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Peatland restoration and potential emissions savings on agricultural land: an evidence assessment

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1 Executive summary

1.1 Aims and findings

Peatland restoration has a significant role in tackling the global climate emergency and helping Scotland meet its ambitious climate change targets. Globally, peatlands are the largest natural terrestrial carbon store, containing about 25% of global soil carbon. However, they have been damaged by overexploitation. The Scottish Government has committed to restoring 250,000 hectares of peatland in Scotland by 2030. About a quarter of Scotland's area is covered in peat, storing over 3 billion tonnes of carbon.

Peat also provides a range of other co-benefits. Changing some current uses of peatland, particularly for agriculture, may lead to significant savings in greenhouse gas (GHG) emissions and offer some of the highest per hectare emissions savings.

This report assesses the current evidence for the potential for emissions savings from re-wetting peatland currently used for agriculture in Scotland and explores alternative uses that might provide an economic return.

1.2 Key findings

- The quality and coverage of spatial data on peatland in Scotland is mixed. In the last 40 years, a variety of different datasets have been gathered at different times on Scotland's soils, land use and land cover. Examples include: where best to grow arable crops, the presence of different vegetation types, and the proportion of different soils within an area of land.
- The relevance of resulting datasets to spatial variability of peat GHG emissions has been inconsistent. Specifically, the definition of what constitutes drainage is critical to the outcome of mapping exercises with currently available data products; no mapping has specifically targeted this question.
- On emissions reduction potential:

  - Emissions resulting from land use on peatlands have only recently been included in the Provisional UK greenhouse gas emissions national statistics.
  - Peatland with the poorest agricultural production capability presents the greatest opportunity for emission reductions.
  - While cropland on peat has a very high emission factor per unit area, it only covers a small area of Scotland, and so does not contribute meaningfully to the emissions inventory. Broadly, emissions are dominated by the drained heather-dominated or grass-dominated or eroded peatland and extensive grassland land categories (due to their spatial extent rather than emission factors).
- We found low capacity (small spatial extent scattered over multiple sites) for and high costs of 'alternative' agricultural practices such as paludiculture (the growth of crops on rewetted peat, often for bioenergy).
- There is strong evidence for emissions reductions potential across a significant proportion of Scotland's peat area, which could be achieved through rewetting/restoration.
  - Most of the emissions reduction could be achieved on poor production quality land where extensive grazing is currently carried out. However, there are social impacts where specific land management practices are common (e.g. crofting).
  - The geographical areas of Scotland likely to provide the highest levels of emission savings are Shetland, Lewis, the Monadhliath Mountains, several areas in the Cairngorm Mountains and in Sutherland, as well as several localised areas within Ayrshire, Dumfries and Galloway, the Borders and Lanarkshire.
  - A relatively small area of good quality agricultural land that is currently under more intensive grazing or arable management could also provide large emission reductions per unit area. However, the financial impacts on land managers would be significantly greater on this higher quality land, while providing only a small fraction of the cumulative GHG emission reductions that could be achieved on the poorer quality land.
- Uncertainties remain as to the extent and location of peat in Scotland, and as to the limitations of the data sources available to classify current land cover. It is important to note that our approach here differed to that used in the data sources for the UK Greenhouse Gas Inventory; further alignment is needed.
- There are management alternatives, including some that permit cropping on rewetted peat. However, only very small-scale Sphagnum farming and bioenergy crop production have some precedent in the UK or EU countries with similar climates. There are significant barriers to these alternatives, due to major changes being required to farming practices, market accessibility and other economic considerations. Additionally, evidence for the effectiveness of these alternatives, both for emission reductions and in terms of economic benefit, is from other countries (largely Germany and the Netherlands), and under different climatic and topographic conditions.

1.3 Conclusions

We have identified specific locations across Scotland where there may be GHG emission reduction opportunities, largely on low-grade agricultural land (very often upland heath vegetation on peat). Holdings for this type of land often cover large areas; because of this the potential exists to achieve significant emission reductions through engagement with a small number of key land managers. Ongoing improvement of datasets would improve the accuracy of this assessment. Additionally, further work would improve our understanding of the effectiveness of various paludiculture practices in reducing GHG emissions.

Contents

Glossary of terms

BEIS: UK Government's Department for Business, Energy & Industrial Strategy

Bioenergy crops: crops that are grown to be processed for fuel or burned directly

CO_2e: the standard unit for greenhouse gas, used to determine and quantify the greenhouse gas impact of different GHGs

Cutover: peat where the biologically and hydrologically active surface layer has been removed, preventing natural sphagnum moss regeneration

Drained (peat context): peat that has been drained either artificially through ditches or (in this report) effectively through management processes that have resulted in the formation of drainage channels

Emission factor: coefficient allowing conversion of activity data into GHG emissions

GHG: Greenhouse Gas

Ha: Hectare

IACS: Integrated Administration and Control System; system for supporting farm subsidy applications

IPCC: Intergovernmental Panel on Climate Change

LCM2007: Land Cover Map 2007 dataset/report, produced by CEH

LCS88: Land Cover of Scotland 1988 dataset/report, produced by Macaulay Land Use Research Institute

Paludiculture: productive agricultural or forestry practices on wet or rewetted peat, aimed at minimising GHG emissions while continuing land use

Peat: soil composed of accumulated organic matter that is only partially decomposed; in Scotland, the technical definition of peat requires 50 cm depth of organic matter from the soil surface

Peatland Action Project: a programme of peatland restoration coordinated by NatureScot, linking funds for site restoration to survey and monitoring

Remote sensing: the use of data captured from equipment at a distance from the object of interest; commonly taken to imply the use of drones, aerial photography or satellite imagery

Sphagnum: a family of moss species commonly associated with peat bogs across the UK, with slow decomposition rates under wet and cool conditions

Tier 1, Tier 2, Tier 3 etc.: levels of increasing methodological complexity and sophistication for approaches adopted by the IPCC for assessment of GHG emission from landscapes

2 Review of evidence

2.1 Summary of geographical peatland areas of Scotland likely to provide the highest level of emission savings

Peat is a soil type formed of organic material from plants that is only partly decomposed, due to climatic or local constraints that manifest themselves through waterlogging at small to landscape scales since the last Ice Age. Approximately a quarter of Scotland's area is covered in peat, storing over 3 billion tonnes of carbon.

Mapping of Scotland's peat has progressed through several stages over the last 50 years, from surveys of individual bogs to national-level efforts combining remote sensing and modelling with field surveys. In the last 20 years, increased appreciation of peat as a carbon sink (and potential source) has created a new impetus to understand where peat is, what condition it is in and what land uses these historically undervalued areas have been converted to. This report targets GHG emissions of agricultural peat, providing evidence of where and how these emissions may be reduced.

2.1.1 The wider context - peatland emissions reporting in the inventory

Scotland's GHG emissions are reported as part of the UK greenhouse gas emissions national statistics[1]. At the present time, the contribution of peatland emissions to the land use sector figures has only recently been included in a provisional version of these statistics[2]. This is based on analysis of draft peatland emission factors and spatial mapping of land use patterns on peat by Evans et al. (2017) [3].

2.1.2 The methodology for this review

We used spatial data products of peat extent, carbon content, land cover and land use (Section 6, Annex of maps and data) to map the likely current land use on peatland across Scotland.

Figure 1 shows the map of peat emission factor categories we developed from existing evidence. This map includes all areas identified as peatland in the previous Evans et al (2017) report to UK BEIS. An improvement on the previous report to BEIS was made in this evidence assessment: we used more advanced peat mapping[4] in which further peat deposits were discovered in Scotland and where areas with significant spatial uncertainty in the Evans et al (2017) underlying data could be clarified.

Figure 2 shows these same areas but with the emission factor categories replaced by their respective emission factor values. Large areas where low to moderate emission factor (0-4 t CO_2e ha^{-1} yr^{-1}) have been identified are visible in green. Several moderately large areas of high emission factor (4-8 t CO_2e ha^{-1} yr^{-1}) are visible in yellow, scattered across the country. Most of the locations with very high emissions (orange, brown) are areas of quite small spatial extent and thus not visible on a national extent map.

Figure 3 is used to clearly show examples of areas with higher emission factors that are scattered throughout Scotland, with large areas visible in Shetland, Lewis and Harris, the area between Inverness and Kingussie, and south of the Central Belt. The data from these figures is summarised in Table 1, which provides an estimated total area and annual emissions for each emission factor category. This gives a total for estimated

[1] https://data.gov.uk/dataset/final-uk-greenhouse-gas-emissions-national-statistics
[2] https://data.gov.uk/dataset/9a1e58e5-d1b6-457d-a414-335ca546d52c/provisional-uk-greenhouse-gas-emissions-national-statistics
[3] Evans et al. (2017)
[4] Aitkenhead & Coull (2019)

emissions from agricultural peat of 8.8 Mt CO_2e, which is lower than the total given in the CCC Net Zero report (9.7 Mt CO_2e). This difference appears due to different peat extent in the multiple maps used, and also to different approaches in identifying emission factor categories between the Evans et al (2017) report and the present work, which uses a different functional definition of drainage to the previous effort (see Annex).

The emissions associated with these land uses (called 'activity data' in the UK Emissions) were used as per the draft UK-specific emission factors (termed 'Tier 2") for consideration to be included in the UK National Greenhouse Gas Inventory[5] (see also Section 4). Further details on the Tier concept are given in the Glossary.

2.1.3 Emission factor mapping

The methodology for developing the following maps is given in the Annex of Methodologies and Underlying Assumptions. Briefly, the steps followed are: (1) identification and mapping of the types of land use/land management on peat throughout Scotland; (2) mapping of the emission factor values using Tier 2 values from[6]. Areas with higher emission factors have the greatest potential for reducing emissions if restored to functional peatland.

