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GLASTIR MONITORING & EVALUATION PROGRAMME

FINAL REPORT – Annex 15

Mapping the extent and condition of Welsh peats

Chris Evans[1], Barry Rawlins[2], Stephen Grebby[2], Paul Scholefield[1] and Pete Jones[3]

[1]Centre for Ecology & Hydrology, [2]British Geological Survey, [3]Natural Resources Wales

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CYNGOR YMCHWIL YR AMGYLCHEDD NATURIOL

Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

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Table of Contents

Summary

Peatlands (defined here as deep (=/>0.4 m) peat soils and supporting both mire habitats and other habitat/land-use types) cover 4.3% of Wales, and represent Wales' largest terrestrial ecosystem store of carbon, as well as important reservoirs of biodiversity. In their natural state they have the potential to contribute to climate regulation through ongoing CO_2 sequestration. However, Welsh peatlands have been detrimentally impacted by centuries of human activity including drainage, over-grazing and conversion to grassland and forestry. As a result Welsh peatlands are currently thought to act as a source of greenhouse gas (GHG) emissions. Measures supported through Glastir, as well as other land management and conservation intervention mechanisms, aim to reduce these emissions, and to restore the carbon sequestration function of Welsh peatlands, through a reduction in land-use pressures and improved management on a range of both upland and lowland bogs and fens.

The work described in this report was undertaken as part of the Glastir Monitoring and Evaluation Programme (GMEP) in order to provide improved data on the extent and condition (in terms of broad habitat cover and drainage, as opposed to the nature conservation definition) of Welsh peatlands, as the basis for i) prioritising areas for restoration; ii) monitoring long-term change in the status of the Welsh peat resource, and iii) estimating current greenhouse gas (GHG) emissions from Welsh peatlands as the result of drainage and land-use change, and iv) estimating the future climate mitigation potential of peat restoration. Specific tasks undertaken were: 1) the creation of a single, 'unified' peat map of Wales, as the basis for further assessment; 2) an assessment of current land cover on peat based on best available data, as well as aspects of land-ownership and conservation designation relevant to the future prioritisation and funding of restoration measures; 3) the creation of a new, detailed map of the occurrence of drainage ditches on peat, focusing on upland blanket bog; 4) the creation of a new map of the occurrence of *Molinia caerulea* (purple moor grass), the encroachment of which is believed to have had a detrimental impact on large areas of Welsh blanket bog; and 5) the production of new, spatially detailed estimates of GHG emissions resulting from human modification of Welsh peatlands.

Key results of the work undertaken include the following:

- Based on the new unified Welsh peat map, peatlands are estimated to cover over 90,000 ha of Wales (4.3% of the total land area) of which 75% is in upland areas, and 25% in lowland areas
- Digital processing of aerial photographs, extrapolated to the full peat area, suggests that there are at least 3000 km of drainage ditches on peatland in Wales (excluding ditches under forestry, which could not be mapped from air photos). Of the total ditch length, approximately two thirds was estimated to be in the uplands, and one third in the lowlands. Given the difference in the proportion of each area mapped, estimates of ditch length in the uplands have a lower uncertainty than those for the lowlands.
- Overall, at least three quarters of the Welsh peatland area is thought to have been impacted by one or more land-use activity, including drainage, overgrazing, management neglect, conversion to grassland and afforestation.
- Evidence of *Molinia* encroachment was recorded from aerial photographs across large areas of Welsh peat, with the highest density in the Cambrian mountains of Mid-Wales.

- As a result of these activities, Welsh peatlands are currently estimated to be generating anthropogenic emissions of around 400 kt CO_2-equivalents per year (equating to around 7% of all Welsh transport-related emissions). These emissions estimates are however based on a very limited set of primary field measurements of GHG fluxes, including many made outside the UK, and are therefore subject to considerable uncertainty.
- For a 1990 baseline year, 58% of peatland GHG emissions are believed to have derived from areas under agricultural grassland management, with a further 17% from conifer plantations, and 15% from drained or modified blanket bog. Subsequent restoration activities and agri-environment measures are believed to have substantially reduced total emissions from upland blanket bog, but other emissions are thought to have remained fairly static.

Task 1. Creation of a unified peat map

To undertake an assessment of broad peat condition across Wales it was necessary to establish the full extent of both lowland and upland peat. We initially collated all the primary strategic datasets concerning peat distribution across Wales from several sources, including the Soil Survey of England and Wales (SSEW) data from Cranfield University (1:250 000 scale). Part of the mapping of peat soils for the SSEW was based on landscape interpretation rather than walkover surveys and we considered there was potential for small areas of peat to be omitted from the data. Additionally, the approach of aggregating soils into large Associations, delineated as polygons (i.e. areas with one dominant soil type, but containing subsidiary Soil Series) tends to increase the apparent area of peat in areas where it is the main soil type (e.g. upland blanket bogs containing smaller areas of other soils, which are mapped as a single 'peat' Association) whereas it decreases the apparent area of peat in areas where it is a smaller component of the landscape (e.g. lowland areas where small areas of peat occur within larger areas of mineral soil). Whilst this approach provides a pragmatic means to represent heterogeneous soils at a broad spatial scale, it is prone to misinterpretation, and problematic for peat condition assessment because the location of peat units within larger Soil Associations is unknown, and land-use/condition data cannot therefore be overlaid.

We compared the SSEW peat data with the Welsh peat polygons of the British Geological Survey (BGS), which were mapped at a higher resolution, and based on more comprehensive ground-based surveys. We observed that the anticipated under-representation of small (lowland) peat units and possible over-representation upland peats was indeed evident in the SSEW dataset, when compared to the BGS dataset, particularly in areas of north and west Wales. We therefore took the decision to combine the following datasets to form a 'unified' peat map: i) BGS surface peat, ii) soil mapping derived from the recent digital capture of Forestry Commission Wales paper survey records by the FC Mapping and Geodata Unit, with soil codes 8a to 14w inclusive being taken as indicative of peats > 45 cm thickness (Pyatt, 1982; Kennedy, 2002), iii) the boundary of deep (>0.5 m) peat determined during the ground-based survey of lowland peatland sites included in the CCW/NRW Lowland Peatland Survey of Wales programme (Jones *et al*., 2011; Bosanquet *et al*., 2013) iv) habitat polygons indicative of deep (=/>0.5 m) peat presence (i.e. all E class with the exception of E2) sourced from the CCW/NRW Habitat Survey of Wales (Blackstock *et al*., 2010). These data-sets provide information on the distribution of peat at least 45 cm thick, and the individual layers were joined sequentially using the UNION function in ArcMap (ESRI). All of the above sources provide information on peat bodies delimited through direct ground survey, although in the case of the Habitats of Wales dataset the distribution of deep peat has been inferred on the basis of polygon boundaries for mire vegetation which can only be mapped as such if present on peat at least 0.5 m thick. This is regarded as fairly reliable for the lowlands, but the boundaries will be less precise in the uplands because of the frequent mapping of mosaics of mire and non-mire vegetation.

We computed the total area (km^2) for each of the layers (including that of the Cranfield peats) and the unified peat map (Table 1) – all areas were calculated using the AREA function in ArcMap (ESRI).

Table 1. *Tabulation of Welsh peat areas based on the available layers (km²)*

Geographic Layer dataset	Area (ha)	Part of unified map?
BGS peat	62,200	Y
Soil Survey of England and Wales	45,880	N
NRW Phase 1 Habitat Survey	47,160	Y
NRW (ex Forestry Commission) peat data	9,800	Y
NRW Lowland Peatland Survey of Wales	3,280	Y
Unified map	**90,995**	

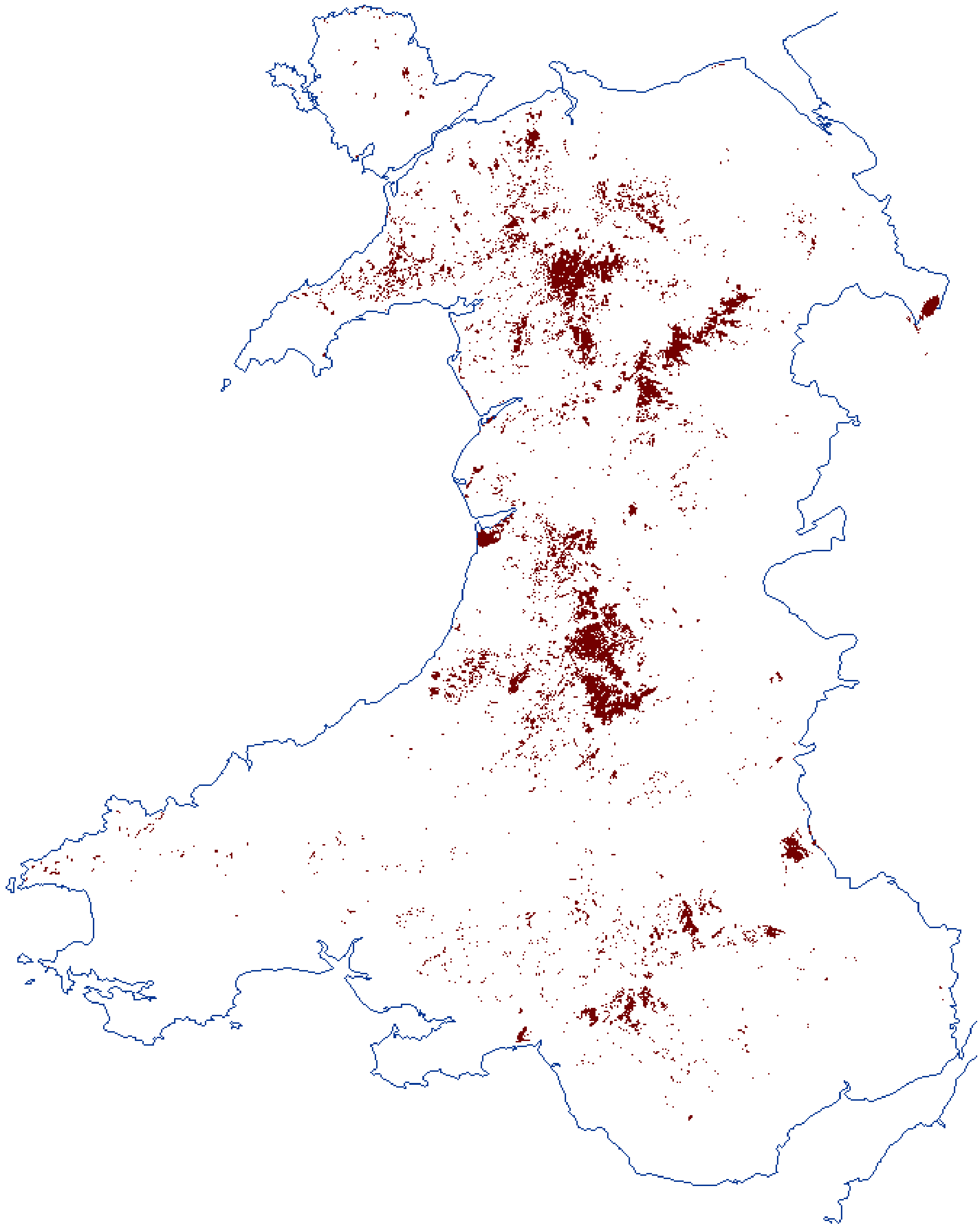

Figure 1. *A unified peat map for Wales, based on combined BGS and NRW data (see Table 1)*

The unified peat map was transferred to the Welsh Government via their secure portal in the form of an ArcMap (ESRI) shapefile. The final map is shown in Figure 1, and formed the basis of all subsequent condition assessments. This map represents a considerable advance on previous attempts to map the deep peat resource of Wales (e.g. Taylor & Tucker, 1968) and yields a significantly larger estimate than that based on the Soil Survey of England and Wales alone (ca. 706 km^2; ECOSSE, 2007). Another recent assessment of peat cover also utilised multiple data-sources (Vangeulova *et al*., 2012) but included the SSEW data-set rejected from this study for the reasons given above.

The map highlights the wide distribution of peatlands across much of Wales, with large areas of upland blanket bog in Northeast and North-central Wales (Migneint, Berwyn) and central Wales (Cambrian Mountains), as well as smaller areas of upland peat in and around the Brecon Beacons National Park. The new unified map also provides a much more detailed picture of the distribution of deep peat in the lowlands, many of which retain significant biodiversity interest. Large numbers of small peat units are found in many lowland areas of Wales, with the largest numbers in Anglesey, Penllŷn, coastal Ceredigion, Pembrokeshire and Carmarthenshire. Larger lowland raised bogs occur at Cors Fochno on the Dyfi estuary, Cors Caron in Ceredigion, and Fenn's and Whixall Moss on the border with Shropshire.

Future development of the unified peat map could include the incorporation of substantial peat-mapping data-sets generated for Environmental Impact Assessments by the renewable energy (primarily onshore wind-farm) sector: these data relate mainly to upland sites. Cross checking of the mapped data against peat thickness estimates collected by NRW and partners in Wales is also recommended as a means of assessing map reliability. This could be extended to include data from specially commissioned peat thickness survey campaigns undertaken at the boundary of deep peat bodies and other critical locations as part of Citizen Science and other initiatives.

Task 2. An assessment of land cover, ownership and designation on peat

The unified peat map developed under Task 1 provided the base layer for a range of assessments utilising existing spatial data. This assessment was divided into two tasks, the first focused on peat land-use and condition, and the second on land ownership and designation

Task 2.1. Mapping land-use and habitat condition on peat

In order to classify the Welsh peat resource into broad land-use and generalised condition categories, a range of existing spatial datasets were collated. These included i) the NRW Phase 1 habitat survey; ii) the CEH Land Cover Map 2007 (LCM2007); iii) Integrated Assessment and Control System (IACS) data on agricultural practices such as stocking rates at the level of individual 'land parcels'; and iv) detailed vegetation surveys (to the level of the National Vegetation Classification, NVC) held for a number of sites, primarily lowland peats, by NRW. The NRW 'Upland Boundary' layer was used to differentiate upland and lowland peats, as this habitat-based threshold was considered to be more meaningful than a simple altitude-based threshold.

***Table 2**. Aggregation of NRW Phase 1 habitat classes into broad peat land-use/general condition categories.*

Category	Description	Phase 1 classes
1	Bog - unmodified	E.1.6 (good condition blanket and raised bog, E2.1 (acid/neutral flush)
2	Bog - modified	E.1.7, E.1.8 (wet and dry modified bog), E.2 (flush and spring)
3	Bog - eroding	E.4 (bare peat)
4	Fen - unmodified	E.3 (fen), E.3.1 (valley mire), E.3.2 (basin mire), E3.3 (flood plain mire), E2.2 (basic flush), E.2.3 (bryophyte-dominated spring)
5	Fen - modified	E.3.1.1 (modified valley mire), E.3.2.1 ((modified basin mire), E3.3.1 ((modified flood plain mire)
6	Fen - swamp	F.1 (swamp), F.2.2 (inundation vegetation)
7	Wet heath	D.2 (wet heath), D.3 (lichen/bryophyte heath), D.5 (wet heath/grassland mosaic)
8	Dry heath	D.1 (dry heath), D.4 (dry heath/grassland mosaic), D.6 (basic dry heath/calcareous grassland mosaic), H8 (coastal heath)
9	Bracken	C.1 (bracken)
10	Marshy grassland	B.5 (marshy grassland)
11	Unimproved grassland	B.1 (acid grassland), B.2.1 (unimproved neutral grassland), B.3.1 (unimproved calcareous grassland), H.8.4 (unimproved coastal grassland)
12	Semi-improved grassland	B.1.2, B2.2, B.3.2 (semi-improved acid, neutral and calcareous grassland), C.3 (herb and fern)
13	Improved grassland	B.4 (improved grass), J1.2 (amenity grassland), J1.3 (ephemeral/short perennial), J1.5 (gardens)
14	Arable	J1.1 (arable)
15	Scrub	A.2.1 (dense scrub), A.2.2 (scattered scrub), J.1.4 (introduced scrub)
16	Broadleaf	A.1.1 (broadleaved woodland),
17	Scattered/felled broadleaf	A.1.3 (mixed woodland), A.3 (scattered trees), A.4 (felled broadleaved/mixed woodland)
18	Conifer	A1.2 (coniferous woodland), A3.2 (scattered conifers), A4.2 (felled conifers)
0	Other	G (water), H (coastal habitats not listed above), I (bare rock), J (man-made features not listed above), unclassified land

For this analysis, a modified version of NRWs Phase I data was used based on a Voronoi analysis of mixed habitat (chiefly upland) polygons which gives more accurate area figures: these yield substantially reduced figures for bog and fen compared to the 1 km square dataset employed by Blackstock et al (2010). In this analysis, we have excluded flush habitat, some of which (possibly c. 4440 ha) is on deep peat.

An assessment of the available datasets revealed significant differences between the two land cover datasets (Phase 1 and LCM2007). The Phase 1 dataset is based on detailed ground-based surveys, whereas LCM2007 data are derived from remote sensing data. A comparison between the two datasets and aerial photographs, as well as expert knowledge of specific sites, revealed some significant areas of apparent misclassification in LCM2007. These included substantial under-representation of semi-natural fens, many of which were classified as other land-cover types, and over-representation of arable land in particular. On this basis, we concluded that the Phase 1 dataset provided a more reliable base layer to describe land cover, and that trying to merge information from the two layers would increase complexity without improving accuracy.

