
	Basic flush		
Improved grassland	Improved grassland	Smart et al (pers comm)	8,065
	Arable		
Semi-improved grassland	Semi-improved acid grassland	Smart et al (pers comm)	9,447
	Semi-improved neutral grassland		

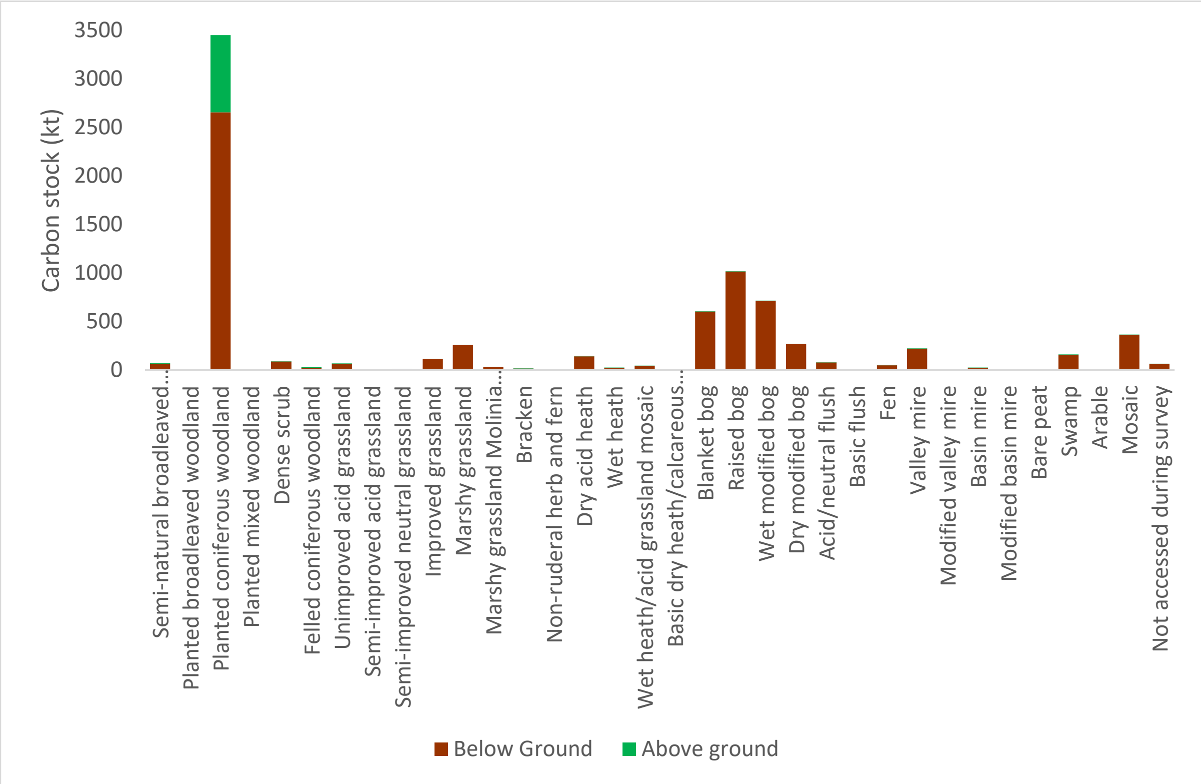

Figure 5: Above and below ground carbon stocks by Phase 1 category.

Total below ground carbon stocks on NRW land were modelled at 7078 kt. It should be noted that this value is based on modelled data and has not been ground truthed. Differences in the bulk density in particular will have large effects on the carbon stocks in peat. Areas of peat shown as being on land categories that were not likely to be compatible with peat, such as rock outcrops and lakes, were removed from this calculation. Modelled carbon stocks in above ground vegetation are very much smaller, at 829 kt, of which 803 kt are conifer forest biomass. Above and below ground carbon stocks split by Phase 1 habitat are shown in Figure 5. As conifer plantation covers the largest land area, the modelled below ground carbon stocks under planted conifer are the highest of any Phase 1 category. Above ground biomass carbon stocks have been estimated for woodland for completeness, but these estimates are from a single study and do not specifically cover felled plantation forestry, differing forest yield classes, or land management.

4 Conclusions

Around 50% of the peat area on NRW land is under conifer plantation. A further 30% is covered by near-natural or modified bog habitat. Current emissions estimates from peat on NRW land suggest that they are a net source of greenhouse gas emissions of 100 kt CO_2-e yr^{-1}, with approximately two thirds of emissions (CO_2-e yr^{-1}) from conifer plantation. NRW peatlands emit 11,500 t CO_2-C yr^{-1} and 369 t CH_4-C yr^{-1}. Current carbon stocks in peat on NRW land are modelled to be in the region of 7,000 kt. Restoration of all peatland areas to rewetted fen or bog could reduce emissions from NRW peatlands by approximately 78 kt CO_2-e yr^{-1}.