[5] Evans et al. (2017)
[6] Evans et al. (2017)

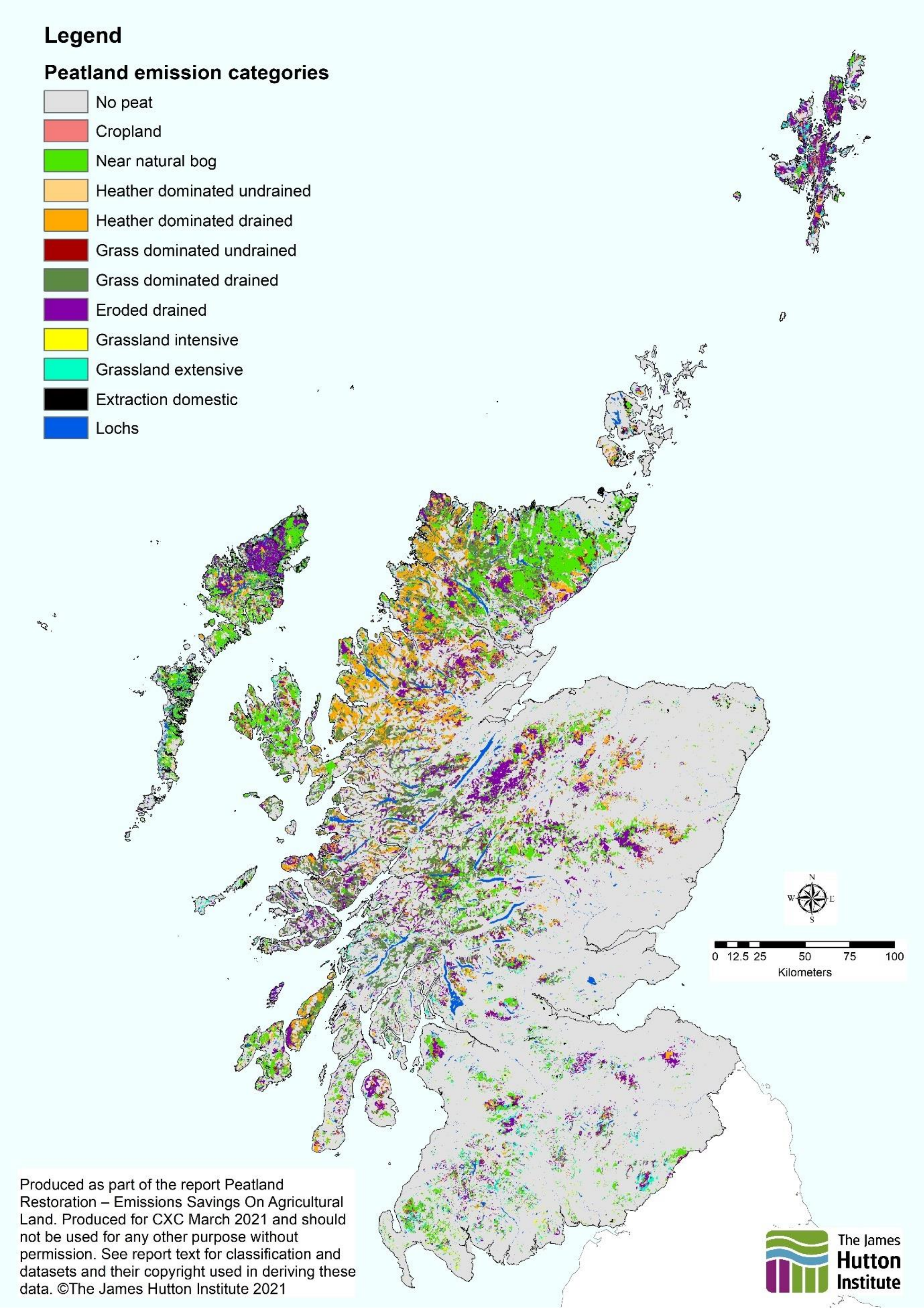

Figure 1. Map of peatland emission categories.

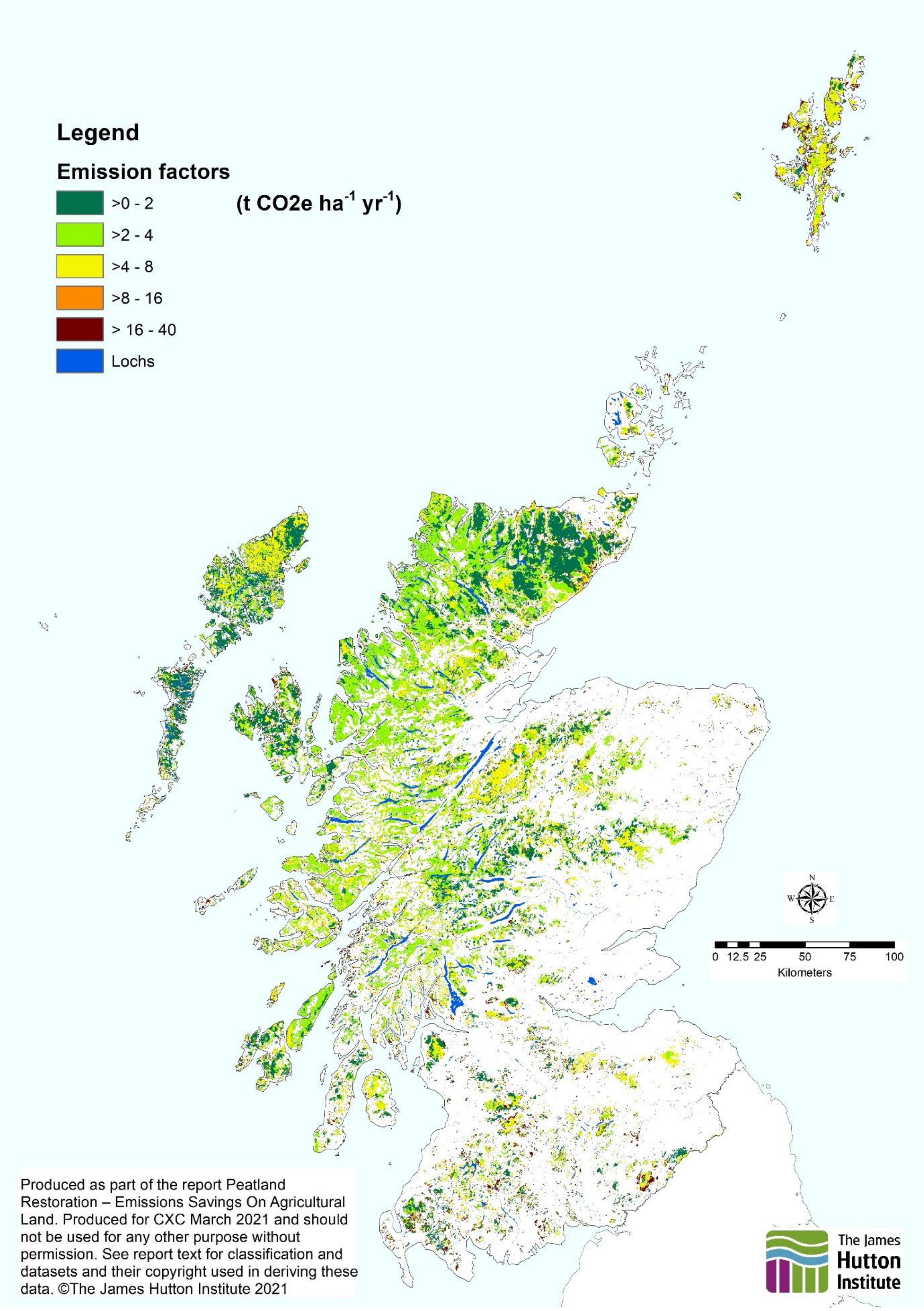

Figure 2. Map of emission factors for peatland under agriculture/no agriculture

Peatland emission category	Area (ha)	Draft Tier 2 Emission factor (t CO_2eq ha^{-1} yr^{-1}	Emissions (t CO_2eq yr^{-1})
Cropland	73	38.98	2,846
Near natural bog	638,100	0.01	6,381
Heather dominated undrained	21,121	2.08	43,932
Heather dominated drained	389,796	3.40	1,325,306
Grass dominated undrained	30,244	2.08	62,908
Grass dominated drained	412,180	3.40	1,401,412
Eroded drained	591,266	4.85	2,867,640
Grassland extensive	108,019	19.02	2,054,521
Grassland intensive	24,111	29.89	720,677
Extraction (domestic)	42,248	7.91	334,181
TOTAL	**2,257,158**		**8,819,804**

Table 1. Areas and total emissions for peatland emission categories.

Emission factor values are taken from[7], area figures are from this current work. Areas under forestry were excluded as these are reported using outputs from the CARBINE (Forest Research) model ("Tier 3") rather than using the draft Tier 2 emission factors.

2.1.4 Cropland

The area identified as cropland in Table 1 is lower than identified in previous work[6]. This is because the two approaches to identifying emission categories are different and used different underlying datasets. In this work, some areas of agricultural land that are part of a cropping-grassland rotation will have been identified as grassland categories due to the methodology used to identify grassland in the LCM2007 dataset used.

We do not consider the difference between this and previous work[6] to imply significant differences in total GHG emissions, as cropped peatland is a very small fraction of the total agricultural peat area in both cases.

2.1.5 Drainage

Drainage classes in this report cover a larger area than in previous work[6] and are responsible for a significant proportion of agricultural peat GHG emissions. This work took a broad view of the definition of drainage in peat as conditions where the water table was 'artificially lowered', and therefore where evidence of land management existed that implied the outcome of a lowered water table, this was assumed to mean drainage. This would therefore include, for example, eroded peatlands as drained eroded land cover classes. In contrast to this, Evans et al (2017) used a definition of drainage that was limited to the existence of man-made drainage ditches. Under their definition, eroded peatland without man-made ditches were classified as 'eroded' whereas those with ditches were classes as 'eroded drained'. This has important consequences for the assignment of emission factors and overall emissions calculation approaches and hence the two methodologies produce different outcomes.

One drawback of the Evans et al (2017) work was that no spatial data product of drainage ditch distribution across Scotland or the UK exists. In the Inventory implementation, drainage proportions were taken to be a proportion of the overall land area, informed by estimates of drainage across Scotland's' peatland area from two 2017

[7] Evans et al. (2017)

pilot studies performed for ClimateXChange[8]. However, while this approach results in a robust reporting method for international emissions reporting, it does not allow for spatial identification of drained versus undrained areas. This is an important data gap that requires to be addressed, for example, by using remote sensing to map drainage features across Scotland and the UK more widely. Further clarification is also required with the Inventory team to make the distinction between ‘intentional’ drainage (i.e. drainage channels) and ‘unintentional’ drainage (e.g. erosion/overgrazing features, vegetation change).

Remote sensing could be used to map peat drainage and erosion classes more effectively. Both visible (e.g., aerial photography, Sentinel-2) and radar (Sentinel-1) have potential in this area and there is a large body of literature on this research topic.