Of the other datasets assessed, the spatial scale of the IACS data was found to be too coarse to assess land-management on peat areas specifically. Many smaller peat areas were found to be subsumed into larger polygons containing areas of more intensive farmland, resulting in clearly unrealistic values if the polygon mean stocking rates were applied to the peatland areas within them. For this reason, we were unable to include agricultural management data in the assessment. Finally, although the NVC-level vegetation survey data provided highly detailed, high-resolution data for those areas surveyed by NRW, the incomplete coverage of these surveys, and the weighting of surveys towards designated sites, presented difficulties in terms of consistent overall assessment. In consultation with Welsh Government and NRW it was determined that these higher-resolution data held should not be used for national-scale condition mapping, to avoid introducing differences in the resolution of spatial mapping and categorisation between different areas. Therefore, a decision was made to use the Phase 1 data as a single, consistent, national-scale baseline dataset for peat condition assessment.

Table 3. *Areas (in ha) of aggregated Phase 1 land-use/condition categories on peat for the entire Welsh peat area, and for areas above and below the NRW Upland Boundary.*

Aggregated Phase 1 category	Total area	Upland	Lowland
Bog – unmodified	24,007	22,324	1,683
Bog – modified	21,532	19,438	2,094
Bog – eroding	226	221	5
Fen – unmodified	2,992	1,157	1,835
Fen – modified	1,392	105	1,288
Fen – swamp	2	1	1
Wet heath	2,369	1,978	391
Dry heath	4,177	3,855	322
Bracken	449	308	141
Marshy grassland	7,132	3,569	3,563
Unimproved grassland	7,247	6,758	490
Semi-improved grassland	1,308	216	1,093
Improved grassland	6,582	306	6,276
Arable	102	1	101
Scrub	325	12	313
Broadleaf	552	9	543
Scattered/felled broadleaf	69	6	64
Conifer	8,574	6,892	1,682
Other	1,198	540	658
Total	90,235	67,695	22,540

The Phase 1 categories were aggregated into broad classes indicative of land-use on peat, and of the condition of peat areas remaining under semi-natural (bog or fen) vegetation cover (Table 2). Phase 1 classes considered incompatible with peat occurrence (e.g. bare rock, open water, intertidal habitats, urban land) were placed into an 'Other' category. A number of categories (e.g. bracken, scattered broadleaf) were included, following consultation with NRW, on the basis that areas of peat within these habitats might be prioritised for restoration.

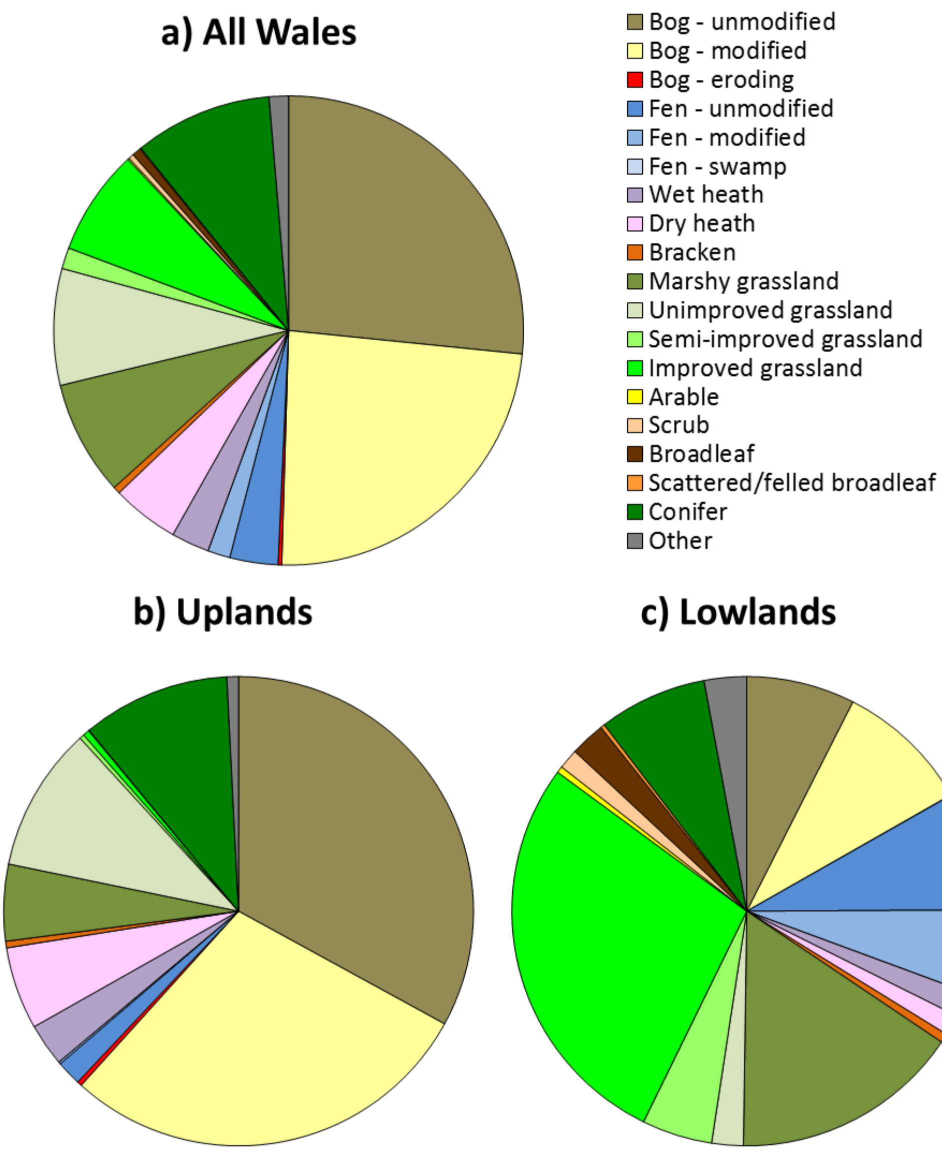

Figure 2. *Proportion of aggregated Phase 1 land-use/condition categories on peat for the entire Welsh peat area, and for areas above and below the NRW Upland Boundary.*

As is evident from Figure 2 and Table 3, there are marked differences in peat classification between the uplands and lowlands. The majority of unmodified bog (over 90%) is located on upland peat, along with 90% of heathland and 80% of conifer plantations. Figure 3 provides illustrative examples of spatial patterns of land-cover and peat condition for four upland areas.

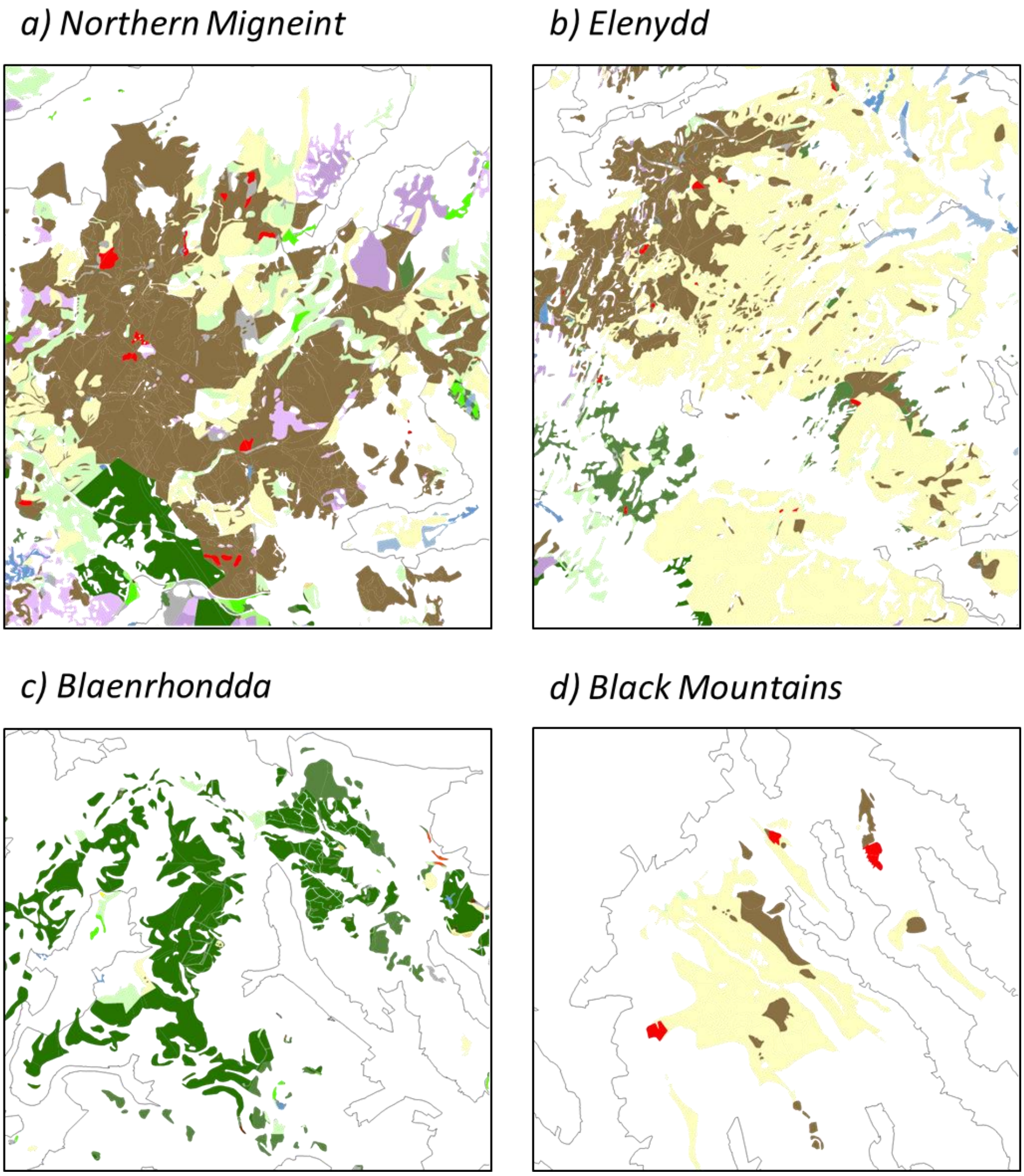

Figure 3. *Illustrative examples of peat land-cover and condition mapping for four upland regions. Colour scheme as in Figure 2. Grey lines show NRW Upland Boundary. Note that spatial scale is not the same in all examples*.

In the lowlands, and as would be expected, the dominant peat types and land-use activities differ considerably from the uplands (Figure 2c). Most of the surviving areas of semi-natural fen (over 70%) are located in the lowlands, along with the overwhelming majority of improved grassland (95%), broadleaf (98%) and arable land (99%). Figure 4 shows three example areas of lowland peat. On Penllŷn, numerous former valley fens have been converted to improved grassland and forestry. At Cors Fochno, a core area of good condition raised bog is fringed by modified bog, broadleaf woodland, vestigial areas of lagg fen and swamp and improved grassland, with the latter covering most of the peat area to the northeast of the surviving raised bog. The area of Ceredigion shown in Figure 4c highlights the relative complexity of lowland peats with many small polygons under different land-use. In the east of the area shown, Cors Caron represents one of the largest areas of extant, good condition raised bog in Wales, albeit with some peripheral modification, scrub and woodland encroachment. In the central area there are numerous small fragments of good condition and modified fen, whereas in the west most areas have been converted to grassland and conifer forest.

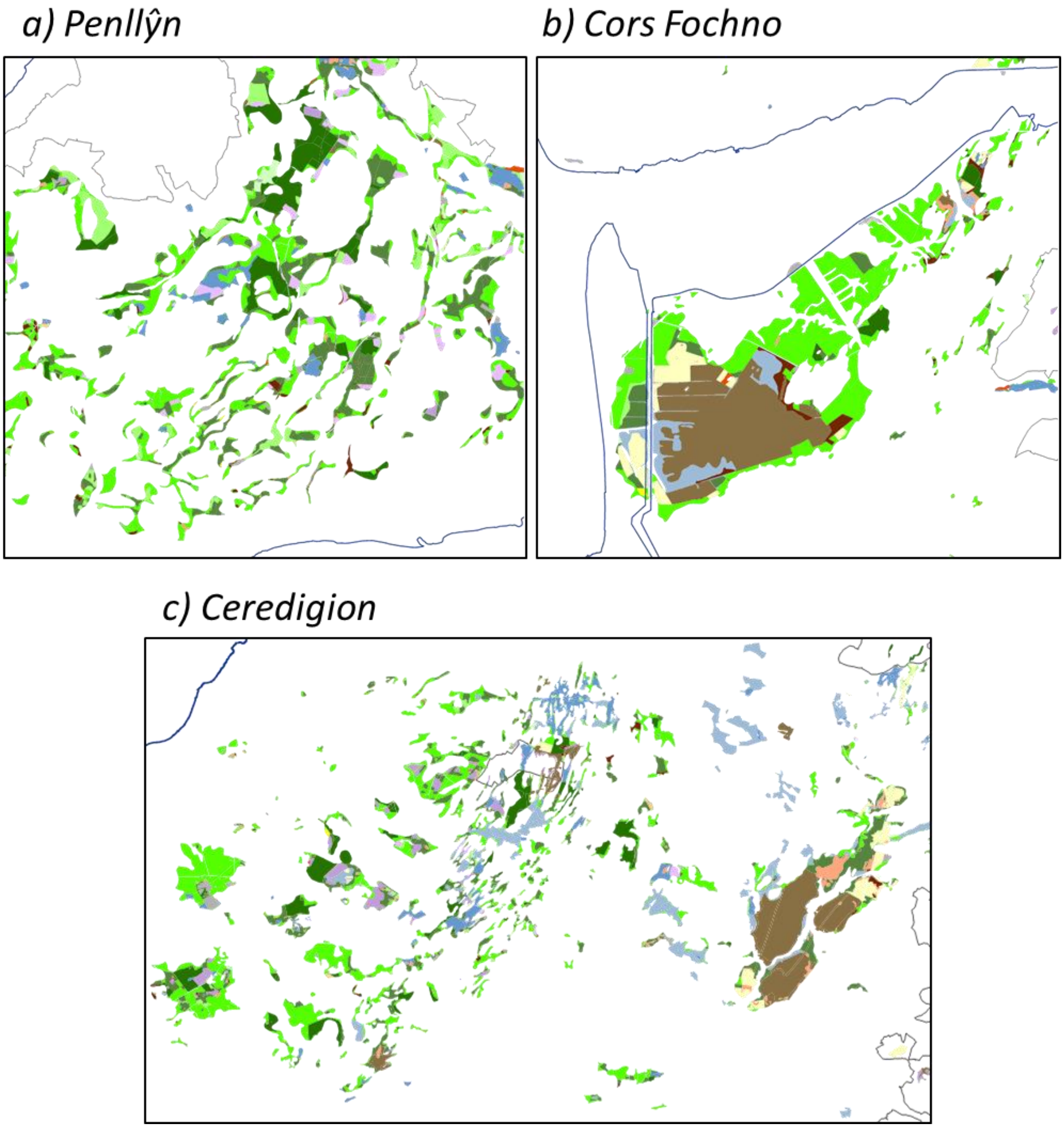

Figure 4. *Illustrative examples of peat land-cover and condition mapping for three lowland regions. Colour scheme as in Figure 2. Grey lines show NRW Upland Boundary. Note that spatial scale is not the same in all examples*.

Overall, the overlay of Phase 1 data on the unified peat map highlights the heterogeneity of Welsh peatlands with regard to their spatial distribution, size and overall range of land-use and condition, as well as large regional and altitudinal differences in these parameters. This complexity emphasises the need to tailor management activities, and restoration measures, to the specific characteristics of individual sites, peat types and regions.

Task 2.2 Mapping potential constraints on peat restoration

Peatlands in Wales occur across a wide range of geographic locations, from small pockets of fen and raised bog in the lowlands to large expanses of blanket bog in the uplands. As shown above, these areas are subject to a wide range of land-use and management. In addition, peatland areas are under a range of ownership (public and private), and are subject to a range of designations, relating for example to their conservation status, which will influence the range of management options and funding instruments relevant to the conservation or (where appropriate) restoration of individual peat areas. To inform decision making and the targeting of restoration activities we overlaid the unified peat map with a range of spatial data held by the GMEP project describing land ownership and designation, as follows:

1) Eligibility for Glastir: All land areas included in the IACS database were assumed to be eligible for Glastir payments. Data on these areas were obtained from the Land Parcel Identification System (LPIS). Note that this should only be considered indicative of Glastir eligibility, since some areas may be eligible but not previously in receipt of payments.
2) Common Land: Areas of common land on peat were taken from the Welsh Government's Glastir database.
3) Woodland: The Welsh National Forest Inventory for 2013 was used to classify areas of peatland under forestry. These areas were subdivided into the National Forest Estate (public owned) and other woodland areas (assumed privately owned).
4) Conservation designations: A range of conservation designations were mapped, including i) European Natura 2000 sites (Special Areas of Conservation, SACs; Special Protected Areas, SPAs); ii) National Nature Reserves (NNRs); iii) Sites of Special Scientific Interest (SSSIs); iv) Areas of Outstanding Natural Beauty (AONBs).