Recommendations for future work include the completion of mapped drainage on peat in Wales, using the aerial photography methodology developed by BGS to give a Wales wide dataset of drainage, and completing the digitisation of restoration projects in Wales to allow the calculation of emissions from all restored sites. Further work to quantify how peat morphology changes following drainage would improve the estimates of the extent of drainage impacts on peat. Other work that would be beneficial is the monitoring of GHG emissions and fluvial carbon losses from degraded blanket bog ecosystems so that separate emissions factors for these habitats can be developed.

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6 Appendices

Appendix 1: step by step procedure for the peat mapping exercise

Peat area and GHG emissions

clip the NRW land holding map to the Welsh peat outline

calculate new area of land

clip the Welsh peat Phase 1 habitat survey to the NRW peat outline

delete unwanted fields

calculate new area of land

add in the bare peat layer

clip the Phase 1 layer to the bare peat layer

change the reclass field to 3 (bare or eroding peat) and phase 1 code to E.4

Update the Phase 1 layer with the bare peat information

clip the BGS ditch map to the NRW peat outline

clip the NRW blocked ditch map to the NRW peat outline

recalculate the length of the ditches

Snap the NRW ditches to the BGS ditches

add fields for emission factors to original Phase 1 map

fill in all of the columns for each Phase 1 category

find out how much NRW land is covered by the BGS tiles

find out how much land ISN'T covered by the BGS tiles

recalculate areas

summarise areas by Phase 1 classification

erase the blocked ditches from the open ditches

erase the upland boundary layer from the ditch layer to get lowland ditches

put a 50 m boundary around the ditches

Use the 50 m buffer to clip the Phase 1 shapefile

clip new ditch layer to the upland boundary to create 10m upland drainage boundary

draw a 10 m buffer around the ditches

Use the 10 m buffer to clip the Phase 1 shapefile

change the classification to drained if semi natural (1,2,4,5) all other sites deemed drained already

Update the original land use layer with the drained EFs

recalculate areas

```
# Recalculate the areas of each Broad habitat type inside the tiles to look at what % of the area is affected.
# finding out how much NRW land is covered by the BGS tiles
# recalculate areas
# calculate the area.
# Use the blocked ditches layer to split into upland and lowland and provide the same 10/50 m buffer.
# Give rewetted EFs to all areas?
# erase the ditch layer to get lowland ditches
# put a 50 m boundary around the ditches
# Use the 50 m buffer to clip the Phase 1 shapefile
# clip new ditch layer to the upland boundary to create 10m upland drainage boundary
# draw a 10 m buffer around the ditches
# Use the 10 m buffer to clip the Phase 1 shapefile
# change the classification to rewetted if semi natural (1,2,4,5,8,10,13)
# Update the original land use layer with the rewetted EFs
# calculate the area.
```

Carbon stocks

```
# Using the DEM to calculate slope and as an input to calculating peat depth and carbon stocks.
# create slope from DEM
#
#
#Edit the depth raster to account for the differing land use practices 90 cm reduction for forest, crop + imp grass, 45 cm for semi-imp grass and 20 for drained peat
# create layers of just each of the different landuses to use as a cookie cutter.
# Write the selected features to a new featureclass
#Write the selected features to a new featureclass

# Cut out the raster with the shapefiles to change the peat depth
# modify the peat depth in the extracted rasters
# Cut the UK peat depth raster to the shape of the NRW peat layer
#merge the rasters together
DepthRaster = Raster("NRW_PeatDpthF")
```

```
NRW_BD = 0.7005 * Power(DepthRaster, -0.347)
NRW_BD.save("P:/NRW_Peatland_Accounting_NEC05964/Data/GIS/NRW_BD")
outCarbon = 10 * Raster("NRW_PeatDpthF") * Raster("NRW_BD") * 0.94 * 0.5
outCarbon.save("P:/NRW_Peatland_Accounting_NEC05964/Data/GIS/NRW_carbon") # values in kg/m2
# to calculate the sum of carbon in each habitat type I need to have a new raster that has the C stock values in each 50*50 grid cell.
sumCarbon = Raster("outCarbon") * 50 * 50
sumCarbon.save("P:/NRW_Peatland_Accounting_NEC05964/Data/GIS/NRW_sumCarbon") # values in kg/grid cell
# Zonal stats to get the total carbon stocks for each habitat type
```

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