[8] https://www.climatexchange.org.uk/research/projects/detecting-peatland-drainage/

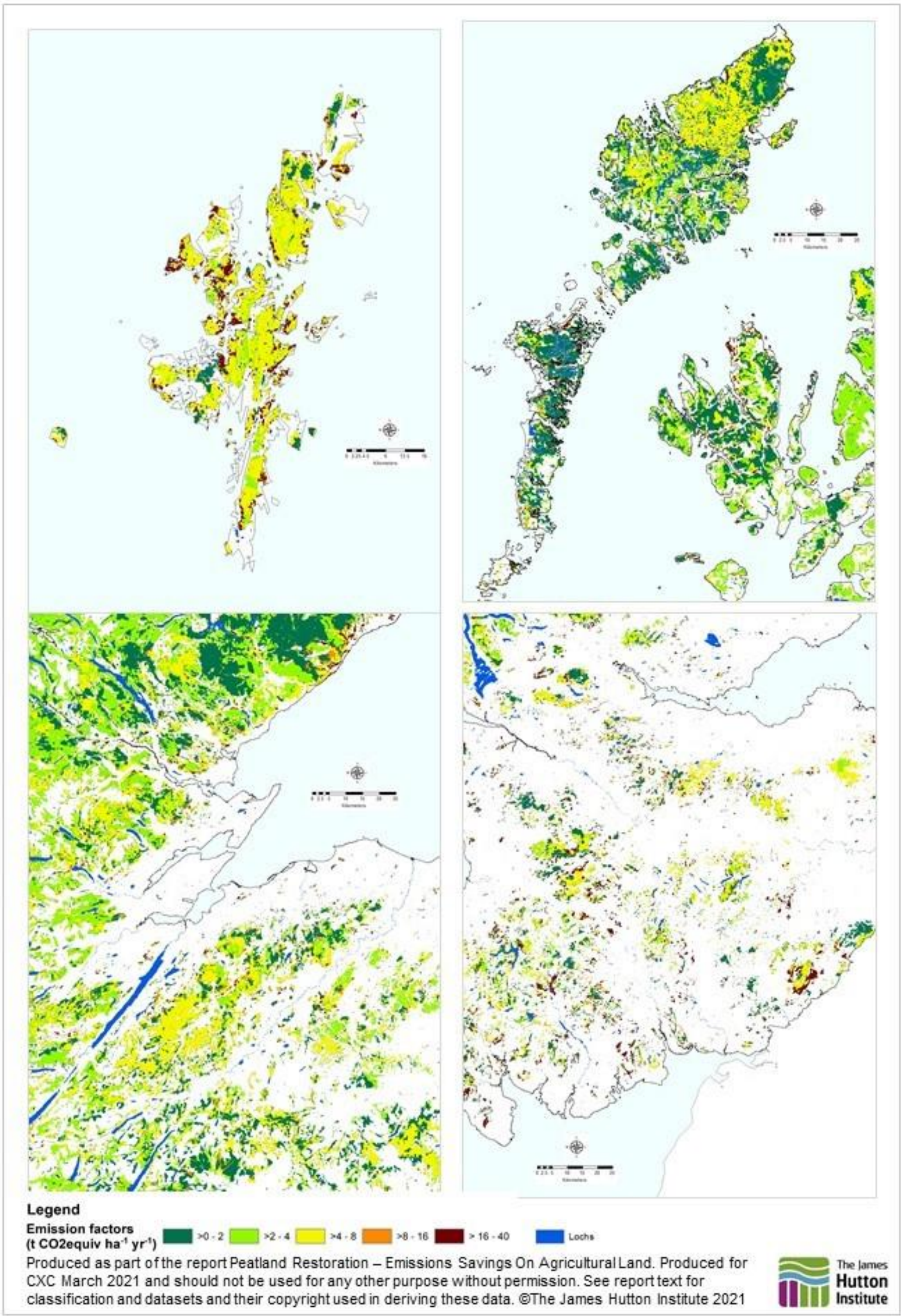

Figure 3. Areas of Scotland with high emission factors for peatland under agriculture.

There are two points of note when considering Table 1 & Figures 2 & 3: firstly, cropland on peat, while having very high emission factor per unit area, only covers a small area of Scottish land, and so does not contribute meaningfully to the emission inventory; secondly, 'semi-natural' categories (e.g., grassland-dominated drained and heather-dominated drained), along with extensive grazing, contribute the vast majority of emissions from agricultural peatland.

An important point is therefore visible here: that **agricultural peat with the poorest capability also presents the greatest opportunity for emission reductions**.

2.1.6 Loss of livestock grazing

Much of the peatland identified as providing an opportunity for GHG emission reductions in Scotland is grazing land. Removal of livestock from this land, to allow other agricultural practices, implies a loss of income for land managers. It is important to quantify this potential loss of income by exploring livestock density and the rate of current income from livestock per unit area.

To provide a benchmark figure for the profitability of livestock grazing in Scotland, figures for 2013/14[9] indicate that the gross margins (sales revenue minus cost of production) of hill farming are approximately 18 GBP per hectare for ewes (assuming a stocking density of 3 animals per hectare) and 118 GBP per hectare for cows (assuming a stocking density of 0.7 animals per hectare). For lowland, the corresponding gross margins are 95 GBP per hectare (assuming a stocking density of 5 animals per hectare) and 288 GBP per hectare (assuming a stocking density of 1 per hectare) respectively. Note that gross margins do not include fixed costs and capital depreciation which could mean many livestock enterprises actually operate at a loss on average. Stocking rates are for UK, while the GBP figures are for Scotland.

Currently, livestock grazing figures are not available at sufficiently high resolution to directly link livestock density to emission factor maps. If successful, this would provide a way to spatially determine trade-offs between gross margins and emission reductions (i.e., ‘what emission reduction can be achieved here per unit of loss to farmer income?’). Livestock movement and preferential stocking within the 2 km resolution mapping available from AgCensus prevents us from linking these two pieces of information.

2.2 Quality and coverage of spatial data on peatland in Scotland

2.2.1 Individual datasets

The quality and coverage of spatial data on peatland in Scotland is mixed. In the last 40 years, there have been many requirements on gathering information on Scotland’s soils, land use and land cover. Examples include where best to grow arable crops, the presence of different vegetation types and the proportion of different soils within an area of land.

The relevance of resulting datasets to spatial variability of peat greenhouse gas emissions has been variable, with no mapping having specifically targeted this question. The result is a complex Venn diagram of data which helps us to understand where peat soils can be found, what condition they are in and what land use is present on them.

Strengths

The LCS88 dataset, although now over 30 years old, is a robust and still relevant source of information. The quality of the original work has been demonstrated multiple times since its development.

Soil mapping at a national level is considered reliable and accurate at the catchment level but needs to be updated and maintained to account for changing soil conditions. For peat soils in particular, recent work provides good-quality mapping including details of location, depth and carbon stock. Currently, multiple datasets exist that need to be harmonised and integrated to provide a dataset for consistent use by all stakeholders.

Weaknesses

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[9] Moxey, 2016

Until recently land cover mapping was not updated frequently, and datasets generated since the LCS88 have been problematic – particularly in relation to heath and peatland vegetation discrimination. This has led to continued reliance on the LCS88 as a 'gold standard' for land cover data in Scotland, and we feel that this reliance is becoming problematic due to the amount of time in which changes to land cover could have occurred.

National-level mapping of soils at sufficiently high spatial resolution for this report requires disaggregation of the 1:250k Soils Map of Scotland. There is ongoing work to accomplish this, but current data requires workarounds and assumptions that reduce confidence in the outputs.

Grazing intensity data derived from LCM2007 & AgCensus 2015 provided livestock stocking density data at 2km resolution. Given the potential variability in soil and land cover within that distance, the effectiveness of this data is not optimal.

Potential improvements

Due to differences in measurement techniques and accuracy of data collection, some of the best quality environmental and land management spatial data in Scotland is relevant to this report but not directly aligned with the questions being asked. We have given recommendations later in the report on how to improve on dataset quality and suitability in future. Reliable high-resolution mapping of Scotland's soil, land use and land cover is recommended in particular.

At the initiation stage for this project, discussions were held about the possible use of IACS data as a tool, given its more detailed and up to date information on land management. However, data privacy and information sensitivity concerns prevent its use for this report. Future work in this area would be greatly improved through the inclusion of IACS data, particularly on (i) livestock density and location and (ii) crop rotation practices.

The use of Peat Scotland data implies some circularity, as it was derived using other datasets used here. The specific categorisation approach used was still effective for evidence assessment, but a more independent map of peat condition would be better.

2.2.2 Uncertainties caused by data integration

It is important to emphasize that the spatial datasets used in this report come from different sources; they were produced in different years and rely on different underlying data sources and methodologies. This means they do not always agree with one another. Details of this uncertainty are explored in detail at Appendix 7.

Additionally, no information could be found for locations where industrial extraction of peat is, or has been, taking place in recent years. An assumption has therefore been made that all extraction areas identified in LCS88 were of a 'domestic' nature i.e., small-scale extraction or domestic use only. The reason for this assumption is that while industrial peat workings are identified in the LCS88 dataset, these would now be over 40 years older than when first identified (and may have been active for many years before that), and many of them will have been exhausted and may now be under different land management. **This assumption should be validated as it may be incorrect.** Recent CXC reporting indicates emissions on the order of 0.1 Mt CO_2e yr^{-1} ([10]).

Two points of note are identified from the uncertainty assessment:

- Firstly, cropland, while having very high emission factor per unit area and being confidently identified, covers a small land area. It is therefore possible to focus

[10] Litterick et al., 2020, https://www.climatexchange.org.uk/research/projects/alternatives-to-horticultural-peat-in-scotland

peatland restoration efforts on non-cropland areas, which generally are considered to have lower productivity. If it were a priority to maximise emission reductions on agricultural peat while minimising impacts on farm productivity, then this would inform the ability to do so. We acknowledge that this would be a policy decision.

- Secondly, the categories that contribute most emissions (eroded peat, heather dominated drained, grass dominated drained) also have greater uncertainty, because it is difficult to distinguish between these specific classes, rather than between these classes and for example, intensive grazing, cropland or near natural bog. The classes where misclassification occurs often have been allocated the same emission factor. This misclassification into functionally similar classes (from an emission perspective) reduces the level of uncertainty for overall emission estimates but may be misleading if the emission factor allocations are incorrect for these classes.

The approach to classification taken in this report also differs substantially to the methodology in[11] and so the results cannot be directly compared. This is predominantly due to differences in classification between the LCS88 and LCM approaches, as well as a difference in how drainage was defined between[12] and the present work. Additionally, the peat depth map[13], based on thousands of measurements from Peatland Action Plan survey work) provided an additional data source not available at the time of the Evans et al. work. For more information, see[14] and Section 4: Annex on methodologies.

It is emphasised that emission category area values in[15] and this report are based on sound methods, but that variation exists due to the remaining uncertainties in both peat extent and land cover mapping data (further discussion in Section 3).

2.3 Review of evidence for potential agricultural uses of rewetted peat

Most of Scotland's lowland peats have been historically drained to create high grade arable and horticultural land. This exposes previously waterlogged organic matter to decomposition, compaction, subsidence and oxidation, ultimately leading to significant emissions of carbon dioxide (CO_2).