The area of peatland covered by these different classifications is summarised in Table 3, and illustrated in Figures 5 to 7.

***Table 4**. Land ownership and designations affecting Welsh peatlands*

Land designation	Area (ha)	% of peat area	Number
Areas eligible for agri-environment payments	80,611	89%	21,184
Common Land	23,539	26%	615
Woodland (Welsh Government Estate)	7,438	8%	465
Woodland (Privately owned)	3,088	3%	2,638
Special Areas of Conservation (SACs)	31,689	35%	44
Special Protected Areas (SPAs)	32,186	36%	7
National Nature Reserves (NNRs)	6,959	8%	33
Sites of Special Scientific Interest (SSSIs)	47,231	52%	256
Areas of Outstanding Natural Beauty (AONBs)	1,003	1%	4
Total peat area	90,235		

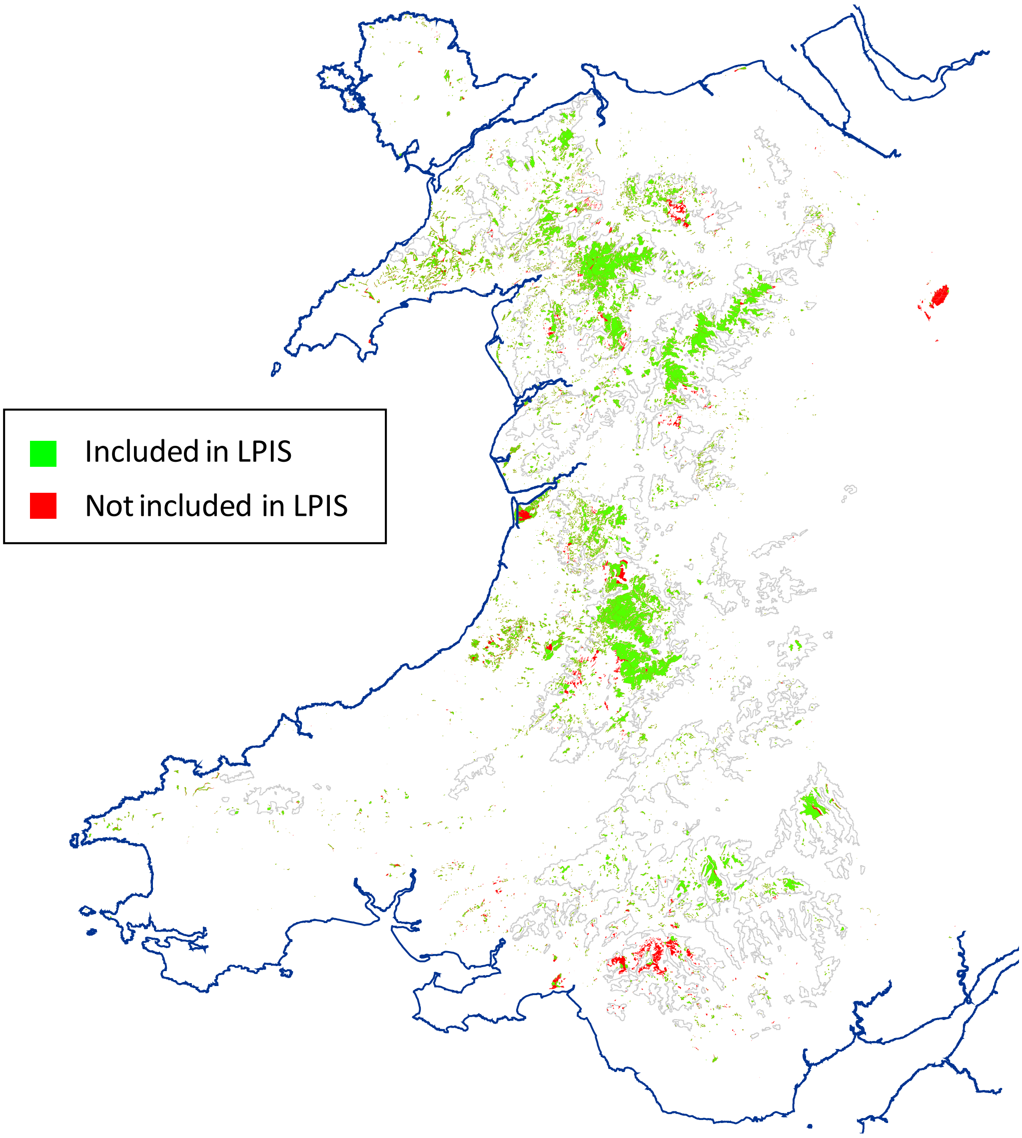

Figure 5*. Welsh peatland areas on land previously in receipt of payments from Glastir or previous schemes (includes in LPIS) and areas not previously in receipt of payments (not included in LPIS)*

The assessment shows that the vast majority of Welsh peatlands are eligible for Glastir funding. The excluded areas, comprising around 10% of the total, are under public ownership (primarily forestry, along with some nature reserves). A quarter of the peat area is common land, with the largest areas in the uplands, and a large number of individual commons (over 600). Much of the upland peat area of North and Mid Wales, lies within Natura 2000 designated sites (SACs and SPAs) and many larger lowland peat areas (as well as some important uplands areas such as the Berwyn) are National Nature Reserves. Over 250 SSSIs were recorded as containing peat, and over 3000 areas of woodland. It is noteworthy that 85% of the individual woodland polygons are under private ownership, despite only occupying 29% of the total area of woodland on peat.

The area covered by the unified peat map was also compared to the Glastir 2015 target area for peat restoration (Figure 8). This target area appears to have been based on the Soil Survey of England and Wales, and as a result gives larger target areas for peat restoration in the uplands than the unified peat map (amber shaded areas), but omits man smaller areas of peat in the lowlands (red shaded areas).

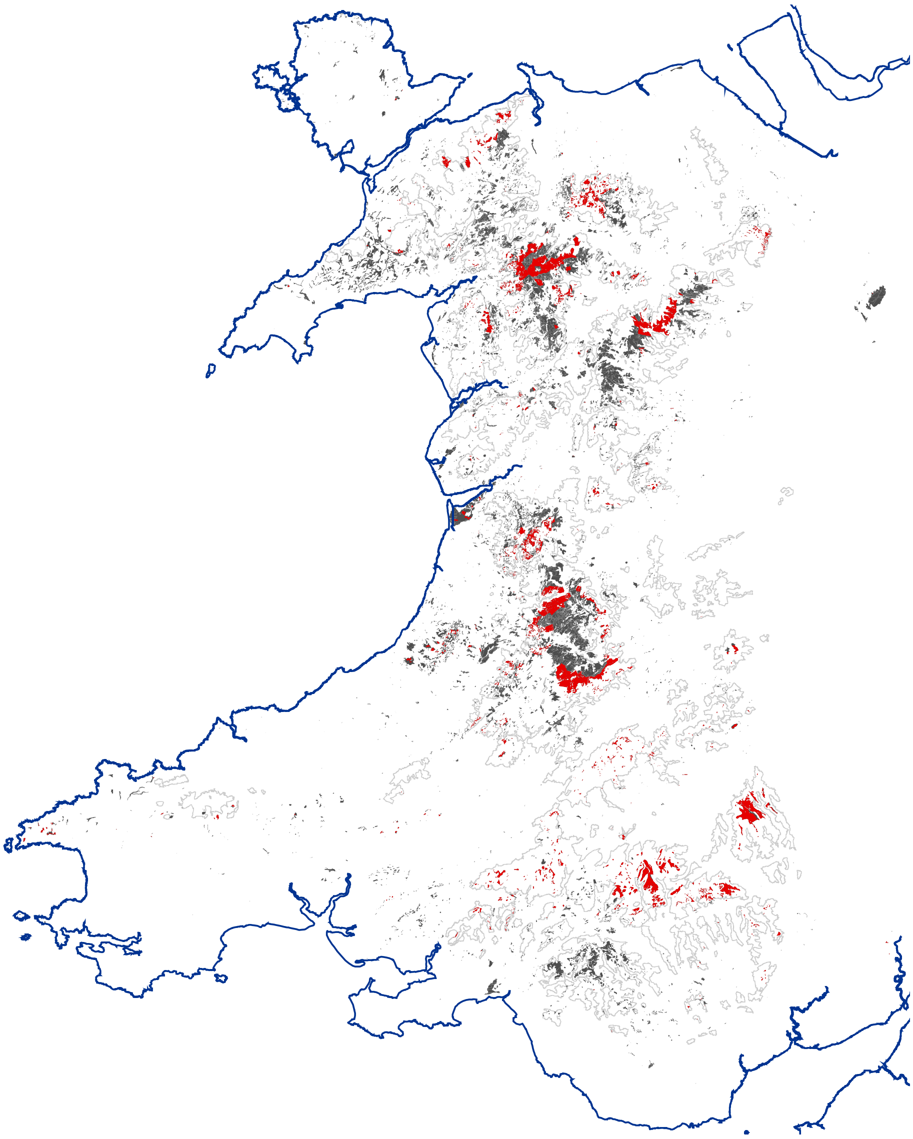

Figure 6. *Common land (red) on peat in Wales. Grey shaded areas represent areas of peat not on common land, pale grey outline shows the NRW Upland Boundary.*

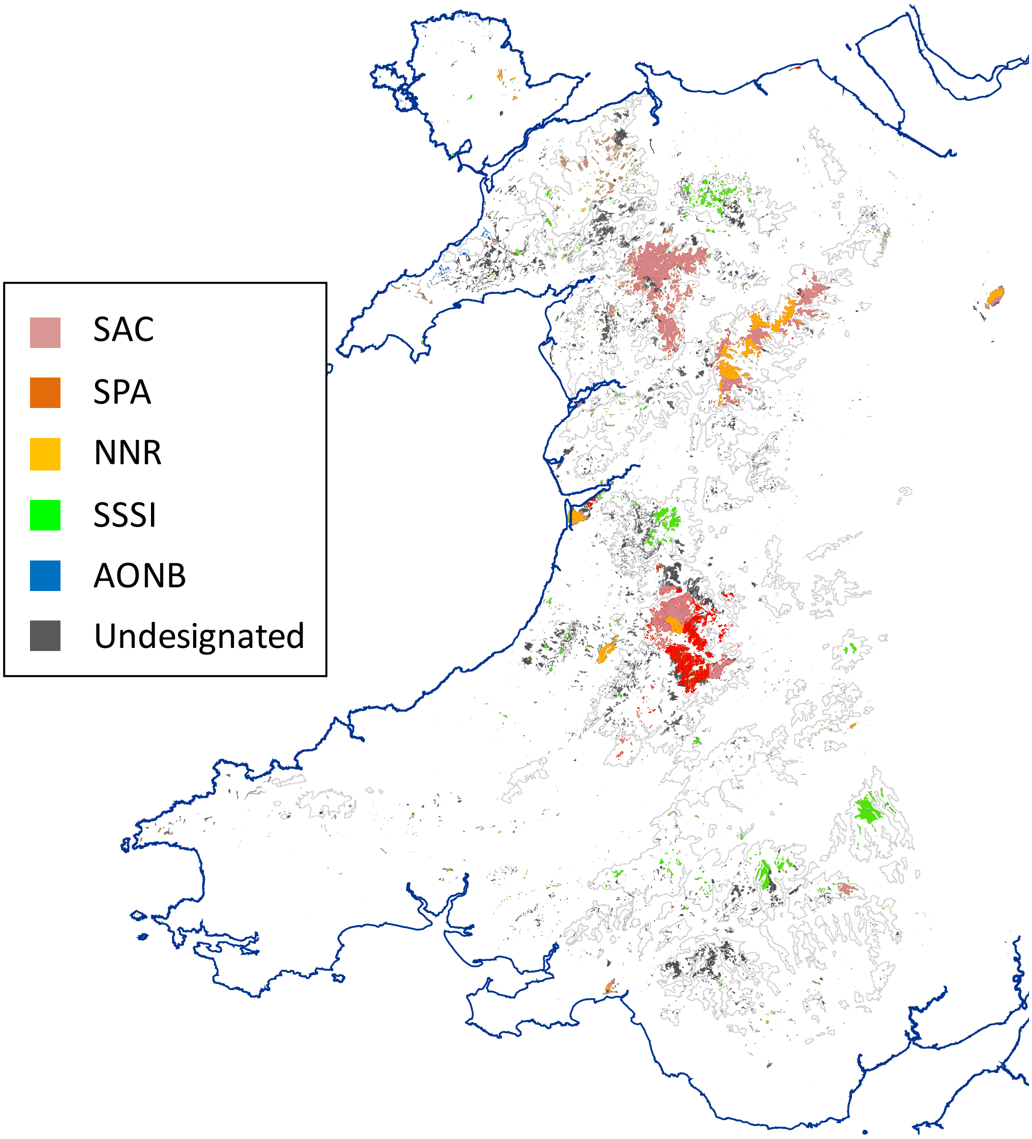

Figure 7. *Areas of Welsh peat subject to a range of conservation designations. Pale grey outline shows the NRW Upland Boundary. Note that many peat areas have multiple designation; in these areas only the top layer (as in the legend) is shown. Pale grey outline shows the NRW Upland Boundary.*

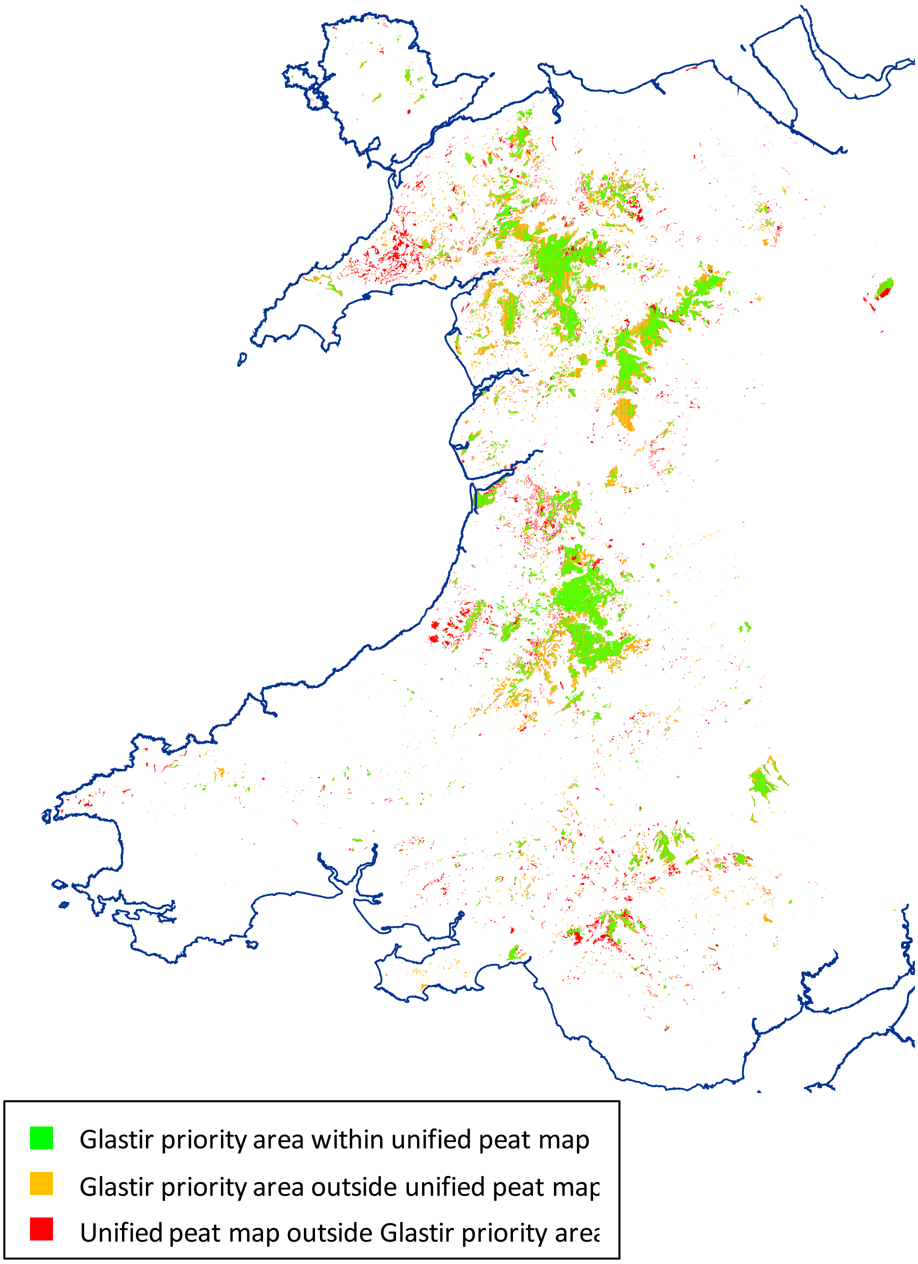

***Figure 8**. Comparison of the unified peat map and the Glastir 2015 target area for peat restoration*

Task 3. Condition mapping of blanket bog

Task 3.1 Ditch mapping

One of the features that determines blanket bog condition (note that ‘condition’ is used here in a broader sense than its specific application for Common Standards Monitoring) is the occurrence of ditches, which have been cut into the peat for the purpose of drainage. Drained peats, where the water table has been lowered artificially, are widely considered to be in a poorer condition than intact areas, in part because more of the organic carbon is prone to aerobic decomposition, and subsequent loss to the atmosphere as CO_2. The objective of this task was to map the occurrence of drainage ditches across upland blanket bog areas of Wales using aerial photography data from automated detection of linear features and extraction of the drainage ditches from this dataset. This method can then be validated for areas where ditches have been mapped by NRW or other organisations using manual techniques.

We used a bespoke software package, PCI Geomatica, with a built-in function LINE for the extraction of linear features from the digital air photos in which four channels were available; near infra-red (NIR), red (R) green (G) and blue (B) at 50 cm pixel resolution. This function applies the Hough transform and then uses parameters for curvature and length to extract suitable lineaments. We chose a set of initial values for these parameters and applied them to an area where drainage ditches had been cut into the peat, but also where other linear features occurred (e.g. roads, plantations). We established a set of parameter values that were effective in identifying all the ditches in a region, but which also returned a number of linear features unrelated to artificial drainage. We found that the linear feature algorithm was very effective in systematically identifying areas with ditches and saved the operator from having to view all regions at small scales. The algorithm helped by focussing on areas to assess ditches in detail. Rather than use the linear features generated by the algorithm we found it was more time efficient to digitise the ditches manually in a new GIS layer. We applied this procedure to all the area of upland peat and a small subset of the areas of lowland peat.

The area of upland peat was defined using the habitat-based NRW Upland Boundary layer, as above. Overall aerial photo coverage relative to the unified peat map is shown in Figure 9. Note that, as the original remit of the task was to map ditches in upland blanket bog, priority was given to aerial photograph ‘tiles’ containing large areas of upland peat, although a substantial area of lowland peat was also included. Overall, approximately 73% of the upland peat area and 29% of the lowland peat area were captured by the aerial photographs analysed.

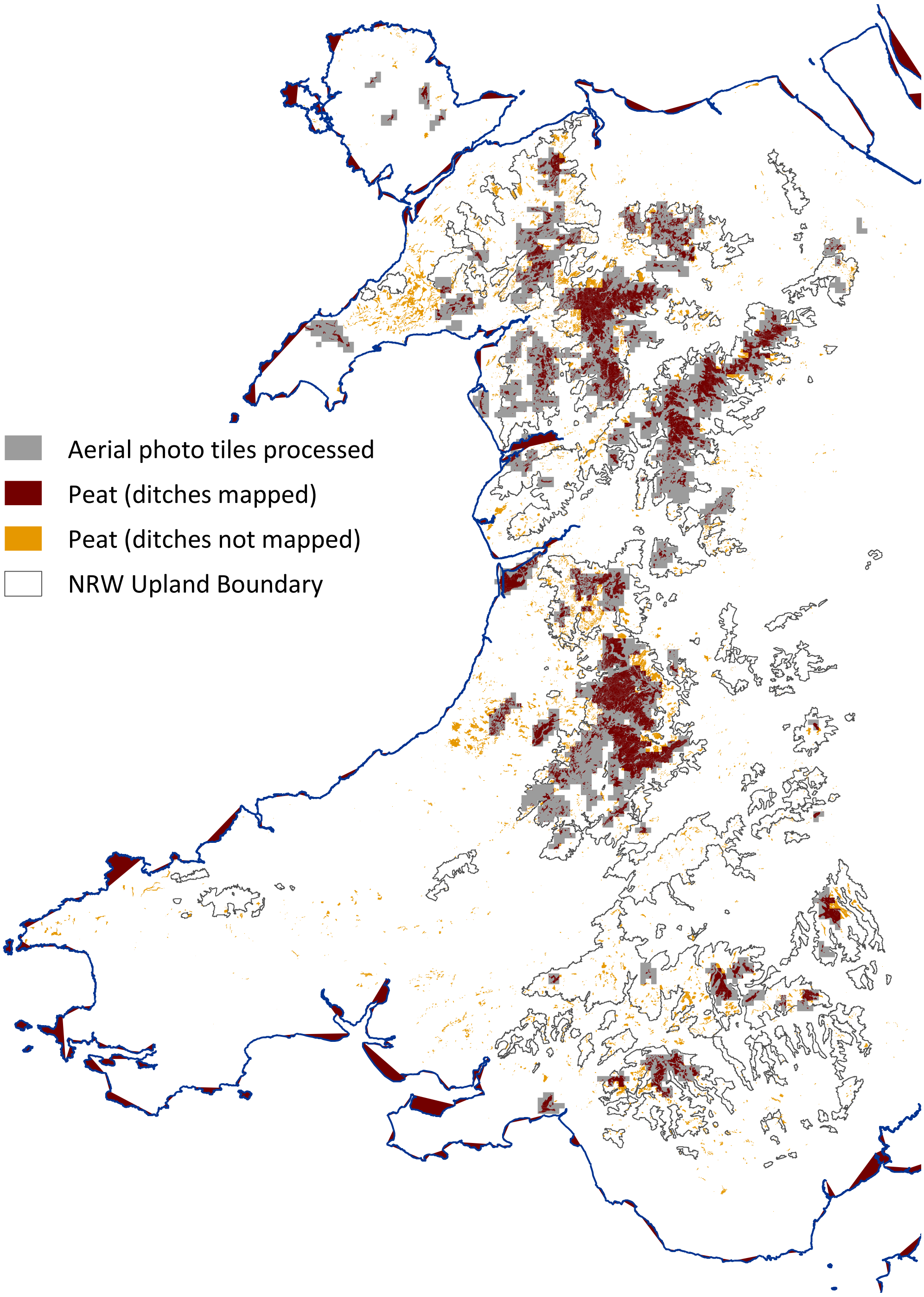

Figure 9. *Peat areas covered by aerial photograph assessment*

From the analysis of aerial photographs, two GIS layers were created: i) all upland ditches (total length of 2296 km); and ii) all mapped ditches, including those in lowland areas (total length 3,144 km). A significant proportion of these ditches fell outside the polygons of the unified peat map, however (e.g. Figure 10). When the ditch layer was clipped to the peat map, the total ditch lengths reduced considerably, to 1810 km (1,502 km in the uplands and 209 km in the lowlands). Thus 1334 km of the ditches mapped were on soils not mapped as peat. This is not particularly surprising; maps depicting peat polygons cannot be 100% accurate and it is possible that some of these ditches are on peat which have not been captured by field mapping. In addition, there may be little difference (from a land-management perspective) between a soil that has been identified as peat (i.e. with an organic layer greater than 40 cm deep) and a soil with a thick organic horizon. It is likely that organo-mineral soils that do not meet the specified thickness of a deep peat may also be subject to drainage by ditching, which would account for their occurrence in areas that have not been mapped as peat. Some drainage ditches also occur on areas of predominantly mineral soil. As the objective of this work was to map ditches on peat, ditches on other soil types have not been mapped as comprehensively, but these observations suggest that further assessment of ditches on other soil types may be useful.

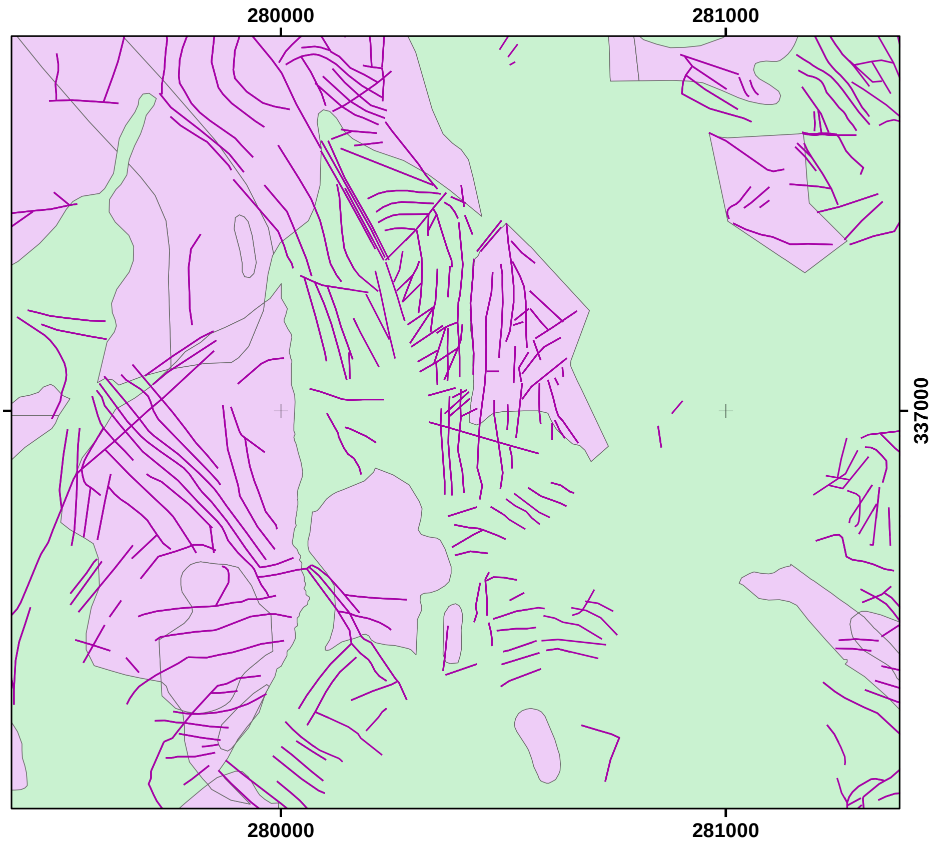

Figure 10*. Image showing ditches as linear features both within the unified peat map (pink polygons) and also in areas outside the peat polygon boundary (green). The geographic coordinates are metres on the British National Grid.*

It is important to note that ditch mapping, based on the procedure described above, includes a component of subjectivity and it is not possible to achieve 100 % accuracy when the results are compared to ground-based surveying approaches. For example, it is sometimes difficult to discriminate artificial ditches from natural drainage channels. Moreover, depending on the orientation and illumination angle from the sun, it can be difficult to distinguish between a ditch and an upstanding feature such as a wall or hedgerow, and ditches under mature forest canopies are not visible in aerial photographs. For these reasons, it is unlikely that i) we have mapped all ditches, and ii) every linear feature mapped is a ditch.

Figure 11 shows two high-resolution examples of ditch mapping in two locations, overlaid on the aerial photographs used. The two sites, both from the Migneint area of North Wales, highlight the different intensity and styles of ditches which occur. Note that most of the ditches shown in Figure 11b have recently (since the aerial photographs were taken) been blocked by the National Trust.

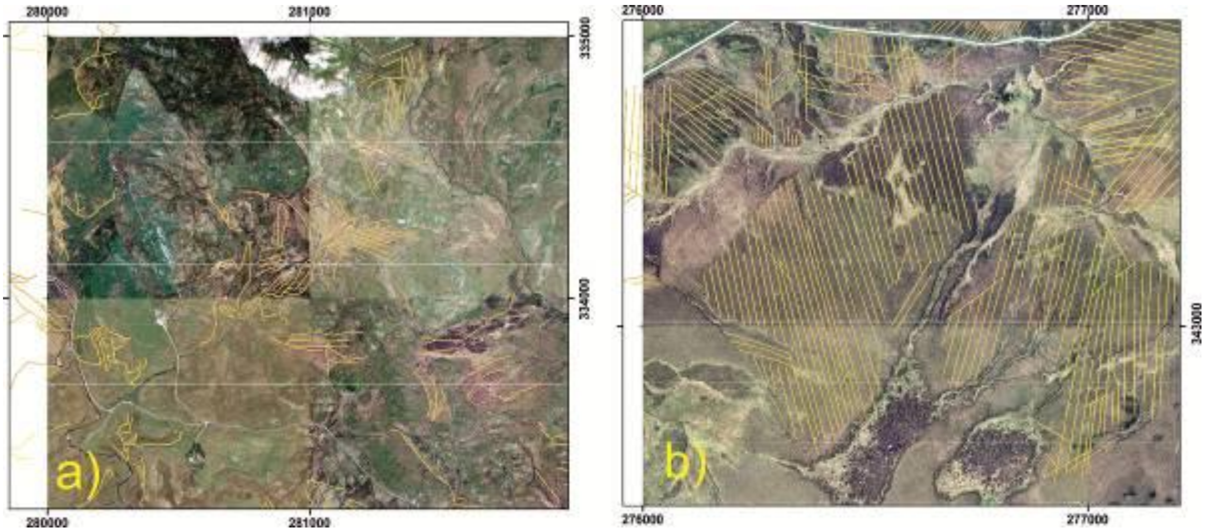

Figure 11. *Two examples of ditches mapped using linear feature extraction from (and here superimposed over) air photos: a) small frequency ditches, and b) large frequency ditches. Coordinates are metres on the British National Grid; note the two images have different scales.*

It was beyond the scope of this project to undertake validation of ditch mapping based on the air photo procedure based on new field observations. However, field data on the distribution of ditches had been collected in some areas, such as parts of Mynydd Hiraethog in North Wales which have been surveyed by NRW and the RSPB. This allowed some qualitative assessment of accuracy of the semi-automated method. As shown in Figure 12, agreement was generally good, although a minority of ditches identified by the ground survey were not captured in the aerial photograph analysis, and some of the ditches mapped from air photos were not mapped on the ground (in some cases probably because these ditches lay outside the boundary of the field survey area.

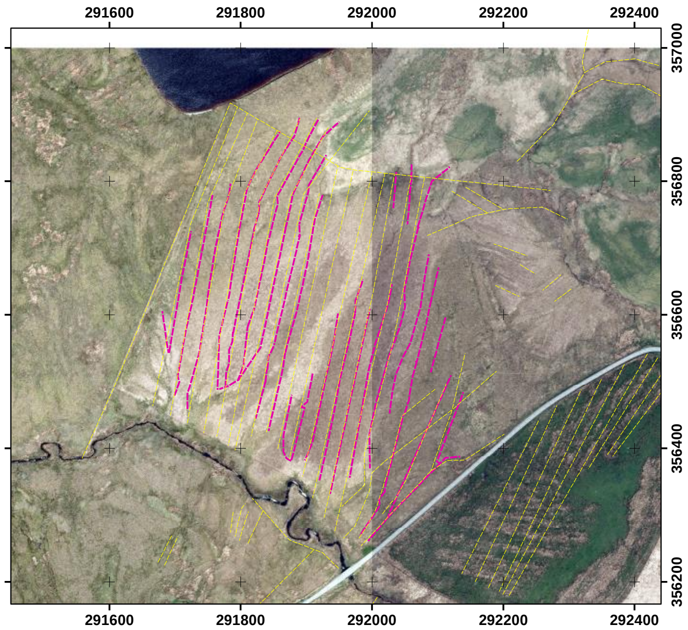

Figure 12. *An example of ditches mapped by the semi-automated method using air photos (yellow lines) and ground-based survey (pink lines), Mynydd Hiraethog, North Wales*

Overall, although ditches were recorded in many peat areas, the highest ditch density (within the upland blanket bog area) was observed in North Wales, particularly in the Migneint and Mynydd Hiraethog areas (Figure 12; note that this does not show ditch density in lowland areas).