Cropped peatland in England (69% of which is horticulture, remainder in arable/cereal production) loses typically 10 to 30 mm of peat yr^{-1} due to subsidence and oxidation, and GHG emissions are 10 times higher than emissions from upland peat[16]. We do not have similar data for cropped peatland in Scotland, although it is likely that values for both depth loss and GHG emissions are similar if slightly lower due to climatic conditions. Reducing vegetation cover (as happens during fallow periods) on carbon-rich soil increases the risk of soil erosion, which thus reduces soil carbon levels. Peatland in good condition can retain carbon and additionally sequester around 0.2 to 0.8 t C ha^{-1} yr^{-1} under optimal conditions[17], [18].

In our analysis, we found evidence of very little area of cropping on peat in Scotland. Discussions with colleagues at the James Hutton Institute indicated that there are likely

[11] Evans et al. (2017)
[12] Evans et al. (2017)
[13] Aitkenhead & Coull, 2019
[14] Evans et al. (2017)
[15] Evans et al. (2017)
[16] Mulholland et al., 2020
[17] Artz et al., 2014

[18] https://www.nature.com/articles/s41586-021-03523-1

to be scattered, small areas of peat soils under arable cropping that have not been included in existing soil maps; these are difficult to identify during field survey or other identification processes (e.g., including remote sensing) due to the very high degree of modification of the remaining underlying peat. Conventional agricultural cropping should be excluded from consideration as an option for land management on peat. Conversion of rewetted peat to agriculture can release significant amounts of additional emissions per year, estimated at 6.5t C ha^{-1} yr^{-1}.

Alternative land management options should be considered, including the option of 'no productive management,' which removes the risk and impact of carbon release from land management activities.

Several strategies have been proposed to tackle emissions from agriculturally used peatland, including:

- Conservation agriculture (e.g., zero tillage systems).
- Seasonally raising water tables (between cropping cycles).
- Raising water tables year-round and replacing arable and horticultural crops with wetland agriculture, also known as paludiculture (e.g., bioenergy crops, Sphagnum for growing media or food/medicinal crops)[19].
- Full restoration of semi-natural wetland habitats.

Conservation agriculture and seasonal water table manipulation require no change in land use but offer only modest emissions savings. They also require investment, intensive effort and constant water table monitoring, while restricting management activities in ways that reduce farm income. Therefore, while appropriate for some land management goals, they are not considered appropriate for achieving the objectives aligned with this report; namely, significant greenhouse gas emission reductions.

In the previous section, we provided spatially discrete information on agricultural peat and the potential emission savings that could be achieved through rewetting. In this section, we explore different paludiculture options that could potentially provide agricultural productivity on rewetted peat.

Paludiculture and full restoration offer more significant emission reductions because they retain high water tables all year round, but there are more significant social and economic barriers to these significant changes in land use. The costs and benefits of paludiculture are complex, and specific conditions in Scotland place significant constraints on the application and effectiveness of this approach.

2.3.1 Paludiculture - introduction

Paludiculture is defined as the "productive land use of wet peatlands that stop subsidence and minimizes emissions"[20]. In principle, paludiculture has potential application in Scotland, particularly for bioenergy cropping. Approaches to paludiculture fall under two categories involving the management and harvesting of either

a) deliberately planted crops, e.g., Sphagnum moss farming (for potential growing media and other uses) or

b) spontaneously established, naturally occurring plants, e.g., reed harvesting.

These two approaches represent an important distinction between *high intensity* and *low intensity* paludiculture. Paludiculture has applications in both lowlands and uplands, as

[19] Schäfer, 2012
[20] Tanneberger et al., 2020a

well as in groundwater-fed land such as fens, and rainwater-fed land, such as blanket bogs[21].

Paludiculture could provide income from a number of sources alongside a wide range of cost savings and other benefits to landowners and wider society. Direct income from paludiculture varies by crop but is typically lower than the income from existing arable and horticultural uses, giving rise to significant opportunity costs (see next section). Given the other costs associated with paludiculture (covered in the next section), this creates a significant economic barrier to farmers considering changing their land use. However, when combined with private payments for ecosystem services and public funding via agri-environment schemes, paludiculture may provide sufficient income to overcome these barriers. In the context of these other income streams, it is therefore important to understand the economics of the main paludiculture crops.

The literature mentions the possibility of producing a wide range of plants under paludiculture, including Sphagnum, sundews (Drosera), purple moor grass, blueberry and cranberry, common reed (Phragmites australis), Reed Canary Grass (RCG) (Phalaris arundinacea), cattail (Typha spec.), willow (Salix species), alder (alnus glutinosa), wild rice (Zizania palustris), celery (Apium graveolens), sedge (Carex spec.) hybrid napier grass, giant reed, meadowsweet (Filipendula ulmaria), valerian (Valeriana officinale) and butterbur (Petasites hybridus)[22] [23] [24] [25] [26] [27] [28].

These species can be used for:

- Growing media – Sphagnum moss
- Packaging and matting – Sphagnum, reeds
- Biofuels – reeds, alder, willow, napier grass
- Building materials – cattail, purple moor grass, reeds, alder, willow
- Water treatment – cattail
- Soil improver (biochar) – reeds
- Compost – reeds, Sphagnum
- As donors of plant material for additional peatland restoration or paludiculture
- Food – cattail, blueberry and cranberry, wild rice, celery
- Medicine/pharmaceuticals – meadowsweet, valerian and butterbur, drosera

Most of these uses have been suggested rather than tested in the field for practicability or economic benefit. Published field studies have mainly focused on Sphagnum moss farming and reed harvesting and none of these have taken place in Scotland, with very few under conditions similar to the Scottish climate. From the perspective of atmospheric impact, the most suitable agricultural option for an abandoned peat extraction area appears to be cultivation of Reed Canary Grass (RCG)[29], which is grown as a commercial bioenergy crop in some northern European countries.

2.3.2 Afforestation

Some forestry practices are included in the definition of paludiculture. However, the UK Forestry Standard states that new forests should not be established on deep peat (where the peat layer is deeper than 50 cm), or on sites where planting would

[21] Ferré et al, 2019
[22] Pouliot et al., 2015
[23] Baranyai & Joosten, 2016
[24] Dragoni et al., 2017
[25] Jensen & Eller, 2020
[26] Jurasinski et al., 2020
[27] Tanneberger et al., 2020b
[28] CANAPE, 2021
[29] Jarveoja et al., 2013

compromise the hydrology of adjacent bog or wetland habitats. This exclusion covers all of the areas identified as peat in this report. The implementation of Short Rotation Forestry (SRF) or Short Rotation Coppice (SRC) (e.g., alder, willow) therefore cannot be carried out on this type of land.

Converting peatland to forestry by draining and planting has been shown to lead to net carbon emissions, over and above the carbon stored in the trees. In general, on shallow peat/organo-mineral soils in Scotland, planting forestry with limited disturbance increases soil carbon storage, whereas on deep peat, planting forestry decreases soil carbon storage and increases GHG emissions. Planting of two Scottish native tree species ((birch (*Betula pubescens)* and Scots Pine (*Pinus sylvestris)*) on peat soils does not result in net carbon sequestration across medium-term (10-20 year) timescales. Current scientific evidence and Scottish Government policy are in agreement that afforestation on peat is extremely high-risk and that alternatives should be sought.

2.3.3 Food / medical crops

There are a number of food and medicinal plants that could be grown as paludiculture crops in Scotland, and there are a range of crops that can be used for building and insulation[30] [31], with experiments currently being conducted on the use of cattail (*Typha spp*) paludiculture for use as insulation material in The Netherlands[32]. See[33] for a database of 800 potential paludicultural plants, many of which could be grown in Scotland. However, most of the interest and published evidence pertains to bioenergy crops (for which there is an existing market), and Sphagnum for direct use in horticulture or as a growing medium (where markets are currently small or under development).

2.3.4 Low intensity harvesting of reeds for biogas or construction

Recent scenario-based economic modelling, based on central European examples, assessed the Contribution Margin (gross margin per unit of product) of harvesting common reed (*p. australis*) for the harvesting of various products. The model calculated costs of harvesting, transportation to field edge and processing, machinery costs, labour and depreciation.

- Chaff for biogas: the modelling suggests that revenues would currently almost certainly not cover costs. The mode Contribution Margin was –195 EUR/ha.
- Bales for combustion: the break-even point would be reached 82% of the time, with a mode Contribution Margin of 53 EUR/ha.
- Bundles for thatching: producing thatching products (including mats, screens etc) would be almost guaranteed to break even and would provide a Contribution Margin of over 500 EUR/ha.

The results indicated that the production of reed bundles for thatching would bring the greatest financial rewards, and thus provide the best income improvement opportunities when moving from livestock grazing.

However, gaining market access for Scottish thatching would be challenging. A new domestic entrant into this market would face strong competition from existing dominant global producers in Hungary, Romania, Turkey and China. Competitivity is also reduced by the fact that the thatching currently grown in the UK is not considered of sufficient quality, which explains why the UK imports the vast majority of its thatching.

[30] Wichtmann & Schäfer, 2007
[31] Wichtmann & Tanneberger, 2011
[32] Jong, 2020
[33] Abel et al. (2013)

Additionally, there are estimated to be only 80 properties in Scotland with thatched roofs and 6 professional thatchers. The domestic market capacity for traditional roof thatching is therefore low.

2.3.5 Bioenergy crops

There is currently limited evidence for the commercial viability of bioenergy paludiculture crops, and as such it is important to avoid making simplistic assumptions about the viability of bioenergy crops for paludiculture in Scotland based on data from other countries where conditions may be very different. One of the most comprehensive farm-level studies of bioenergy production from paludiculture focussed on reed (*Phragmites australis*) production in central Europe using three different harvesting options. This estimated that after subtracting variable costs and fixed machinery costs, returns could range from a loss of around £870 ha^{-1} yr^{-1} to a profit of £1300 ha^{-1} yr^{-1}, with winter mowing for direct combustion the most cost-efficient option[34].

Research in England has investigated a range of options for bioenergy from rewetted peatland sites, including an assessment of potential yields of different crops based on data from the UK and Europe, a cost comparison of different harvesting machinery and options for on-site bioenergy production including anaerobic digestion and conversion to briquettes and pellets[35]. The report also considered pyrolysis to convert biomass to biochar for use as a soil amendment to improve soil structure and fertility while increasing soil carbon storage, options for supplying existing conversion plants, including large-scale anaerobic digestion and combined heat and power plants, and reviewed Government funding schemes at the time to incentivise renewable energy production from biomass. Of particular interest was the proposal of community funding models based around district heating schemes where local communities form a co-operative organisation and receive a share of the profits from the sale of bioenergy or receive cheaper energy[36].