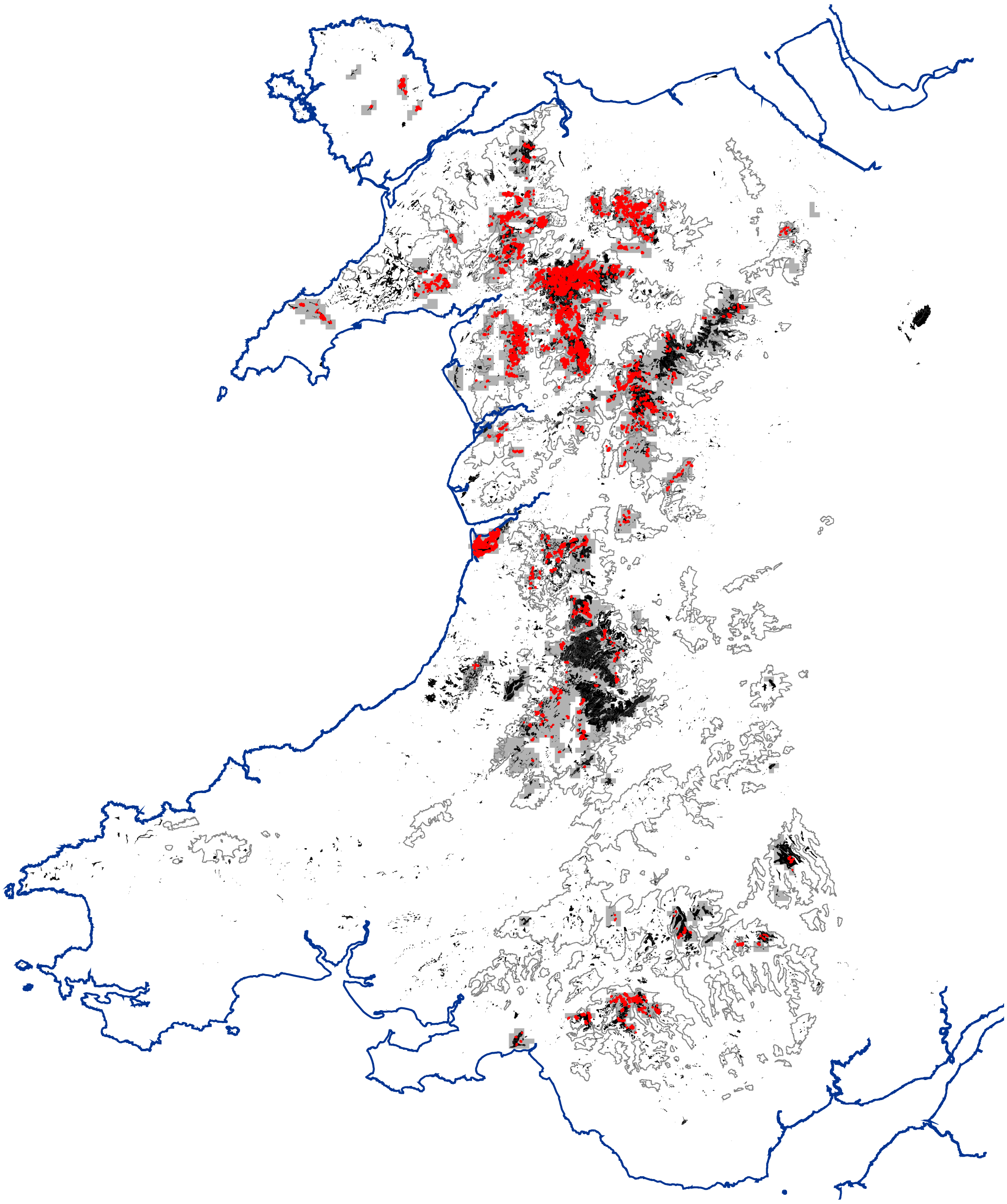

***Figure 12**. Peatland areas affected by ditching in Wales. Light grey tiles show areas over which aerial photos were analysed, red areas contained drainage features. Dark grey areas show areas of peat where drainage features were not observed (within light grey tiles) or which were not analysed (outside tiles). Pale grey outline shows the NRW Upland Boundary. Note that forestry ditches could not be mapped from air photos.*

In order to estimate the total area of peatland impacted by drainage ditches, rather than simply the ditch length or density, it is necessary to estimate the distance over which each ditch is effective in drawing down the water table in the surrounding peat. In reality, this drainage distance will be highly variable as a function of ditch depth, local slope, ditch orientation relative to the topography, peat type, vegetation etc. It will also vary temporally as a function of weather conditions and time of year. These controls are being investigated as part of an ongoing study commissioned by NRW (Baird et al., in prep.), and such a comprehensive analysis of drainage impacts is beyond the scope of the current study. However, we generated an initial estimate of the drainage-affected area based on a simple set of fixed buffer distances around each of the mapped ditches, ranging from 10 m either side of each ditch to 50 m. Examples of buffered ditch data are shown four example areas in Figure 13. As can be seen from these examples, the choice of buffer distance is relatively unimportant for areas of very high ditch density (e.g. parts of Figure 13a, d) because even a low buffer distance suggests that the area is fully drained. On the other hand in areas of lower drain density (e.g. Figure 13c) the choice of buffer distance makes a large difference to the total drained area calculated.

To calculate total drained areas, we first overlaid the ditch layer with the reclassified Phase 1 habitat map derived for Task 2. A simple set of rules were then defined, reflecting differences in the expected sensitivity of different peat types to drainage, as well as the degree of drainage required to permit certain land-use activities. Previous studies (e.g. Evans et al., 2014a) have concluded that fens and raised bogs are more sensitive to drainage than upland blanket bogs, due to their greater hydraulic conductivity. However, estimates of the width of drainage influence vary greatly in the literature, and in reality will also varying according to additional factors such as ditch depth and orientation relative to local topography, that could not be taken into account within the current study. For this assessment, we assigned fixed buffer distances either site of each mapped drain, using a value of 10m for drains on upland bog, heath and all non-improved grassland. Lowland raised bogs and fens, as well as areas mapped in Phase I as lowland heath, were a 50 m buffer distance. For all woodland, improved grassland and arable land, we assumed that all peat under these land-cover types was effectively drained (reflecting the fundamental need for land to be drained to support the associated land-use activities, and also the difficulty of mapping drainage ditches under forest canopies). The same assumption was applied to all other grassland types on lowland peat.

Finally, given that the ditch map did not extend over the entire Welsh peat area, we also needed to make assumptions about areas which had not been mapped. To do this, we calculated the percentage of the mapped peat area within each land-use/condition category (as defined in Table 2) that was drained, according to the method described above. This analysis was undertaken separately for upland and lowland areas, to reflect likely differences in both drainage extent and drainage impact as defined above. We then assumed that these drained area percentages would be the same in those areas of peat in the same aggregated (upland/lowland) Phase 1 class for which drains had not been mapped. We recognise that this assumption may not be accurate, given that the drain mapping focused on larger peat areas and thus represents a non-random sample of the total population. It is particularly uncertain for the lowlands, where only 25% of the total area was mapped. Nevertheless, this approach allowed us, for the first time, to provide an estimate of the total drained peat area for Wales (Table 5).

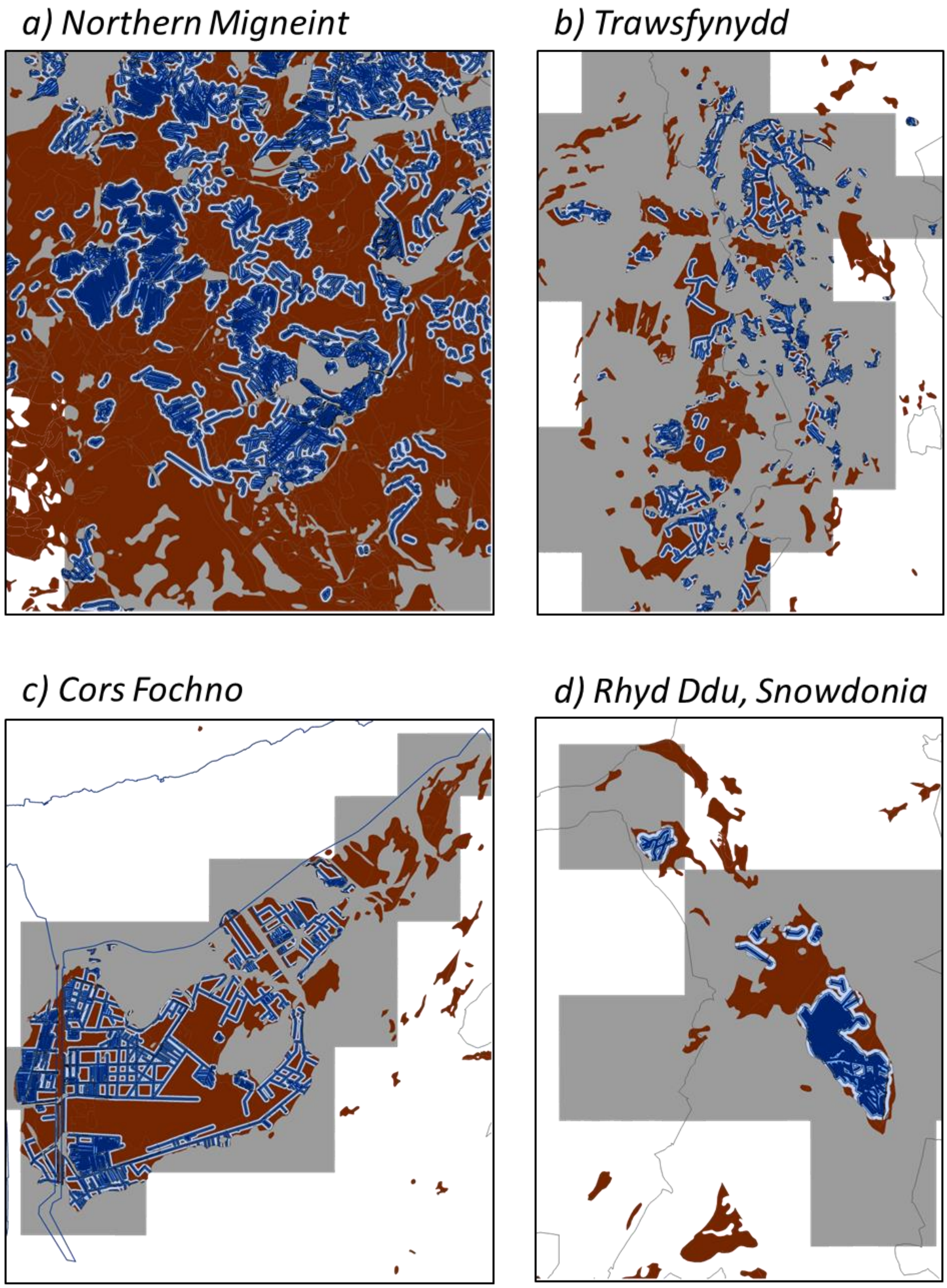

Figure 13. *Example ditch maps for four peat areas. Brown area shows the extent of peatland, grey 'tiles' show areas within which ditches have been digitised from aerial photographs, and blue shading shows a range of buffer distances (i.e. assumed drainage impacts) around each ditch, from 10 m (dark blue) to 50 m (light blue).*

Table 5. Estimated total and drained areas of peat by land-cover/condition class, for peat areas above and below the NRW Upland Boundary, and for the total Welsh peat area

Land cover/condition category	Upland			Lowland			Total		
	Total area	Drained area		Total area	Drained area		Total area	Drained area	
	ha	ha	%	ha	ha	%	ha	ha	%
Bog – unmodified	22,324	2,415	11%	1,683	483	29%	24,007	2,898	12%
Bog – modified	19,438	1,035	5%	2,094	586	28%	21,532	1,621	8%
Bog – eroding	221	3	1%	5	0	1%	226	3	1%
Fen – unmodified	1,157	306	26%	1,835	717	39%	2,992	1,023	34%
Fen – modified	105	6	5%	1,288	237	18%	1,392	242	17%
Fen – swamp	1	1	96%	1	0	0%	2	1	52%
Wet heath	1,978	447	23%	391	33	8%	2,369	480	20%
Dry heath	3,855	278	7%	322	65	20%	4,177	344	8%
Bracken	308	7	2%	141	8	6%	449	15	3%
Marshy grassland	3,569	326	9%	3,563	3,563	100%	7,132	3,888	55%
Unimproved grassland	6,758	878	13%	490	490	100%	7,247	1,368	19%
Semi-improved grassland	216	64	30%	1,093	1,093	100%	1,308	1,156	88%
Improved grassland	306	306	100%	6,276	6,276	100%	6,582	6,582	100%
Arable	1	1	100%	101	101	100%	102	102	100%
Scrub	12	5	41%	313	10	3%	325	14	4%
Broadleaf	9	9	100%	543	543	100%	552	552	100%
Scattered/felled	6	6	100%	64	64	100%	69	69	100%
Conifer	6,892	6,892	100%	1,682	1,682	100%	8,574	8,574	100%
Other	540	54	10%	658	46	7%	1,198	99	8%
Total	67,695	13,039	19%	22,540	15,995	71%	90,235	29,034	32%

From this analysis (also illustrated in Figure 14) we estimate that around 30% of the total peat area of Wales has been affected by drainage. The proportion is considerably higher in the lowlands than in the uplands (71% versus 19%). The largest drained areas in both the uplands and lowlands are associated with coniferous woodland (53% and 30% respectively of the total drained area) although collectively the different grassland categories contribute 45% of the total drained lowland area. Upland bog is estimated to account for 27% of the drained upland peat area, with the majority of the drained area lying within unmodified (rather than modified or eroding) bog. Although somewhat counterintuitive, this is a reflection of the greater density of drainage in the less modified blanket bogs of North Wales, relative to the more modified but relatively undrained bogs of the Cambrian Mountains and South Wales.

It is important to recognise that these estimates of drained peat area are highly sensitive to the assumptions made in the analysis, as described above. For example, the contribution of forestry and grassland to the totals reflects the high assumed extent of drainage under these land categories, whereas the proportion of the total drained area associated with bog (16%) is much less than the percentage of ditch *length* mapped within this category (54%) due to the low drainage width buffer applied to upland blanket bog. Consequently, there is a need for some caution when interpreting these results in terms of overall peat condition and prioritisation of restoration measures.

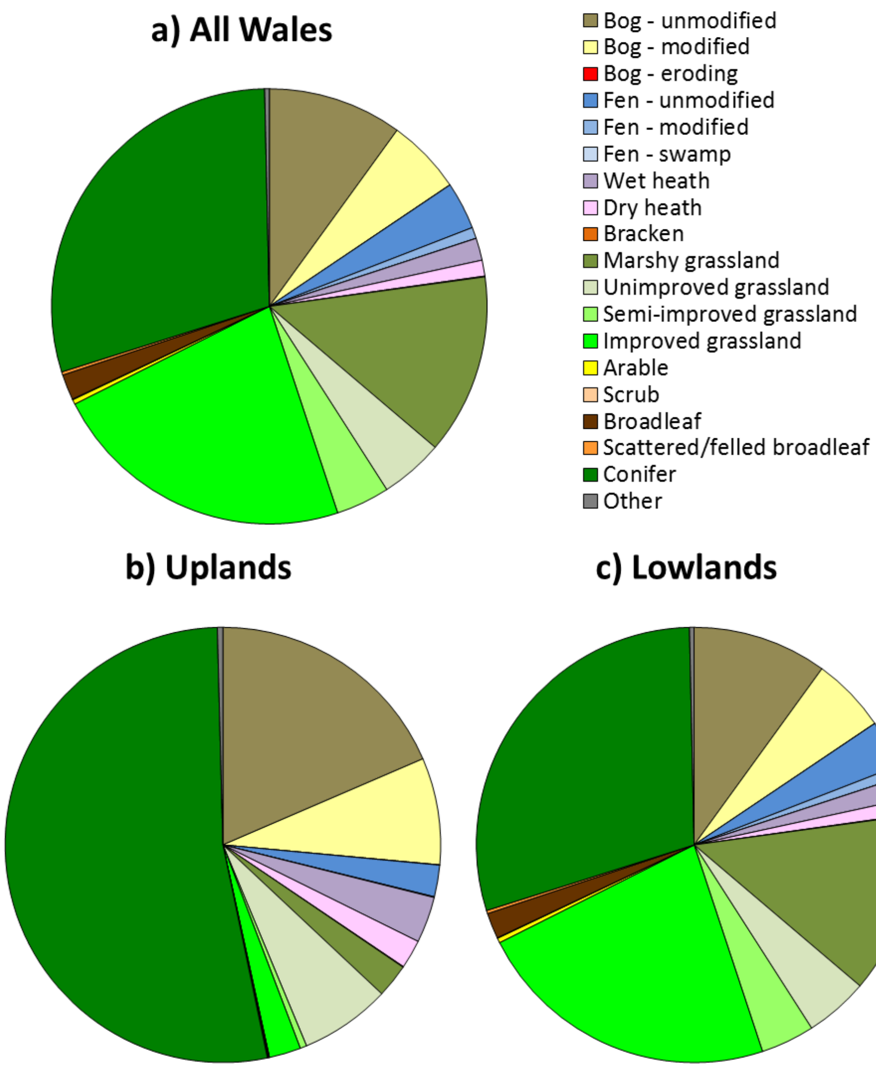

Figure 14. *Fraction of total estimated drainage-affected peat area by aggregated Phase 1 land-use/condition categories on peat for the entire Welsh peat area, and for areas above and below the NRW Upland Boundary.*

Task 3.2 Vegetation assessment

The primary purpose of this task was to determine the distribution of *Molinia caerulea* (purple moor grass) across the mapped areas of upland blanket peat, based on the unified peat map of Wales (see Task 1). Previous research (Kabir, 2014) has shown that it may be possible to discriminate between different vegetation communities using spectral information from a combination of aerial photographs with a pixel resolution of 50 cm; traditional red-green-blue images, colour infra-red, and a Normalised Difference Vegetation Index (NDVI) derived from these. *Molinia* dominance is widespread across large areas of Welsh blanket bog, and considered by many to signify poorer peat condition in terms of biodiversity and landscape quality. It may also have a detrimental impact on carbon accumulation rates, because the leaf litter produced by *Molinia* is relatively degradable, and therefore less likely to contribute to peat formation than that produced by *Sphagnum* or other bog species.

The 25 cm and 50 cm pixel resolution aerial photography data (RGB and colour infra-red images) we used across Wales were captured between April 2007 and October 2010 (see Figure 15). It is noteworthy that the images from the northern half of Wales were captured predominantly during April, May and June of 2009, whilst those in the southern part of Wales were captured largely during September 2009. This is significant because the spectral signatures of *Molinia*, a deciduous grass species, are likely to show strong phenological variation through the growing season.

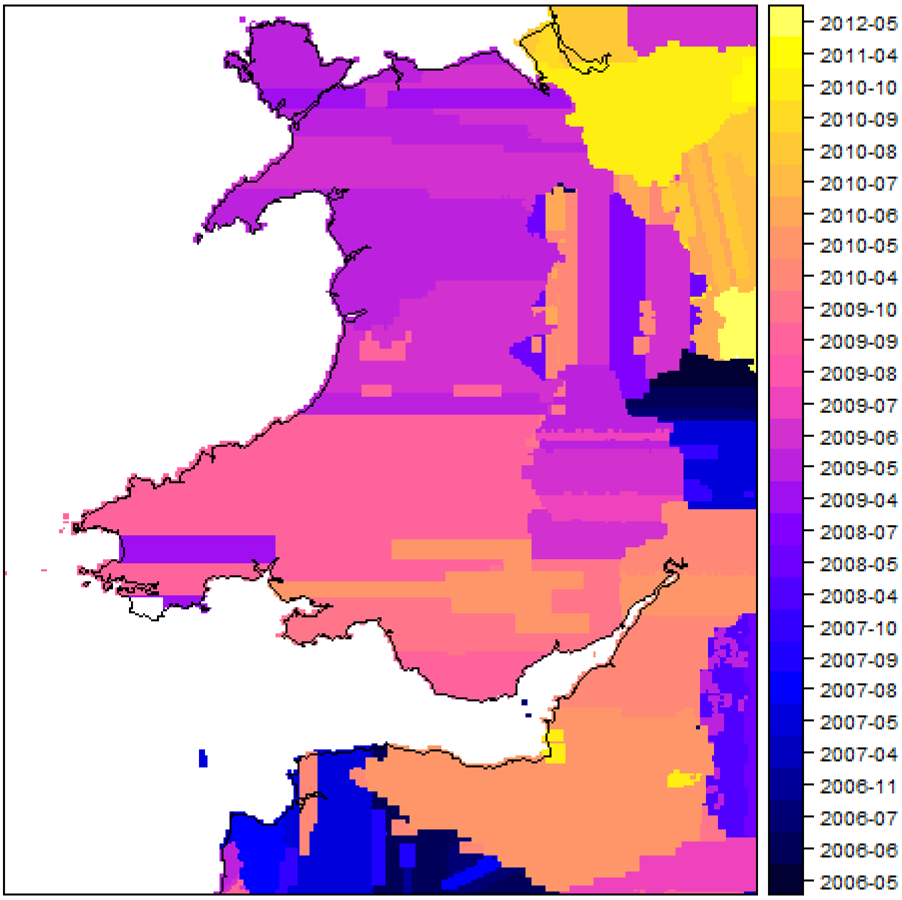

Figure 15. *Dates (expressed as year-month) on which the air photos (1km tiles) used in this study were captured across Wales.*

In addition to the air photo data, NRW supplied a set of polygons from the National Vegetation Classification (NVC) of Wales which could be used to attribute classes to mapped areas. The NVC includes a large number of major vegetation classes which are also subdivided based on specific descriptions. To ensure the NVC data could be used for the task of assigning polygons to particular dominant features it was necessary to combine the NVC classes into seven major classes, specifically:

1. Acid grassland,
2. *Eriophorum vaginatum* dominated
3. *Juncus* & *Sphagnum* mire
4. *Molinia* dominated
5. Other near-natural bog
6. *Sphagnum* pools/hollows
7. *Sphagnum*-rich near natural bog

We used a table supplied by NRW to reclassify the original NVC polygon data into these seven classes and then merged the polygons into these seven classes in ArcMap (ESRI). We then overlaid the reclassified polygons for the Elenydd region (where *Molinia* is particularly abundant) on top of the colour air photos. We found that there was considerable variation in the aerial photographs within the polygons classified as *Molinia*-dominated, which made it challenging to identify a robust *Molinia* spectral end-member that could be used as the basis of a supervised classification. Instead, an objective routine in the ENVI software package (Exelis VIS) was utilised to automatically extract spectral end-members from the dataset for the Elenydd region. These end-members were then used to perform a supervised classification in ENVI, whereby the spectral properties of the individual pixels in the imagery are compared to those of the end-members. Pixels closely matching the end-members were accordingly assigned to the class represented by that end-member, while weakly matching pixels were left unclassified.

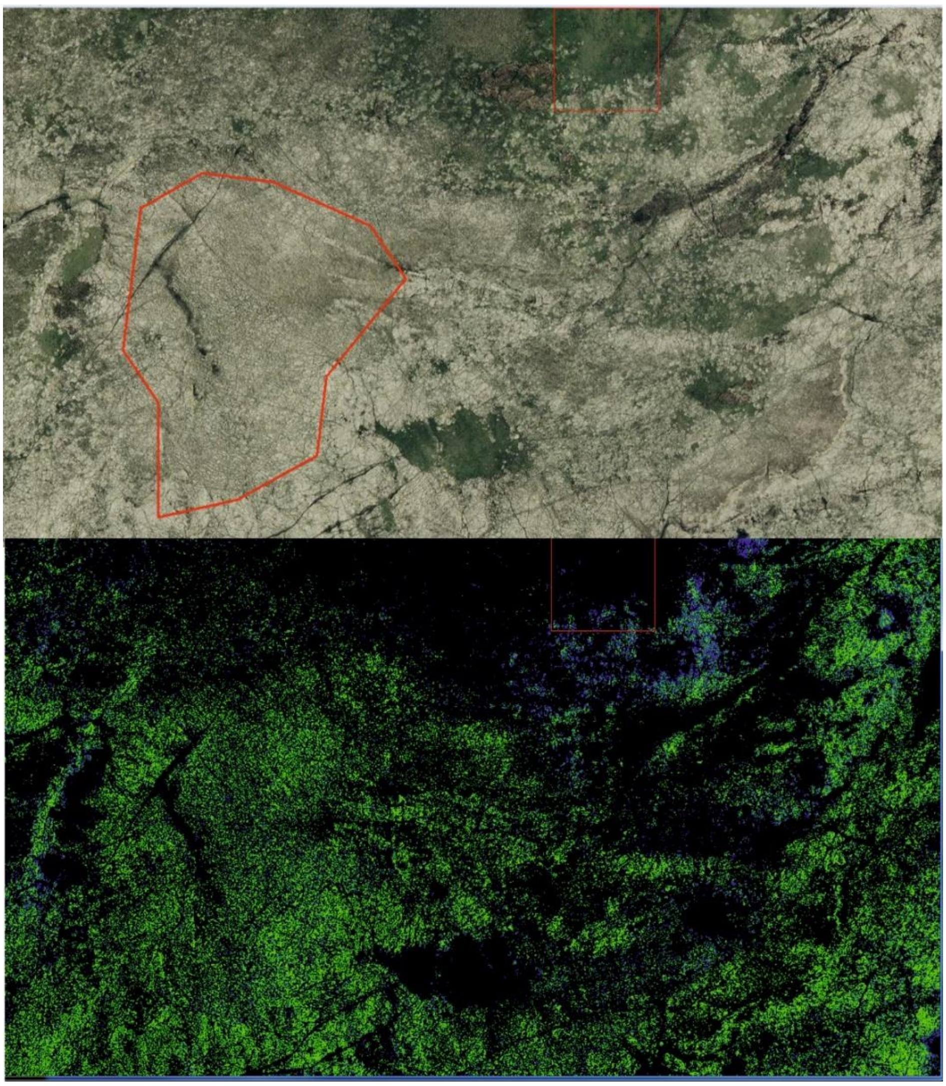

Figure 16. *An air photo of part of the Elenydd region (above) and a large irregular polygon from the National Vegetation Classification survey (red) highlighting* Molinia-*dominated vegetation, and (below) a supervised image classification of the same area highlighting regions dominated by* Molinia *(green), and one other non-*Molinia *dominated vegetation types (blue); Unclassified areas are shown as black.*

The results of the Elenydd classification were compared with air photos of the region and the polygons from the reclassified NVC data (see Figure 16). The classification appeared to accurately capture the occurrence of two different types of vegetation. Discussion of the preliminary results with ecologists from NRW identified one of the classes as *Molinia*, thus indicating that the algorithm was capable of accurately mapping its spatial distribution. This approach of utilising the *Molinia* end-member — extracted from the Elenydd region — in conjunction with a classification algorithm was employed to identify pixels with similar spectral characteristics (assumed to be *Molinia*) in all aerial photo mosaics analysed (the same mosaics for which ditches were mapped, shown in Figure 17). We subsequently undertook preliminary visual comparisons of several air photo mosaics for different parts of Wales and found there to be a very good correlation between the distribution of mapped *Molinia* and that apparent in the aerial photos. The initial results suggest that the acquisition date of aerial photographs did not adversely affect the ability to identify and map *Molinia* across Wales. Some relatively minor classification confusion was noted for some pale rock exposures, sand and road surfaces due to the spectral similarities with *Molinia* in the visible-near infrared part of the reflectance spectrum. It will also be necessary for an external partner such as NRW to undertake some further detailed validation of the final layer showing the areas classed as *Molinia*.

The result of applying the supervised classification to the entire area of upland Wales is shown in Figure 17, with regional examples shown in Figure 18. In the national-scale figure the size of the pixels where *Molinia* is present have been increased to 100 x 100 m (a 200 fold increase in both x and y scales) so that its occurrence can be viewed at this scale, whilst in the regional examples the data have been aggregated to a 10 x 10 m resolution. The data show clear spatial variations in *Molinia* presence, with the greatest occurrence in the Elenydd region of the Cambrian Mountains, and comparatively low occurrence in the Migneint area of Snowdonia. Locally high densities of pixels containing *Molinia* were observed in some areas of the Heads of the Valleys (e.g. Figure 18c), although it is possible that this could result from misclassification of other land cover types, such as forest clear-cuts.

At the original pixel scale (50 x 50 cm) *Molinia* was estimated to be present over a total area of 36 km^2 of upland peats in Wales, as defined by the unified peat map. However, this is likely to be an under-estimate of the true cover, because even areas mapped as having a high density of 50 x 50 cm *Molinia* pixels (i.e. pixels with the spectral characteristics of *Molinia*) were often found to contain a majority of 'non-*Molinia'* pixels (i.e. pixels lacking these spectral characteristics), which at this scale could (for example) represent inter-tussock areas that were not recognised by the classification algorithm as *Molinia*, or shaded areas, which nevertheless form part of a *Molinia*-dominated landscape. This is apparent for example in southern and western parts of the illustrative area shown in Figure 19, where pixel density is lower than in the north-eastern area shown. If such areas were considered *Molinia*-dominated, then the associated area would be considerably higher. For example, of the 830 km^2 of peat area analysed, 101 km^2 (12%) has a density of 50 cm pixels positively identified as *Molinia* per 10 m cell of more than 5%, and 68 km^2 (8%) has a density exceeding 10%. In reality, these areas may be partly or wholly *Molinia*-dominated, but this remains to be tested. Further consultation with NRW experts and comparison with ground-based assessments could be used to develop consistent definitions of *Molinia*-dominance for Wales, and to provide the basis (along with flux data from this under-studied habitat type) for future GHG reporting for these areas.

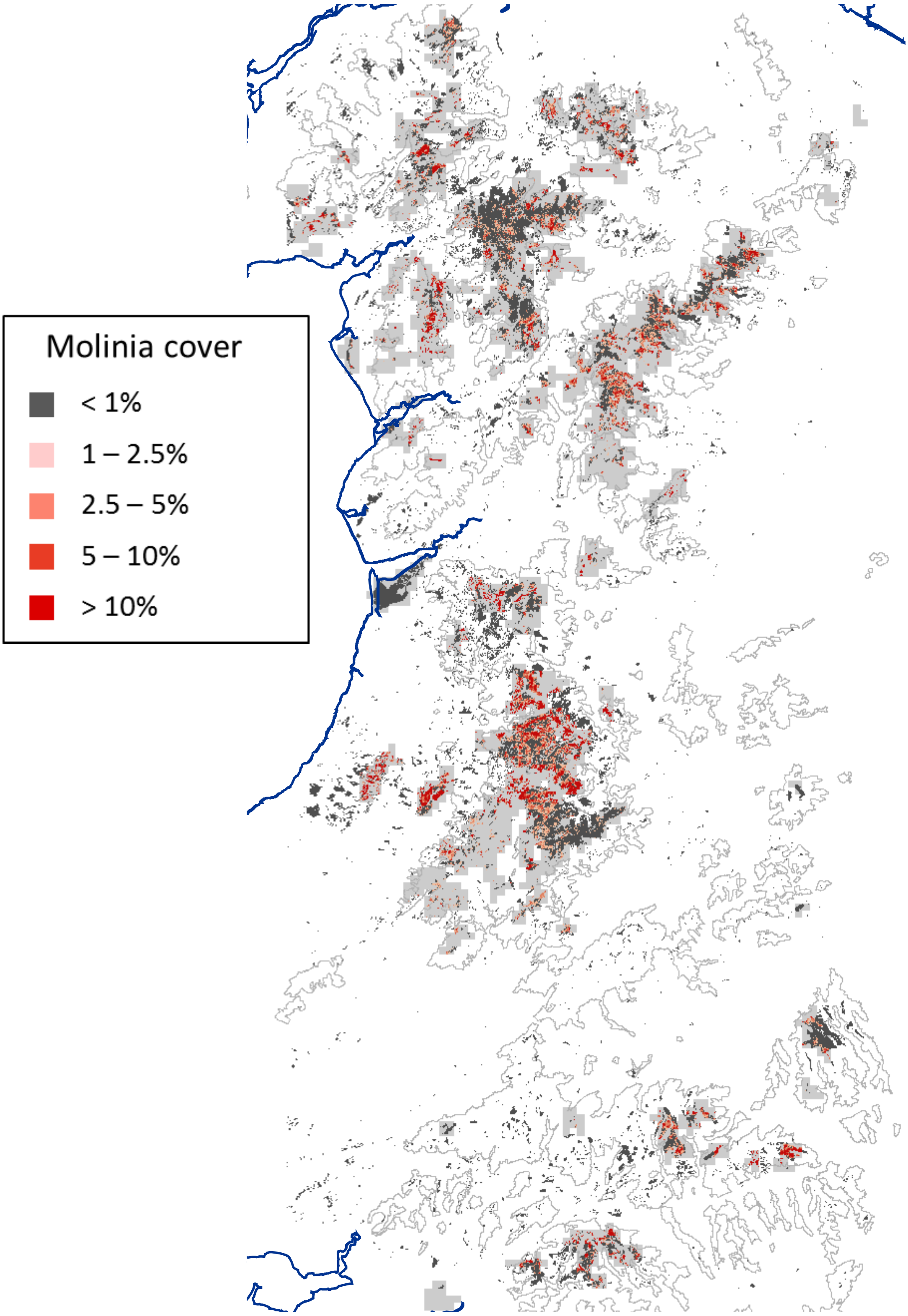

Figure 17. Molinia *dominance in upland regions of Wales based on supervised classification of 50 cm pixel air photos, clipped to the unified peat map. Data have been aggregated to a 100 m grid to permit visualisation of results at the national scale.* Molinia *density is expressed in terms of the percentage of 50 cm pixels within each 100 x 100 m pixel that were positively classified as* Molinia. *Grey 'tiles' show the areas for which aerial photographs were analysed, and the light grey outline represents the NRW Upland Boundary.*

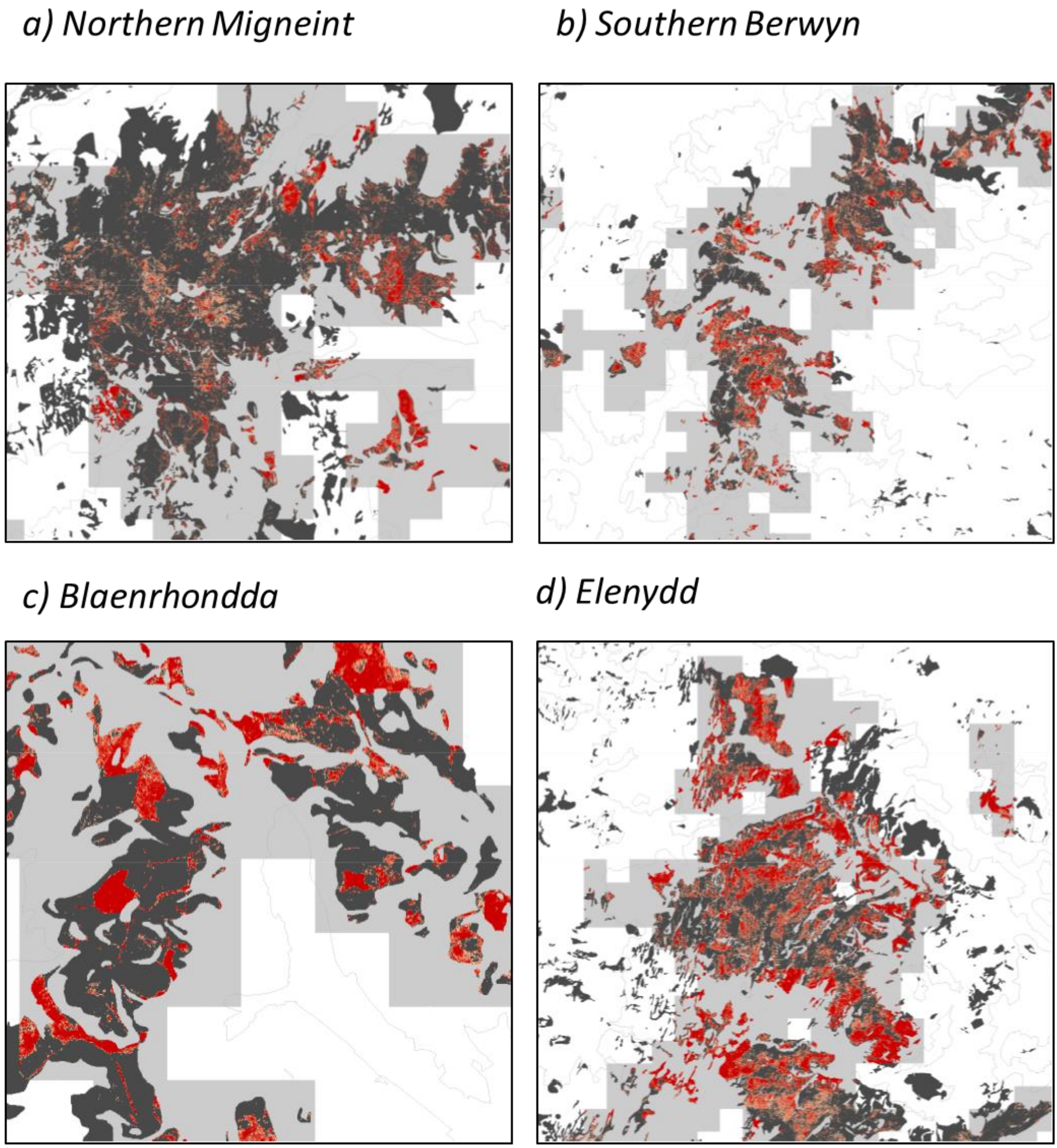

Figure 18. Molinia *dominance in upland habitat regions of Wales based on supervised classification of 50 cm pixel air photos, clipped to the unified peat map. Data have been aggregated to a 10 x 10 m grid. Colour scheme as in Figure 17.*