There are organic soils where cultivation of perennial bioenergy crops is possible with low resulting emissions in nitrogen oxide and methane (two significant greenhouse gases)[37], but it has not been demonstrated that this is possible in Scotland. Studies of the properties of carbonized biomass (either hydrochar or pellets) reveal that fuel grade hydrochar can be produced from peat moss, or from the blend of peat moss and miscanthus (agricultural biomass/energy crops). It is possible that this carbonised biomass can be used in existing coal-fired power plants[38]. *Calluna vulgaris* (heather) and could also represent an efficient energy crop in areas where it would not be possible to revert to functioning peat bogs, but evidence is limited to modelling work (e.g., [39].

Reed Canary Grass (RCG)

RCG cultivation could be a good land use option in terms of mitigating GHG emission from rewetted peatlands, potentially turning these ecosystems into a sink of atmospheric carbon dioxide[40]. No significant short-term effect of biomass harvest on net greenhouse gas balances was found in one study from Germany, in which 17 t CO_{2e} ha^{-1} yr^{-1} was saved by rewetting compared to a drained state[41]. However, no such studies have been

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[34] Wichmann, 2017
[35] Mills, 2016
[36] Mills, 2016
[37] Hyvonen et al., 2009
[38] Roy et al., 2018
[39] Worrall & Clay, 2014
[40] Karki et al., 2015
[41] Gunther et al., 2015

carried out in Scotland, which has markedly different climate, soil and topographic conditions that make comparison with studies from other countries problematic.

Overall, it is suggested that maximizing plant growth and the associated carbon dioxide uptake through adequate water and nutrient supply is a key prerequisite for ensuring sustainable high yields and climate benefits in RCG cultivations established on organic soils following drainage and peat extraction[42].

Studies of Reed Canary Grass grown on cutover peat (i.e., peat where cuttings have been made for extraction) in Ireland found that biomass yields were lower than expected[43]. For bioenergy-based paludiculture, combustion quality/efficiency varies between different crops, depending on nutrient availability and other conditions[44]. Site-specific management would therefore be necessary to optimise productivity in different locations. Combustibility performance also appears to be influenced by having a combination of different crops grown under different conditions[45].

Studies have shown that the cultivation of Reed Canary Grass transformed degraded peat from a net source of carbon into a net sink of carbon (e.g., [46]. After six years of cultivation, old peat decomposition contributed less to total soil respiration than respiration of recent plant material (30% vs. 70% on average, respectively), but the relative proportions were highly variable over the growing season[47]. Maintaining a high water table is critical to preserve this, because of growth requirements. Wet years create conditions which enable a high uptake of atmospheric carbon dioxide by Reed Canary Grass. Dry years on the contrary are marked by long dry spells during important phases of crop growth, which results in corresponding reductions in gross ecosystem productivity[48].

Other grasses

The perennial high yielding energy grass *Miscanthus* (commonly known as Elephant grass, a tropical species) is reported to not fully compensate for organic matter loss in drained peatland. *Miscanthus* is also more suited for organo-mineral and mineral soils. See also the description of the UK Forestry Standard exclusion in the Afforestation section above which has been interpreted to specifically exclude miscanthus.

The Common Reed (*Phragmites australis*) can sequester substantial amount of carbon dioxide each year (estimated at 4-13 tonnes CO_2e per hectare per year depending on climate conditions). However, this is re-emitted if the reed is used as a substitute for fossil fuels creating an overall negative carbon balance from using this reed plant for burning. If the reed crop is used as building materials or returned to the soil in unreactive forms, it has the potential to contribute directly to long-term sequestration of carbon dioxide. Another peatland plant, Bulrush/cattail (*Typha latifolia*) has unknown impacts on management of levels of methane (which contributes to the CO_2e inventory) and it is likely that biogas production may be economically unviable. Additionally, these two plants grow on fen habitats rather than blanked or raised bog, and so potential growth in Scotland is limited.

2.3.6 Sphagnum for horticulture

Peat is currently the most widely used growing medium for professional growers in the UK, but the environmental impact of peat extraction for horticulture has driven calls for

[42] Jarveoja et al., 2016
[43] Laasasenaho et al., 2020
[44] Ren et al., 2019
[45] Giannini et al., 2016
[46] Mander et al., 2012
[47] Biasi et al., 2011
[48] Shurpali et al., 2013

peat to be phased out, with voluntary targets set by Defra and CCC[49] [50]. However, progress has been limited by a lack of viable peat-free alternatives due to cost or performance issues[51] [52] [53] [54].

Sphagnum farming aims to provide a renewable and therefore more sustainable source of biomass for growing media with similar properties to peat. Several factors influence the commercial viability of Sphagnum production including: the growth rate of the chosen species of Sphagnum, the effect of species choice on the water holding capacity and air-filled porosity of the resulting growing media, and the nutrient content of water supplying plants (growing media needs to be low in nutrients so growers can tailor nutrition to the species they are growing).

Moreover, there are several notable challenges to production, including sourcing material for propagation, the irrigation and management of water quality to ensure Sphagnum outcompetes weed species, weed control and challenges around the mechanisation of planting, harvesting and processing[55]. Despite several ongoing experiments demonstrating that it is possible to achieve harvestable yields (e.g.[56] [57] [58] [59] [60]), [61]concluded that continued testing was required to determine the suitability of farmed Sphagnum as a growing medium, prior to any evaluation of commercial viability.

2.3.7 Paludiculture & solar power/wind turbine

Paludiculture could be complemented with photovoltaic panels supported by scaffolding or rail systems above the peat surface[51]. This option could particularly be considered for Sphagnum cultivation as the increased humidity and partial shade caused by the photovoltaic panels may support the growth of sphagnum. Wind turbines could also be an option, as long as the installation and management of the wind turbines do not lead to large-scale damage of the peat[51]. Academic literature emphasises that future policy should avoid constructing wind farms on undegraded peatlands unless impacts can be minimised.

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[49] Defra, 2018
[50] CCC, 2020
[51] AHDB, 2016
[52] Defra, 2011a
[53] Mulholland et al., 2020
[54] Litterick et al., 2020
[55] Mulholland et al., 2020
[56] Gaudig et al., 2008
[57] Emmel, 2008
[58] Kumar, 2017
[59] Kämäräinen et al., 2018
[60] Gaudig et al., 2017, 2018
[61] Mulholland et al., 2020

3 Conclusions and recommendations

2.3.1 Confident knowledge

A large proportion of Scotland's agricultural land on peat is of relatively poor production capability, with associated low productivity but with significant GHG emissions. The economic cost of incentivising land managers to reduce agricultural practices (mostly grazing) on this land is relatively low per unit area. However, changing these land management practices will have economic impacts in parts of Scotland where opportunities for replacement income are poor; there are also social impacts to consider where specific land management practices are common (e.g., crofting). Challenges with traditional grazing practices on peat exist, but there may be opportunities for low-density, high-quality livestock grazing with low GHG emissions on restored peat.

Specific geographical locations have been identified where conditions combine to provide a good opportunity for significant emission reductions. The case for replacement agricultural practices that are economically and physically viable is less strong than the case for rewetting and restoration of natural peat vegetation; in many cases, it is not to be recommended. Financial incentivisation for land managers to implement these emission reductions therefore appears mostly aligned with 'compensation' rather than 'market opportunities'.

Sphagnum cultivation for biomass production as a growth medium to replace peat-based compost does not have a strong economic case and has multiple biophysical and socioeconomic barriers. It is currently mostly practiced in the northern hemisphere in rewetted cutover bogs previously used for peat extraction. The cultivation of reed for bioenergy, in combination with providing additional land-use functions, is not a viable option under current economic and political conditions. However, it may become competitive within the next twenty years if policy is implemented that increases bioenergy prices[62]. It may also become viable if policy is implemented that stimulates water buffering and the preservation of peat soils to improve the physical condition of peat soils to a state where reed cultivation is possible. However, reed growing on peat has not yet been tested at scale in Scotland; there may be value in experimental work to evaluate viability, and carbon benefits, of this option.

In the past, afforestation has been demonstrated as the most popular after-use method for agricultural and cutover (extracted) peatland among landowners[63]; however, this is no longer policy in Scotland and has been demonstrated to increase emissions.

Of the suitable options studied here, energy crop cultivation has potential, but is highly dependent on economic profitability and subsidies. Landowners with interests in achieving high environmental standards have been shown to be more interested in biomass production. However, evidence gathered for this report shows that the biological and physical suitability of energy crop cultivation on peatland is restricted to peats that have largely been extracted or degraded to the point where they are no longer able to sustain peat vegetation (e.g., Sphagnum).

Spatial analysis methods used in this report to identify peatlands suitable for emission reductions could be applied in many other countries, if appropriate data is available.

[62] Kuhlman et al., 2013
[63] Laasasenaho et al., 2017

2.3.2 Significant knowledge gaps

A future goal could be to use cutover/extracted peat production lands for bioenergy crop production to mitigate climate change while providing farmer income[64], but many questions remain before this can be assured.

There is reasonable agreement on the location of peat in Scotland, from datasets produced using a number of different approaches. This provides a strong evidence base for peat location at good spatial resolution. However, the different approaches taken in[65] the present report have predicted peat in some locations in disagreement with one another, for example on floodplain valley bottoms or small pockets of land in the north-west Highlands. Exploring the discrepancies between these maps would provide insight into peat formation and allow us to improve our understanding of the conditions necessary for restoration.

The uncertainties in the extent and specific location of peat deposits across Scotland therefore also place significant uncertainties on the areas that are likely to be under a given land cover, even if spatial mapping of land cover were accurate, complete for all the condition categories required for the UK GHG inventory, and up to date. At present, land cover mapping for Scotland has considerable uncertainties both in terms of potential misclassification errors and the degree to which certain land cover types or drainage are mapped. These issues compound when data products of different vintages are combined and thus lead to considerable mismatches between the outcomes of[66] and the present work. This also makes it difficult to carry out serious spatial analyses of the potential of specific approaches such as paludiculture (e.g.,[67]).

The long-term impacts of harvesting common reeds or other bioenergy crops on GHG emissions in peatlands are unknown, and future studies would be useful to assess the sustainability of such practices for bioenergy production. In addition, the short-term benefits are not proven for Scottish conditions. Environmentally sound bioenergy production has been demonstrated on peat soils in a small number of field experiments (e.g.,[68]). However, as long-term experimental data on the GHG balance of bioenergy production are scarce, more (and more detailed) scientific data stemming from field experiments are needed to help shape renewable energy source policies[69].

2.3.3 Active debate

Results from ongoing field experiments suggest that paludiculture has the potential to reduce overall GHG emissions relative to conventional drainage-based agriculture or peat extraction; the reduction is mostly created by avoided emissions from deep-drained peat cropland (as high as 25-30 t CO_2e ha^{-1} yr^{-1}). Several studies, albeit based in other countries, suggest that paludiculture sites could become a net CO_2 sink. However, results from other field experiments disagree with those studies. The harvesting of sphagnum biomass, in particular, is considered likely to prevent peat from being a long-term carbon store and is also likely to cause further peat degradation[70]. Full life-cycle analysis of harvested products on all types of paludiculture is also not complete and is needed to provide a clearer understanding of **which** paludiculture crops could provide a net carbon sink under **what** conditions, and **where** this may be possible.

[64] Laasasenaho et al., 2016
[65] Evans et al (2017)
[66] Evans et al (2017)
[67] Schlattmann & Rode, 2019
[68] Shurpali et al., 2010
[69] Karki et al., 2016
[70] Wichmann et al., 2020

Some bioenergy crop production on peat would require pH adjustment, usually accomplished through liming. There is disagreement on whether this would lead to negative impact by increasing emissions, as has been reported in multiple field experiments, or whether the impacts of liming on cultivated peat have been overestimated due to misunderstanding of the effects on soil biological processes.

Appendix 1: rationale and policy links

The Intergovernmental Panel on Climate Change (IPCC) published a new report on emissions from drained peatland in 2014, the 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands[71], which requires a more refined reporting method for peatland areas. As this IPCC report also recommended that countries with significant peatland extent implement a country-specific reporting approach, the UK Government Department for Business, Energy & Industrial Strategy (BEIS) commissioned a report to compile spatial data of land use on peatlands and their likely emissions. The resulting report, "Implementation of an Emissions Inventory for UK Peatlands", suggested total emission from peatlands were likely to be significant and would require a major change in Inventory reporting[72]. The subsequent Committee on Climate Change Net Zero report[73] suggests peatland emissions to be in the order of 18.5-23 Mt CO_2e for the whole of the UK, and up to 9.7 Mt CO_2e for Scotland. These values are in the same order as the entire forestry carbon sink for Scotland and therefore it is of high interest to examine where emissions mitigation may be feasible. The UK GHG Inventory captures emissions by calculating the emissions for a given land use category (collectively these are called 'activity data') times its associated emission factor (EF, a single average value of the equivalent of carbon dioxide, CO_2).

[71] https://www.ipcc.ch/publication/2013-supplement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories-wetlands/
[72] Evans et al. (2017)
[73] https://www.theccc.org.uk/publication/net-zero-the-uks-contribution-to-stopping-global-warming/

Appendix 2- methodologies and underlying assumptions

All the datasets used in this report were aligned with common grid size of 100 metre. Datasets were simplified where necessary, to reduce the number of classes. All existing combinations of peat- or agriculture-related class across the different datasets were identified. This produced 1849 combinations. Each combination was then evaluated to determine which of the peatland emission categories it matched. For most of these combinations, clear agreement existed between the different maps, enabling relatively straightforward categorisation. Where disagreement between datasets existed, the number of map disagreements was counted to give a sense of how confident we were with the peatland emission category identified.

Simplification of classes in maps carried out to reduce the number of combinations of map class. For the LCM2007 map for example: two classes correspond to woodland; three classes correspond to different types of seminatural grassland and five classes correspond to bare surfaces.

The LCS88 map was simplified to 4 classes, as follows:

1. No peat (i.e., no peat vegetation identified – could still be peat underneath)
2. Semi-natural peatland vegetation (blanket bog and other peatland vegetation with no erosion or workings)
3. Peat workings
4. Peat erosion

The LCM map was simplified to 8 classes, as follows, based on the original 22 class definitions:

1. No agriculture (bare/water)
2. No agriculture (bog)
3. Heather-dominated seminatural
4. Grass-dominated seminatural
5. Extensive grassland
6. Intensive grassland
7. Arable
8. Woodland

The Peat Scotland map was not simplified, as each class was considered distinctly important for categorisation work in this report. The classes used were:

1. Peat soil with peatland vegetation
2. Dominant peat with peatland vegetation
3. Peat/non-peat soil mix with mixed vegetation
4. Dominant mineral soil with some peat
5. Peat soil with non-peat vegetation
6. Mineral soil with no non-peat vegetation
7. Unknown
8. No soil

AgCensus map was kept ‘as is’ with 7 classes:

1. No grazing
2. Improved grassland, not overgrazed
3. Improved grassland, overgrazed
4. Seminatural grassland, no overgrazed
5. Seminatural grassland, overgrazed

6. Heather, not overgrazed
7. Heather, overgrazed

The 1:250,000 soil map was used to provide a percentage estimate of peat at each location, from the mixed mapping units. This does not give a precise yes/no answer to the presence of peat at each location within a map unit, unless that map unit is 0% or 100% peat.

Development of evidence for specific components of interest from each map was carried out using expert knowledge. Some maps provided more direct evidence for specific components of interest than others, with evidence considered as either:

- Indirect (does not dispute a fact but also does not dispute others)
- *prima facie* (supports a fact, but can be refuted)
- *Direct* (directly indicates a fact)

Evidence can be positive or negative, for example the presence of a specific feature (A) can be evidence against feature B if Class A and Class B cannot both exist in the same place (e.g., cropping or grazing).

The components of interest were:

- Peatland vegetation (Blanket or raised bog type, also fen/marsh)
- Agriculture (broad definition)
- Erosion
- Woodland (removed from final analysis due to different emission factor accounting but kept in evidence assessment to allow discounting of other emission categories).
- Cropland
- Seminatural
- Heathland-type vegetation (can be natural on shallow peat or indicative or degradation)
- Grassland
- Extensive grazing
- Intensive grazing
- Extraction
- Drainage

An important distinction to highlight here is that there is the technical definition of drainage as per IPCC emission categories, and there is 'functional' drainage from peat soils that have been degraded, eroded or otherwise intensively managed to put them in a state where they function as a drained peat[74]. In the exploration of evidence carried out for this report, strong evidence was found for functional drainage in many cases, resulting in a higher incidence of drained categories than in previous reports (e.g.[75]). Examples of evidence for functional drainage from different datasets include the following: erosion features or peat workings (direct evidence from LCS88); overgrazing

[74] The decision to use this technical definition of drainage as per the IPCC and now UK GHG Inventory categorisation was made on the basis of how to represent methane emissions from drainage ditches. We do not know whether 'functional' drainage is equivalent in emissions terms to man-made drainage ditches. It is possible that the analysis here used a total emissions factor for eroded peatland that implies there are significant emissions of methane from drainage ditches, i.e., too high an EF. But this is equally contentious with regards to the eroded peatland EF for on-site CO_2 and CH_4 losses in the current Inventory, which is a compound EF made up of the proportional losses from heather-dominated and bare (using extracted as a proxy) land and which may also not be entirely correct.

[75] Evans et al., 2017

(prima facie evidence from AgCensus); peat soils with non-peat vegetation, or mineral soils with no peat vegetation (prima facie evidence from Peat Scotland).

Most of these components correspond directly to emission categories, although some (e.g., agriculture, peat, seminatural) are broader categories that are considered to provide prima facie evidence for several emission categories. For each of the 1849 combinations of map class, evidence for each component in the above list was developed from each dataset. The evidence for each component was then used to determine whether a specific emission category could be confidently assigned to that combination. For 518 combinations corresponding to 53% of Scotland's peat, there was evidence for a single emission category with no evidence for any other.

Examples of evidence for specific emission categories that occurred frequently are given below:

- No peat: QMSoils indicates some probability of peat but peat depth map indicates shallow <50 cm organic horizon; LCS88 indicates no peatland vegetation; LCM2007 indicates extensive grazing; Peat Scotland indicates no peat; AgCensus indicates no grazing. While the evidence for and against grazing is contradictory, there is strong evidence from multiple datasets that peat is not present.
- Woodland: QMSoils and peat depth map indicate peat; LCS88 indicates peat erosion; LCM2007 indicates woodland; Peat Scotland indicates predominantly non-peat soils with some peat; AgCensus indicates no grazing. This provides direct evidence for woodland on peat, with no evidence against.
- Cropland: LCS88 indicates blanket bog or other peatland vegetation; LCM2007 indicates arable; Peat Scotland indicates peat soil with no peat vegetation; AgCensus indicates 'no grazing'. This provides prima facie evidence (used to be, but data is old) for near natural peatland, but also indirect (no grazing) and direct evidence (arable land cover) for cropland. The assumption made here is that peat vegetation has been converted to cropland in the last 30 years.
- Near natural bog: QMSoils and peat depth map indicate peat; LCS88 indicates blanket bog or other peatland vegetation; LCM2007 indicates heather dominated grazing; Peat Scotland indicates near natural peatland; AgCensus indicates no grazing. There is multiple strong evidence for near natural peatland, and the decision is made that the AgCensus outranks LCM2007 evidence for grazing presence based on concerns about LCM2007 mapping of heath vs. peatland vegetation. An underlying assumption used is that heathland vegetation cover on peat is caused by repeated burning and grazing, which is not indicated as occurring here.
- Heather dominated undrained: Peat indicated by QMSoils and peat depth map; LCS88 indicates blanket bog or other peatland vegetation; LCM2007 indicates rough grazing; Peat Scotland indicates near natural peatland; AgCensus indicates heather dominated with no overgrazing. This provides conflicting evidence for near natural peatland, extensive grassland and seminatural heather dominated. The decision is made that as AgCensus incorporates more recent LCM2015 data than the LCM2007 (and is considered more accurate for identification of seminatural land cover) and also as there is no evidence of drainage, the category is as given.
- Heather dominated drained: QMSoils and peat depth indicate peat; LCS88 indicates peat with erosion; LCM2007 indicates heather-dominated seminatural; Peat Scotland indicates heath with some peatland; AgCensus indicates overgrazed heather. Taken together, this provides strong direct evidence for heather-dominated seminatural grazing. It also provides direct evidence for both erosion and overgrazing, resulting in the decision to categorise this as

functionally drained (as opposed to the stricter IPCC definition of drainage as a direct human intervention, i.e. drainage ditch).