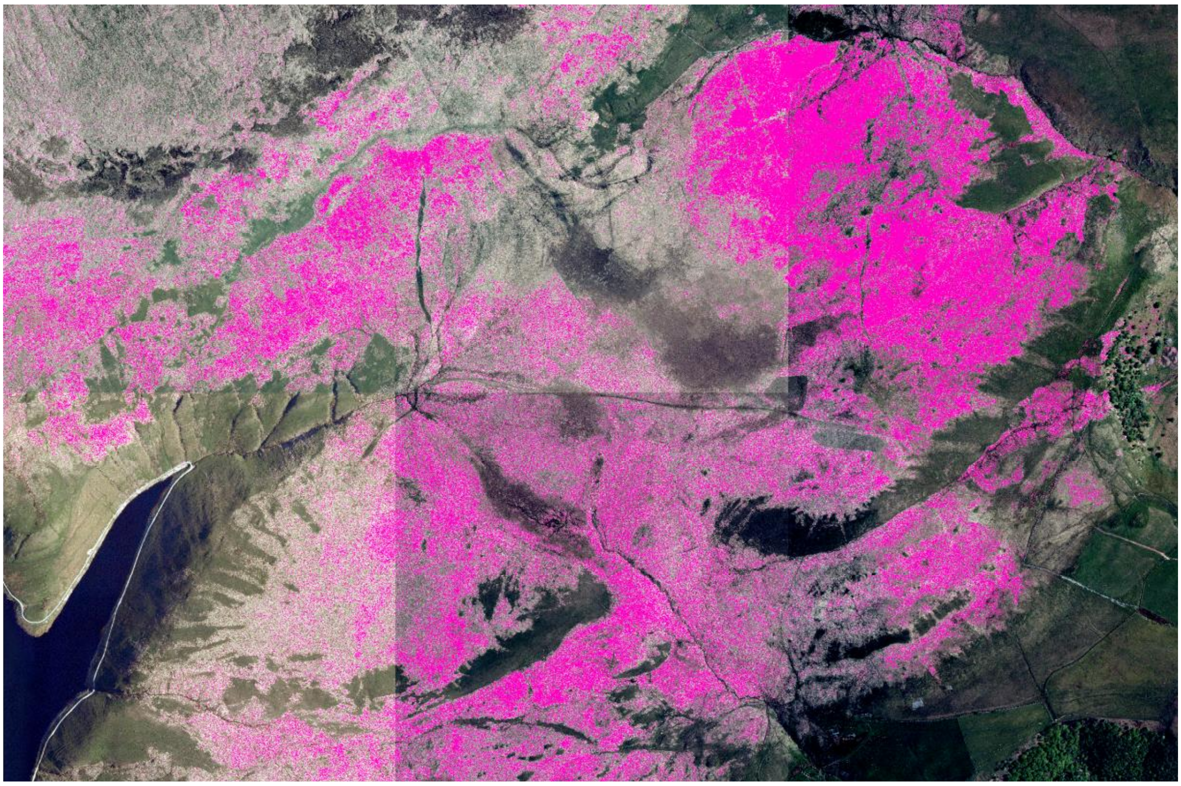

Figure 19*. An area of 3km (east-west) and 2km (north-south) to the east and north of Claerwen Reservoir, Cambrian Mountains, showing pixels with spectral characteristics indicative of* Molinia *presence*

Task 4. Condition mapping of lowland peat

As originally conceived, Task 4 involved the analysis of spatial land cover data for lowland peats, together with an assessment of whether the image classification methods developed under Task 3 could be applied to lowland areas. In practice, we have included an assessment of lowland peat condition as an integral component of the overall national-scale condition assessment, and have used to NRW Upland Boundary to differentiate patterns of land use and peat condition between the uplands and lowlands. As a result, all work relating to this task has been described elsewhere. The baseline condition assessment is described under Task 2. The identification of drainage ditches from aerial photographs was extended to include 25% of lowland peats (see Task 3), and lowland peats have been fully included in the development of national-scale GHG emissions estimates (see Task 5).

Task 5. Greenhouse gas emissions and mitigation potential of Welsh peatlands

During 2014, the new unified Welsh peat map provided the basis for a separate, preliminary assessment of the greenhouse gas emissions and mitigation potential of Welsh peatlands, as a contribution to a broader review of the potential role of land-use in climate change mitigation for the Welsh Government led by ADAS (2014). For this assessment, the peat area was classified into one of nine broad land-use and condition classes based on the CEH Land Cover Map 2007 (LCM 2007), as shown in Table 6. An estimate of the area of eroding bog was obtained from the NRW Phase 1 Habitat Map, and a number of simplifying assumptions were made, in particular that all areas mapped by LCM2007 as Heathland had been drained, whilst all areas of near-natural and modified bog remained undrained. 'Emission factors' (annual greenhouse gas fluxes per unit area of peat under a given land-use, in to CO2-equivalent ha^{-1} yr^{-1}) were obtained for CO_2, CH_4, N_2O and waterborne carbon from a combination of the IPCC Wetland Supplement (IPCC, 2014) and interim values from generated for UK blanket bogs for the Defra Peatland Code (Smyth et al., 2014). A crude estimate of the offsetting effects of tree biomass accumulation (taking into account the after-use of harvested timber) was included in the emissions calculations for peatland under forest, based on information presented in Broadmeadow and Matthews (2003). For further details see Annex 8 of ADAS (2014). The results of this assessment suggested that Welsh peatland emit in the region of 390 kt CO_2-eq yr^{-1}, with peatland under improved grassland making the largest overall contribution, followed approximately equally by coniferous woodland on peat, and modified and drained bog (Table 6). The largest emissions per unit area result from peat under improved grassland or arable agriculture, and from eroding (primarily upland) bog. A 'theoretical maximum' estimate of the climate change mitigation that could be achieved through fully re-wetting and restoring all Welsh peatlands to near-natural status was put at 320 kt CO_2-eq yr^{-1}.

Table 6. *Preliminary assessment of emissions and mitigation potential of Welsh peats based on the unified peat map, the reclassified CEH Land Cover Map 2007, and IPCC/Peatland Code emission factors (ADAS, 2014)*

land-use category	Area	Current emissions	Emissions if restored	Maximum potential emissions reduction	
	(ha)	kt CO_2-eq yr^{-1}	kt CO_2-eq yr^{-1}	kt CO_2-eq yr^{-1}	t CO_2-eq ha^{-1} yr^{-1}
Improved grassland	5453	134	3	131	24.0
Coniferous woodland	6887	60	4	56	8.2
Modified bog and rough grassland	53306	77	28	49	0.9
Heathland (assumed drained)	13527	55	7	48	3.6
Arable	972	33	7	26	27.3
Eroding bog	450	10	0	10	22.8
Broadleaf woodland	1612	14	11	3	1.9
Near-natural bog	7301	4	*Not applicable*		
Near-natural fen	367	2	*Not applicable*		

Following this analysis, a revised analysis of Welsh peatland emissions was carried out as part of a broader UK assessment for the Department of Energy and Climate Change (DECC) (Evans et al., 2014b).

The methodology broadly corresponded to that described above, but with a number of differences. Firstly, interim data from Task 3.3a above were used to generate an initial estimate that 10% of the peat area of Wales comprised drained semi-natural bog; this estimate was used in place of the heathland value (around 15% of the total peat area) derived from LCM2007. Additionally, data from the UK Greenhouse Gas (GHG) Inventory were used to estimate the (small) area of peat extraction sites in Wales, and their associated emissions. Offsetting CO_2 sequestration into tree biomass was omitted, as this is accounted for separately in the GHG Inventory. Finally, revised EFs were taken from recently completed work for the Peatland Code (Smyth et al., 2015), and assigned to each of the broad condition categories of Table 2. This assessment provided a slightly higher estimate of total peatland GHG emissions in the 1990 base year for GHG reporting, of 418 kt CO_2-eq yr^{-1}, reducing to a value of 383 kt CO_2-eq yr^{-1} at present day, as a result of peat restoration projects and agri-environment measures undertaken during the intervening period.

Following the completion of Task 3, we are now able to undertake a revised assessment of Welsh GHG emissions based on i) the unified peat map (as above); ii) the reclassification of peat land-use/condition based on NRW Phase 1 data; and iii) digitised ditch data. Note that at this stage the *Molinia* cover data have not been used.

Estimates of total drainage extent were derived as follows (see also Task 4):

1) Peat areas were divided into upland and lowland regions based on the NRW Upland Boundary, and areas of each aggregated Phase I peat land-use/condition category were calculated.
2) For each land-use/condition category (split by upland and lowland), the drained area was estimated (for those areas where ditches had been digitised) for a range of buffer distances (10m to 50 m)
3) For each land-use/condition category, the percentage of the total area present within each region (i.e. upland/lowland) for which ditches had been digitised was calculated
4) Estimates of total drained area within each category were made by assuming that the proportional area drained was the same in unmapped areas as it was in mapped areas.
5) For more intensive land-use categories (i.e. conifer forest, intensive grassland, arable), all areas were assumed to be drained (note that drains could generally not be detected beneath tree canopies from aerial photographs, but are a consistent feature of conifer plantations).

To estimate GHG emissions it was also necessary to further aggregate some peat land-use/condition categories (as in the previous assessments) because sufficient data are not yet available to support the use of different emission factors; for example, areas of modified bog, heathland and acid grassland on peat were all assigned the single set of emission factors for modified peatland. Similarly, for fens remaining under semi-natural vegetation there are currently no emissions data that would permit different emissions estimates to be applied. The aggregation used is shown in Table 7. The small area of former peat extraction site in Wales (located on the border with Shropshire) was not specifically captured in the analysis undertaken for Task 2, but has been mapped from aerial photographs for the UK Greenhouse Gas Inventory (see Evans et al., 2014b) and was therefore included in the assessment. Investigation showed that the area concerned was largely classified as modified bog in the Phase 1 assessment, and the equivalent area was therefore subtracted from this category.

Table 7. *Aggregation of Phase 1 classes for estimating GHG emissions*

Aggregated Phase 1 category	Area (ha)	EF category (undrained)	EF category (drained)	EF source
Bog – unmodified		Bog - near natural	Bog - drained	Peatland Code
Bog – modified		Bog - modified	Bog - drained	Peatland Code
Bog – eroding		Bog - eroding	Bog - eroding	Peatland Code
Fen – unmodified		Fen – near natural	Fen – near natural[1]	IPCC
Fen – modified		Fen – near natural[1]	Fen – near natural[1]	IPCC
Fen – swamp		Fen – near natural[1]	Fen – near natural[1]	IPCC
Wet heath		Bog - modified	Bog - drained	Peatland Code
Dry heath		Bog - modified	Bog - drained	Peatland Code
Bracken		Bog - modified	Nutrient-poor grassland	IPCC
Marshy grassland		Bog - modified	Nutrient-poor grassland	IPCC
Unimproved grassland		Bog - modified	Nutrient-poor grassland	IPCC
Semi-improved grassland		Bog - modified	Nutrient-poor grassland	IPCC
Improved grassland		Nutrient-rich grassland[2]	Nutrient-rich grassland	IPCC
Arable		Arable[2]	Arable[2]	IPCC
Scrub		Bog - modified	Forest[3]	IPCC
Broadleaf		Forest[3]	Forest[3]	IPCC
Scattered/felled broadleaf		Forest[3]	Forest[3]	IPCC
Conifer		Forest[3]	Forest[3]	IPCC
Peat extraction[4]	482	Peat extraction	Peat extraction	IPCC

[1]*No EF data currently available for drained, degraded or modified fen remaining under semi-natural vegetation, therefore the IPCC Tier 1 EF for near-natural fen was applied to all categories*

[2]*All improved grassland and arable land assumed drained*

[3]*Forested areas assumed to be drained, and assigned the single IPCC Tier 1 EF for drained temperate forest*

[4]*Peat extraction areas mapped separately by UK LULUCF Inventory, subtracted from the area of modified bog*

Compared to the previous, LCM2007-based emissions assessments (ADAS, 2014; Evans et al., 2014b), the classification of Welsh peat according to Phase 1, and incorporating the new drained area estimates, resulted in some significant changes in the total areas assigned to each emission factor category (Table 8). In particular, the new assessment suggests a much larger area of undrained, near-natural bog, but smaller areas of modified and drained bog. The total conifer area is larger, whilst the broadleaf area is reduced. As noted earlier, the Phase 1 classification suggests much larger areas of peat under grassland and fen, and greater reduced areas under arable.

***Table 8**. Total areas assigned to each emission factor class based on the current assessment ('Phase 1', including new drained area estimates) and for the previous DECC analysis ('LCM2007', based on interim drainage estimates)*

Emission factor category	Areas (ha)		
	LCM2007	Phase 1	Difference
Bog - Near natural	7301	21109	13807
Bog - modified	57252	35171	-22081
Bog - drained	9099	5343	-3756
Bog - eroding	450	226	-224
Woodland - conifer	6887	8574	1687
Woodland - broadleaf	1612	635	-977
Nutrient-poor grassland		6428	6428
Nutrient-rich grassland	5453	6582	1129
Cropland	972	102	-870
Fen - near natural	367	4387	4020
Peat extraction	482	482	0

Based on this analysis we estimated that total GHG emissions from Welsh peatlands are currently in the region of 550 kt CO_2-eq yr^{-1}. This compares to estimated natural emissions from Welsh peatlands (i.e. if all currently mapped peat area was natural bog or fen) of approximately 140 kt CO_2-eq yr^{-1}. A crude assessment was also made of the changes in emissions that have occurred since 1990 as a result of drain-blocking restoration work that has taken place (primarily on upland blanket bogs) during this time, and of the area of upland bog that was subject to grazing reductions under Tir Gofal. This analysis, which was made as part of the initial assessment of Welsh GHG emissions for DECC (Evans et al., 2014b) assumes that all peat re-wetting projects were effective, and that the grazing measures implemented under Tir Gofal were sufficient to convert blanket bog from 'modified' to 'near-natural' status. These are fairly significant and possibly questionable assumptions, which should be possible to test based on results from GMEP in future. Comparing estimated present-day emissions to natural 'reference' emissions suggests a maximum climate mitigation potential (if all Welsh peatlands were returned to near-natural condition) of around 300 kt CO_2-eq yr^{-1}.

Figure 20 illustrates the contribution of different land-use/peat condition categories to total GHG emissions. Figure 21 represents the first national-scale map of GHG emissions from Welsh peatlands, and Figure 22 shows some smaller-scale examples for individual peat-dominated regions, highlighting the small-scale and inter-regional variability of mapped emissions, as a function of land-use (e.g. improved grassland in Figure 22a, conifer plantations in Figure 22c, and drainage ditches in Figures 22a-b. For Welsh peatlands as a whole, the main sources of GHG emissions are believed to be improved and unimproved grassland on peat (58% of all emissions), followed by conifer plantations (17%). Drained, modified and eroding bogs are estimates to have contributed around 15% of GHG emissions in 1990, reducing to around 7% at the present time as a result of restoration and agri-environment measures. However it is important to note that the latter figure carries a large uncertainty as it assumes a high success rate for the restoration measures undertaken, which may not have been achieved in reality. Furthermore, it is worth noting that gains achieved through grazing measures may be delayed due to lags in ecosystem recovery, or temporary if grazing controls are not maintained under subsequent agri-environment schemes.