- Grass dominated undrained: QMSoils and peat depth indicate peat; LCS88 indicates blanket bog or other peatland vegetation; LCM2007 indicates grass-dominated seminatural grazing; Peat Scotland indicates peat soil with peat vegetation; AgCensus indicates seminatural grassland with no overgrazing. This provides direct evidence for semi-natural peat and grass-dominated seminatural grassland. The lack of evidence for degradation, erosion or overgrazing results in the 'undrained' categorisation.
- Grass dominated drained: QMSoils and peat depth indicate peat; LCS88 indicates peat erosion; LCM2007 indicates grass-dominated seminatural grazing; Peat Scotland indicates peat soils with non-peat vegetation; AgCensus indicates overgrazed seminatural grassland. This provides direct multiple direct evidence for grass-dominated seminatural. The additional evidence for peat erosion and overgrazing indicate functional drainage of the soil, resulting in the 'drained' category.
- Eroded drained: QMSoils indicates 100% peat in map unit, backed up by the peat depth map with a depth >50 cm; LCS88 indicates peat workings; LCM2007 indicates heather moorland; Peat Scotland indicates mineral soils with no peatland vegetation; AgCensus indicates overgrazed seminatural grassland. This provides direct evidence for and against peat being present, but also prima facie evidence for historically worked peat with both heather and grassland. In this case, evidence is mixed and conflicting, indicating a timeline in which peat has been worked and degraded through overgrazing, and is now functionally drained.
- Grassland extensive: QMSoils and peat depth map indicate peat; LCS88 indicates peat workings; LCM2007 indicates improved grassland; Peat Scotland indicates peat soil with no peatland vegetation; AgCensus indicates improved grassland. This provides direct evidence for improved grassland (LCM2007 and AgCensus) and indirect evidence for non-pristine peat (Peat Scotland).
- Grassland intensive: QMSoils and peat depth map indicate peat; LCS88 indicates peat workings; LCM2007 indicates improved grassland; Peat Scotland indicates peat soil with no peat vegetation; AgCensus indicates overgrazed improved grassland. This provides strong evidence for improved grazing and prima facie evidence for a lack of peatland vegetation. The evidence of peat workings is taken to indicate likely erosion features but this is not sufficient alone to categorise as eroded drained given the weight of evidence for other categories.
- Extraction domestic: QMSoils and peat depth map indicate peat; LCS88 indicates peat with workings; LCM2007 indicates no peat; Peat Scotland indicates predominantly peat with predominantly peaty vegetation; AgCensus indicates 'no grazing'. This provides direct evidence for peat and peat workings but also evidence of areas with no peat. Taken with the indirect evidence for an emission category that is not grazed, this indicates historically extracted peat.

Having identified a peatland emission category for each of the existing dataset combinations, we identified where each combination occurred and allocated each 100 m grid cell to the associated peatland emission class and associated uncertainty level.

Future work in this area could include additional datasets, for example:

- National Forest Inventory map: could be used to provide strong evidence for/against forestry/woodland.
- Topographic and hydrological flow mapping (e.g., HOST – Hydrology Of Soil Types) to improve evidence for peat-formation conditions.

An important summary message is that **NONE of the currently available land cover mapping products are ideal for distinguishing different vegetation classes on peatland**. There is a lot of contradiction between different datasets and methodologies, even in areas where there has been no known land use change since the late 1980s. The use of IACS data under a system of approval that is currently being developed would greatly help with this issue, particularly on agricultural land.

Appendix 3: maps and data used in this report

1. **Carbon stock**
    a. Purpose: To provide information on the peat depth and organic carbon stock of Scotland's soils at 100 metre resolution.
    b. Abstract: The spatial distribution of soil organic carbon is an important factor in land management decision making, climate change mitigation and landscape planning. In Scotland, where approximately one-quarter of the soils are peat, this information has usually been obtained using field survey and mapping, with digital soil mapping only carried out recently. Here a method is used that integrates legacy survey data, recent monitoring work for peatland restoration surveys, spatial covariates such as topography and climate, and remote sensing data. The aim of this work was to provide estimates of the depth, bulk density and carbon concentration of Scotland's soils in order to allow more effective carbon stock mapping at 100 metre resolution over Scotland. Mapping of depth to the bottom of the organic layer, and of carbon stock at different depths was carried out. This allowed estimation of soil carbon in mineral and organic soils in Scotland to a depth of one metre (3498 megatons) and overall (3688 megatons).
    c. Source: National Assets Register
    d. Website: http://nar.hutton.ac.uk/dataset/soil-profile-depth-bulk-density-and-carbon-stock-of-scotland/resource/ceb425a3-c9d1-412d-94a7-0cb2bb7676a7
    e. Citation: Aitkenhead, M.J., Coull, M.C., 2019. Mapping soil profile depth, bulk density and carbon stock in Scotland using remote sensing and spatial covariates. European Journal of Soil Science. 10.1111/ejss.12916
    f. Copyright: © The James Hutton Institute (2019)
2. **Peat depth**
    a. Purpose: To provide information on the peat depth and organic carbon stock of Scotland's soils at 100 metre resolution.
    b. Abstract: The spatial distribution of soil organic carbon is an important factor in land management decision making, climate change mitigation and landscape planning. In Scotland, where approximately one-quarter of the soils are peat, this information has usually been obtained using field survey and mapping, with digital soil mapping only carried out recently. Here a method is used that integrates legacy survey data, recent monitoring work for peatland restoration surveys, spatial covariates such as topography and climate, and remote sensing data. The aim of this work was to provide estimates of the depth, bulk density and carbon concentration of Scotland's soils in order to allow more effective carbon stock mapping at 100 metre resolution over Scotland. Mapping of depth to the bottom of the organic layer, and of carbon stock at different depths was carried out. This allowed estimation of soil carbon in mineral and organic soils in Scotland to a depth of one metre (3498 megatons) and overall (3688 megatons).
    c. Source: National Assets Register
    d. Website: http://nar.hutton.ac.uk/dataset/soil-profile-depth-bulk-density-and-carbon-stock-of-scotland/resource/cf7cea84-b620-4866-8855-636788d3ef40?view_id=3baa10bf-4230-40be-be97-6afe7a03e510
    e. Citation: Aitkenhead, M.J., Coull, M.C., 2019. Mapping soil profile depth, bulk density and carbon stock in Scotland using remote sensing and spatial covariates. European Journal of Soil Science. 10.1111/ejss.12916
    f. Copyright: © The James Hutton Institute (2019)
3. **Carbon and peatland 2016 map (Peat Scotland)**

a. Purpose: The map shows the distribution of carbon and peatland classes across the whole of Scotland to be used as a planning tool in accordance with Table 1 in the Scottish Planning Policy (SPP).
b. Abstract: Allocates a value to indicate the likely presence of carbon-rich soils, deep peat and priority peatland habitat for each individually-mapped area, at a coarse scale.
c. Source: Scotland Soils (Scotland's Environment)
d. Website: https://soils.environment.gov.scot/maps/thematic-maps/carbon-and-peatland-2016-map/
e. Citation: Carbon-rich soils, deep peat and priority peatland habitat mapping, Consultation analysis report, Scottish Natural Heritage June 2016
f. Copyright: ©Scottish Natural Heritage (2016)

4. **Land Cover Map 2007**
   a. Purpose: Provides land cover information for the whole of the UK.
   b. Abstract: Derived from satellite images and digital cartography. Land cover is based on UK Biodiversity Action Plan Broad Habitats, and assigned based on spectral criteria.
   c. Source: UK Centre for Ecology and Hydrology
   d. Website: https://www.ceh.ac.uk/services/land-cover-map-2007
   e. Citation: Countryside Survey: Land Cover Map 2007 Dataset Documentation, Centre for Ecology and Hydrology, July 2011
   f. Copyright: © NERC (CEH) 2011. © Crown Copyright 2007. Ordnance Survey Licence number 100017572. © Crown Copyright 2011. Licence number 100,427. © third-party licensors.
5. **Land Cover Map 2015**
   a. Purpose: Provides land cover information for the whole of the UK.
   b. Abstract: Land Cover Map 2015 (LCM2015) is a parcel-based land cover map for the UK, created by classifying satellite data into 21 land cover classes. The classes are based on the UK Biodiversity Action Plan Broad Habitat definitions (Jackson, 2000). LCM2015 was created by classifying two-date composite images, based on spectral criteria, and is based mainly on data from Landsat-8 (30m resolution) supplemented with AWIFS data (60m resolution) as required. LCM 2015 updates the 2007 Land Cover Map and uses an updated version of the LCM2007 spatial framework. LCM2015, like LCM2007 before it, is therefore constructed from polygons that reflect real-world boundaries. This increases both its ease of interpretation for users and also its compatibility with other geospatial data sets. The LCM2015spatial framework was derived from generalised digital cartography (Ordnance Survey MasterMap topographic layer (OSMM) for GB and Land & Property Services Large-scale Vector for Northern Ireland), refined with rural payment boundary data (see Morton et al., 2011 for details).
   c. Source: UK Centre for Ecology and Hydrology
   d. Website: https://www.ceh.ac.uk/sites/default/files/LCM2015_Dataset_Documentation_22May2017.pdf
   e. Citation: Countryside Survey: Land Cover Map 2007 Dataset Documentation, Centre for Ecology and Hydrology, July 2017
   f. Copyright: © NERC (CEH) 2017. © Crown Copyright 2007. Ordnance Survey Licence number 100017572.
6. **LCS88**
   a. Purpose: To produce a detailed baseline land cover inventory.
   b. Abstract: The Land Cover of Scotland 1988 (LCS88) survey was the first ever detailed, national census of land cover in Scotland. It was derived from aerial

photography surveys carried out in 1988 and resulted from concerns about the nature and rate of change in rural Scotland and the need for baseline information for future research and policy needs. The mapping units are mosaics of identified land cover types which can then be classified as a particular mapping unit, and assigned based on spectral criteria.

c. . An important aspect of the classification system is that it allows for mosaics of the land cover types to be identified, where the pattern of cover types was so complex that individual types could not, at the selected interpretation scale, be separated. Over 1300 mosaics are identified in the LCS dataset. The data was mapped at 1:25 000 scale.
d. Source: James Hutton Institute
e. Website: Data available from https://data.gov.uk/dataset/c373c59e-7b4b-4852-ab1d-553324655917/land-cover-scotland-lcs-1988. A more detailed description of the data is available from https://www.hutton.ac.uk/learning/exploringscotland/landcover-scotland-1988
f. Citation: The Landcover of Scotland 1988, Macaulay Land Use Research Institute, Aberdeen, 1993 ISBN 0 7084 0537 1
g. Copyright: © The James Hutton Institute (date of publication)

7. **Agricultural Census 2015**
    a. Purpose: Census of agricultural activity in Scotland (in this instance).
    b. Abstract: The Agricultural Census is conducted in June each year by the government departments dealing with Agriculture and Rural Affairs for Scotland, England, and Wales (see appropriate governmental website for the devolved region). Each farmer declares the agricultural activity on the land via a postal questionnaire. The respective government departments collect the 150 items of data and publish information relating to farm holdings for recognised geographies.
    c. Source: EDINA please note, access to the data is by registration only.
    d. Website: http://agcensus.edina.ac.uk/description.html
    e. Citation: EDINA (2015) EDINA Agricultural census for England, Wales and Scotland [Agcensus]. EDINA at Edinburgh University Data Library and the Department of Environment, Food and Rural Affairs (DEFRA) for England, The Welsh Assembly Government, and The Scottish Government (formerly SEERAD), covered by Crown Copyright. http://agcensus.edina.ac.uk/ (accessed 13/01/2021)
    f. Copyright: The grid square agricultural census data, as converted by Edinburgh University Data Library, are derived from data obtained for recognised geographies from the Department of Environment, Food and Rural Affairs (DEFRA), The Welsh Assembly Government, and The Scottish Government (formerly SEERAD), and are covered by Crown Copyright.