It is also worth noting that the analysis presented here suggests a higher total GHG emission from Welsh peatlands than the two analyses carried out previously (ADAS, 2014; Evans et al., 2014b). The reasons for this lie in the different land areas in each emissions category shown in Table 8, which result from the use of different land cover and drainage data. This increase is overwhelmingly attributable to the larger grassland area on peat derived from the Phase 1 dataset, which has high emission factors based on IPCC Tier 1 defaults. Whether such high emission factors (derived from flux studies carried out on lowland grassland sites in England, the Netherlands and Germany) are applicable to Welsh grasslands, and to unimproved upland grasslands in particular, is open to question. If unimproved upland grassland was instead assigned the emission factor for modified bog, for example, total emissions for Wales would reduce to 413 kt CO_2-eq yr^{-1}, similar to the previous assessments (and with the remaining difference attributable to higher 'reference' emissions due to the larger areas of fen peat identified from the Phase 1 analysis). The sensitivity of the total emission estimates to the grassland emission factor highlights both the need for caution in relation to the values presented, and to the specific need for improved emissions data for the different types of Welsh grassland on peat.

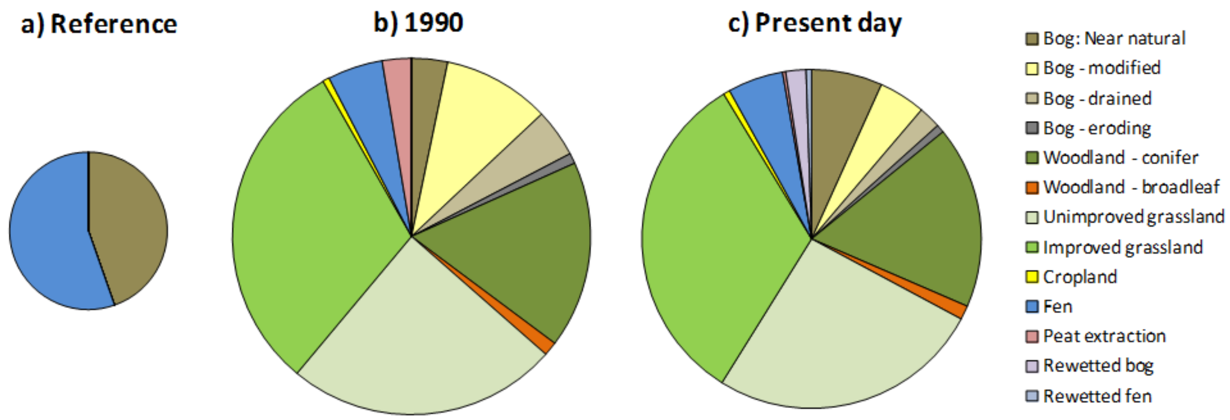

Figure 20. *The estimated contribution of different peat land-use/condition categories to total greenhouse gas emissions from Welsh peats under a natural 'reference' condition, in 1990, and at present day. The size of each pie chart is illustrative of the overall level of emissions.*

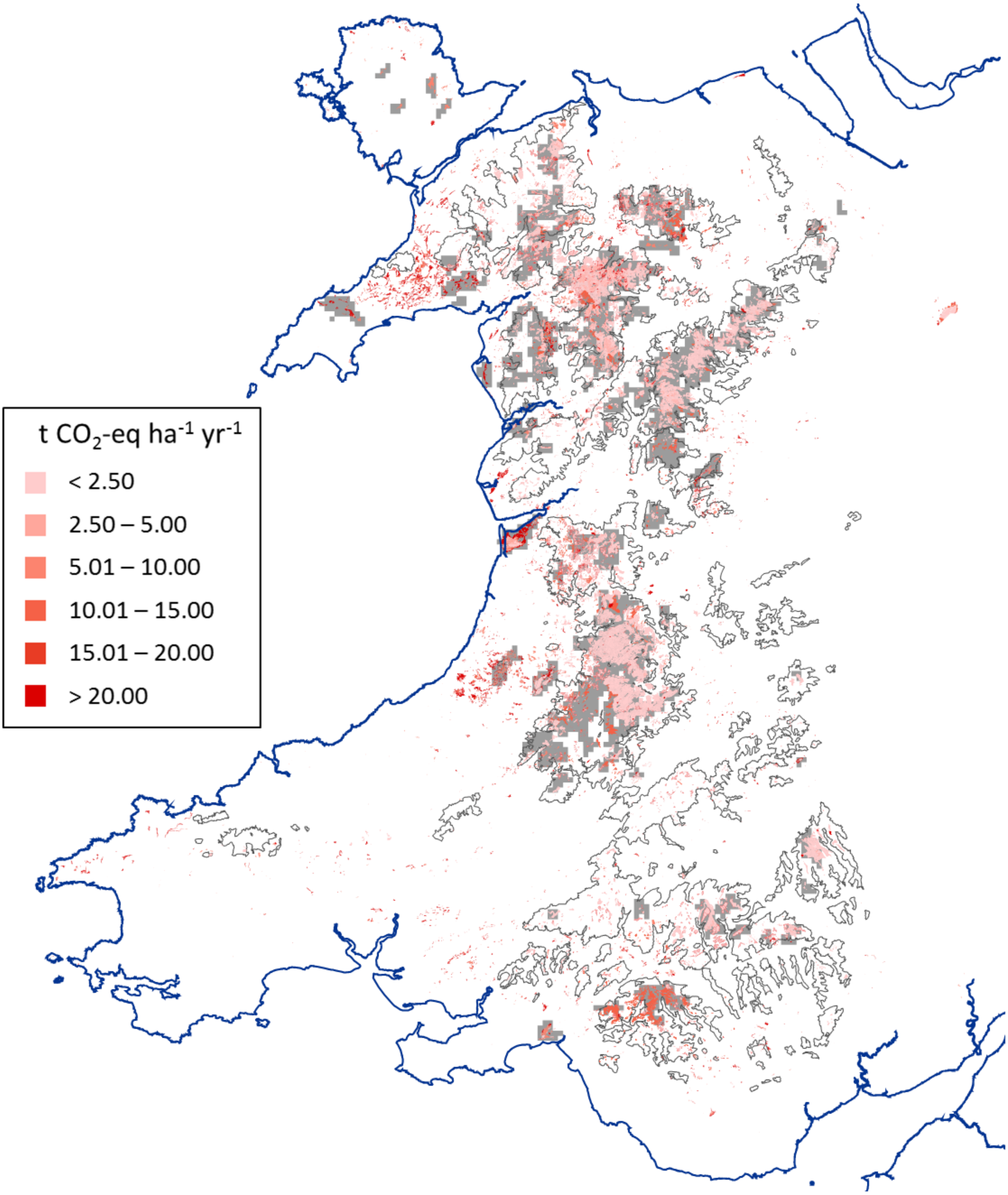

Figure 21. *A map of estimated total greenhouse gas emissions from Welsh peatlands. Note that emissions associated with drainage can only be shown for areas where drains have been mapped (grey tiles) and for land-use categories where full drainage is assumed (e.g. forestry, improved grassland). The effects of drainage in unmapped areas is incorporated in national emissions estimates, but cannot be presented on the map. Grey lines show the NRW Upland Boundary.*

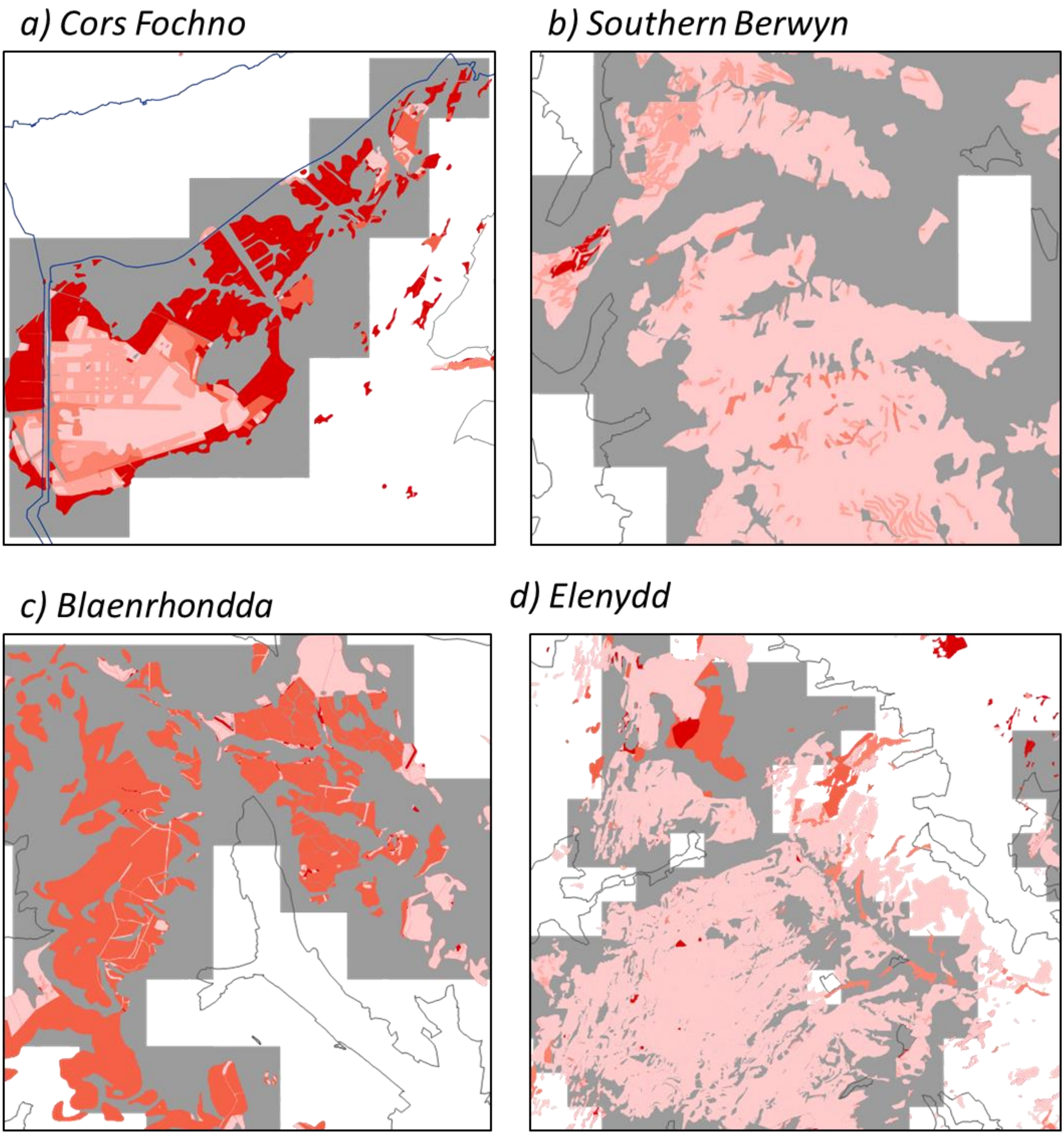

Figure 22. *Example maps of estimated total greenhouse gas emissions for a range of peatland areas. Note that emissions associated with drainage can only be shown for areas where drains have been mapped (grey tiles) and for land-use categories where full drainage is assumed (e.g. forestry, improved grassland). Grey lines show the NRW Upland Boundary. Scale varies between figures.*

Recommendations for Future Work

The work described here represents one of the most comprehensive, national-scale assessments of peat extent and (broad) condition that has been undertaken to date. To our knowledge, this is also the first time that national-scale peat land-use and condition ('activity') data have been combined with IPCC default (Tier 1) and country-specific (Tier 2) 'emission factor' data in order to generate a fully spatially distributed assessment of total greenhouse gas emissions from managed peatlands, following the methodology set out in the IPCC Wetland Supplement (IPCC, 2013). Nevertheless, this remains a preliminary assessment, and the work undertaken to date has highlighted a number of key areas of uncertainty, or incomplete evidence, that could be resolved through additional work. On this basis, we make the following recommendations for further work that could be undertaken in order to produce more robust estimates of GHG emissions from Welsh peatlands, as well as the GHG benefits of peatland restoration, in future:

1. **Ground truthing**. Mapped data on peat extent, dominant vegetation and ditch occurrence would all benefit from ground-based verification via new field surveys (e.g. peat probing, ditch surveys) and/or assessment against existing high-resolution data such as NVC-level vegetation mapping. This work could be undertaken by, or in collaboration with, NRW. Opportunities may also exist to support this work through the involvement of other organisations such as the National Parks, NGOs and/or volunteers. The benefit of these activities would be maximised if coordinated with the existing mapping work to identify areas where ground-truth data would be beneficial, and to ensure the application of consistent methods across sites.
2. **Completion of ditch mapping**. For this assessment, ditches were mapped from aerial photos encompassing 73% of upland peat and 29% if lowland peat. Estimates of total ditch length were obtained by extrapolating results from these areas to unmapped areas, assuming the same ditch density, but this assumption may not be correct as the selection of areas for mapping was biased towards larger, predominantly upland peat areas (in order to maximise the spatial coverage possible with the resources available, and to reflect the original remit to map ditches on blanket bog) and the drainage characteristics of smaller (especially lowland) peat units may be different. Additionally, although national-scale estimates of GHG emissions could be obtained by extrapolating results to unmapped areas, we could not directly map drainage-related emissions from areas without digitised ditch data. Completing the task of mapping all drainage features would enable a more reliable and complete assessment of GHG emissions from Welsh peatlands to be undertaken, and would also support prioritisation of restoration activities based on a comprehensive national dataset.
3. **Use of digital terrain data to improve mapping of drainage impacts.** The mapping of drainage ditch impacts on water table in the current assessment was based on a simple method whereby fixed buffer distances (10 to 50 m depending on peat type) were applied either side of each ditch. In reality the impact of a ditch on surrounding water tables depends on the local slope, and the orientation of the ditch relative to that slope. For example, ditches running laterally across a hillslope may be more effective than ditches running directly downslope, as they intercept and divert flow moving down the hillslope, creating a 'dry shadow' effect below the ditch. Combining the existing ditch map with digital terrain data and a simple hydrological model would permit a more accurate assessment of the drainage impacts of ditches. Again, this would also support the prioritisation of restoration investment towards those ditches shown to be having the greatest drainage impact.
4. **Further development of *Molinia* classification methods from aerial photographs.** In the current assessment, we prioritised the mapping of *Molinia* as a dominant feature of modified blanket bogs, which is believed to have had a detrimental impact on peat carbon sequestration. The '*Molinia* dominant' data-set needs to be ground-truthed against field survey based assessments of areas

dominated by *Molinia caerulea*. This includes the NVC mapping undertaken by NRW and its contractors where *Molinia* dominated vegetation has been mapped either in terms of plant communities (including M25 and the non-NVC M25 species-poor *Molinia* category) or stands where dominant *Molinia* has been mapped as a condition category, and also Phase I habitat surveys where *Molinia* was mapped as a dominant species-code. There is also potential to 'calibrate' the aerial photograph based classification (which appears to provide an indication of *Molinia* presence rather than an absolute cover estimate) using ground survey data, in order to produce more accurate large-scale cover estimates.

5. **Application of classification methods from aerial photographs to other vegetation types.** The potential exists to extend this approach to capture a broader range of vegetation types, such as *Calluna*, *Eriophorum* or *Sphagnum* dominance, as the basis (together with ditch data) for mapping peat condition and associated GHG emissions at a landscape scale, particularly given that NVC data is available for 'training' remote sensing data-sets . This would be particularly valuable for blanket bogs, where variations in peat condition and condition occur continuously across the landscape, and may be hard to capture fully using through ground-based surveys. Establishing an objective classification system for bog vegetation based on aerial photograph data would both enhance the current assessment of Welsh peat condition, and also provide a baseline from which future changes in condition could be monitored at the landscape scale.
6. **Collection of new greenhouse gas flux data**. At present, the resolution of greenhouse gas emissions mapping is limited more by a lack of reliable flux data than by the spatial resolution of the underpinning mapping data. For example, the 'modified' blanket bog category used in the Peatland Code, and used for GHG mapping in the current study, currently encompasses multiple forms of modification, such as grouse moors subject to managed burning, areas with high pollution levels that have been subject to *Sphagnum* dieback, and areas affected by *Molinia* encroachment. It is probable that these areas all have different associated GHG fluxes, but a lack of primary flux measurement data currently precludes their treatment as separate categories. In particular, there are *no* published data on GHG emissions from *Molinia*, despite the large areas of Wales and Southwest England affected by its encroachment. Similarly, there are few UK flux data from improved grassland of forestry on peat, and none from Wales, so that it has been necessary to use the (high) IPCC Tier 1 default emission factors for these land-use categories. Further flux measurements from peat land-use/condition categories shown to occupy a large part of the Welsh peat resource, and/or to make a large contribution to total estimated peat GHG emissions, would contribute greatly to reducing current uncertainties in emissions estimates.
7. **Development of national prioritised framework for action**. This is already being taken forward by NRW, but additional resources could be used to help develop a robust GIS-based framework which summarises the priorities for restoration in terms of biodiversity and carbon within the context of a range of key data-sets, including SSSI condition, associated species, climate change, connectivity benefits and likelihood of coastal/alluvial flooding.

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