8. **QMSoils**
    a. Purpose: Derived from the Scottish Soil Map at 1:250,000 scale, with map units comprising a mix of different soil types.
    b. Abstract: Digital data of soils covering the whole of Scotland produced at 1:250 000 scale. The soil map units are mainly soil 'complexes' based on a limited number of repeated landforms found throughout Scotland and, as such, often comprise of more than one particular soil type. A series of handbooks give additional information of the distribution of the individual soil types within these map units. The data are suitable for strategic scale but in some cases this is the only data available for what is considered as non-arable areas at the time of production.
    c. Source: James Hutton Institute

d. Website: Data available from https://www.hutton.ac.uk/learning/natural-resource-datasets/soilshutton/soils-maps-scotland/download#soilmapdata. A more detailed description is available from https://www.hutton.ac.uk/learning/natural-resource-datasets/soils/quarter-million-soils
e. Citation: Soil Survey of Scotland Staff (1981). Soil maps of Scotland at a scale of 1:250 000. Macaulay Institute for Soil Research, Aberdeen, 1984. ISBN 0 7084 0309 3
f. Copyright: © The James Hutton Institute (date of publication)

9. **Land use grazing intensity (based on AgCensus 2015 2km livestock data and LCM 2007 updated with NWSS 2014 & NFIS 215)**
a. Purpose: Produced as part of RESAS Program Deliverable 1.4.2, to be used in NetZero land use scenarios.
b. Abstract: The dataset draws information on livestock density (AgCensus 2km data for 2015) and land cover (LCM 2007 + NWSS 2014 + NFIS 215) in order to produce estimations of the grazing intensity (either intensive/ overgrazed or extensive/not overgrazed) across 3 land cover types (improved grassland, semi-natural grasslands and heathers).
c. Source: James Hutton Institute
d. Website: Alessandro Gimona/ Marie Castellazzi, The James Hutton Institute
e. Citation: Gimona A., Castellazzi M.S. (2021). Land use grazing intensity maps based on AgCensus 2015 and LCM2007+NWSS14+NFIS15. Part of RESAS deliverable O1.4.2ciiD25 Spatially disaggregated scenarios of land use change: where the change could take place and what consequences there would be for Carbon storage, Nutrient export and soil erosion.
f. Copyright: © The James Hutton Institute (date of publication), Acknowledgement of input datasets:
- AgCensus 2015 (The grid square agricultural census data, as converted by Edinburgh University Data Library, are derived from data obtained for recognised geographies from the Department of Environment, Food and Rural Affairs (DEFRA), The Welsh Assembly Government, and The Scottish Government (formerly SEERAD), and are covered by Crown Copyright.)
- LCM2007 (© NERC (CEH) 2017. © Crown Copyright 2007. Ordnance Survey Licence number 100017572).

10. **Land Capability for Agriculture**
a. Purpose: Provides spatial information on the flexibility and suitability of land in Scotland for different agricultural land uses.
b. Abstract: The LCA classification is used to rank land on the basis of its potential productivity and cropping flexibility. This is determined by the extent to which the physical characteristics of the land (soil, climate and relief) impose long term restrictions on its use.
The LCA is a seven class system. Four of the classes are further subdivided into divisions. Class 1 represents land that has the highest potential flexibility of use whereas Class 7 land is of very limited agricultural value.
The LCA classification is applied through a series of guidelines that allows a high degree of consistency of classification between users. The classification is based upon several assumptions. These specifically include the potential flexibility of cropping and agricultural options, assuming a high level of management. However they exclude other factors, such as distance to market and individual landowner choices, all of which can influence actual land use decisions.
c. Source: James Hutton Institute

d. Website: https://www.hutton.ac.uk/learning/natural-resource-datasets/soilshutton/soils-maps-scotland/download#soilmapdata for more detaols see https://www.hutton.ac.uk/learning/exploringscotland/land-capability-agriculture-scotland seee https://www.hutton.ac.uk/sites/default/files/files/soils/LAND%20CAPABILITY%20CLASSIFICATION%20FOR%20AGRICULTURE.PDF for more details
e. Citation: Bibby et al, Land Classification For Agriculture, Macaulay Land Use Research Institute, 1991, ISBN 0 7084 0508 8
f. Copyright: © The James Hutton Institute (date of publication)

Appendix 5: quality & suitability of spatial data used in this report

The quality and coverage of spatial data on peatland in Scotland is mixed.

Due to differences in measurement techniques and accuracy of data collection, some of the best quality environmental and land management spatial data in Scotland is relevant to this report but not directly aligned with the questions being asked. We have given recommendations later in the report on how to improve on dataset quality and suitability in future.

This report is based on information derived from several spatial datasets, as described in detail below and in Section 4: Annex on methodologies.

The following datasets were central to the work, with further details on collection/development of each one given in Section 6: Annex on maps and data. They have been listed in the order in which they were developed (from oldest to youngest):

- LCS88: despite being over 30 years old, this dataset can still provide useful information about where peat workings existed at the time of the dataset's development. However, given the age of the data and the technology available at the time of the initial assessment, we place strong caveats on the data in this dataset as a tool for showing current peat workings (due to likely vegetation change in the intervening period).
- QMPeat: identification of peat-dominated map units was used as evidence of peatland presence/absence. Map units with 100% peat were considered as providing stronger evidence than those with less than 100% because the location of peat within these map units is more confidently asserted (i.e., if it's 100% peat then we know that each location has peat – if it's 50% peat then we don't).
- LCM2007: this dataset was developed by the Centre for Ecology & Hydrology (CEH) and provides broad land use/land cover categories. Again, the age of the dataset and concerns regarding accuracy in distinguishing between heath & peatland vegetation, means that this data was considered only in an 'advisory' manner.
- Peat Scotland: 2016 dataset on condition of Scottish peat. Shows distribution of carbon and peatland classes in accordance with Table 1 in the Scotland Planning Policy. Derived from Scotland's Soils map, so has some circularity with that data (although the interpretation classes are informative).
- Grazing: a map of grazing intensity, derived from LCM2007 & AgCensus 2015 data as part of a RESAS-funded project led by Alessandro Gimona at the James Hutton Institute. This makes use of livestock stocking density data at 2km squares.
- Soil carbon stock and peat depth datasets generated by Matt Aitkenhead and accessible on the Natural Asset Register[76].

Use of LCM2015 data would enable updated and probably more accurate assessment of the kind carried out here. However, this dataset become available during February 2021, and it is still unclear whether licence conditions will allow its use in future reports. There is now also restricted-use access to annual LCM products that we are exploring for future applications. This will provide additional benefit as all of the datasets listed above are 'one-off' with no current plans to update them (although the LCM2007 is superseded by the later LCM maps).

Each of the datasets used above provided full coverage of Scotland. For soils, a 1:25,000 scale map exists that covers mainly agricultural areas in the east coast and

[76] http://nar.hutton.ac.uk/

Central Belt. This part of Scotland has relatively little peat coverage, hence this map was not used in this report. Instead, soils and peat coverage data were derived from the 1:250,000 full-Scotland mapping.

Possible improvements in relevant spatial data

Land cover/land use: the LCM2007 data used for this work is over a decade old, and it would have been better to use the more recent LCM2015 dataset. However, we did not have access to this data for this project. Since February 2021, LCM2015 data for Scotland has become freely available and so future work in this area should use it. However, even this dataset has some issues as the land cover classes are relatively broad, making it difficult to discriminate between semi-natural 'emission factor' classes in practice as more than one of these often fall into a single LCM class. Access to recent land cover mapping of sufficient spatial resolution is an ongoing challenge that can realistically only be resolved using recent, high-quality remote sensing data linked to detailed ground observations. This kind of remote sensing data is not currently available without significant cost, although the James Hutton Institute is in discussions with multiple data providers who may be able to provide cheaper national-level high-quality remote sensing imagery.

Land management: at the initiation stage for this project, discussions were held about the possible use of IACS data as a tool, given its more detailed and up to date information on land management. However, data privacy and information sensitivity concerns prevent its use for this report. Future work in this area would be greatly improved through the inclusion of IACS data, particularly on (i) livestock density and (ii) crop rotation practices. The land management data used in this report contains only broad land use classes and is largely derived from remote sensing data, rather than directly from land manager reporting, so is considerably less accurate than we would like.

Soil: Scottish soil mapping at a national level is considered reliable and accurate at the catchment level but needs to be updated and maintained to account for changing soil conditions. For peat soils in particular, recent work provides good-quality mapping including details of location, depth and carbon stock. Currently, multiple datasets exist that need to be harmonised and integrated to provide a dataset for consistent use by all stakeholders.

Peat condition: there is a scarcity of data on peatland condition at the national level. Local studies integrating remote sensing, ground survey and expert knowledge have demonstrated the ability to provide information on degradation, drainage, and other factors of peat condition. However, these need to be rolled out at a national level to provide useful information for further work in this area.

Mapping the uncertainty and disagreement between datasets

Highlighting the level of disagreement between the sources of evidence is important, to provide a sense of how reliable the maps we have produced are. We have therefore taken a simple but effective approach to assessing disagreement between sources, and indicating that this disagreement creates uncertainty, by counting the number of 'disagreements' between these spatial datasets at each map cell. If there are no disagreements between datasets then this does not mean that the map is perfect, but it does increase confidence in the mapping.

Figure 4 shows a map developed for this report that incorporates disagreement and uncertainty between the multiple datasets used for this work. Lower values (dark-blue and green) indicate where there is greater confidence in the mapping, which means that the data can be considered accurate. Small areas in purple are where substantive disagreement exists between datasets (i.e., data in one dataset does not match that in another, creating uncertainty about the accuracy of said datasets). These areas are mostly in Shetland, north Sutherland coastal areas and on Lewis and Harris. Table 2 summarises the uncertainty mapping across different emission factor categories.

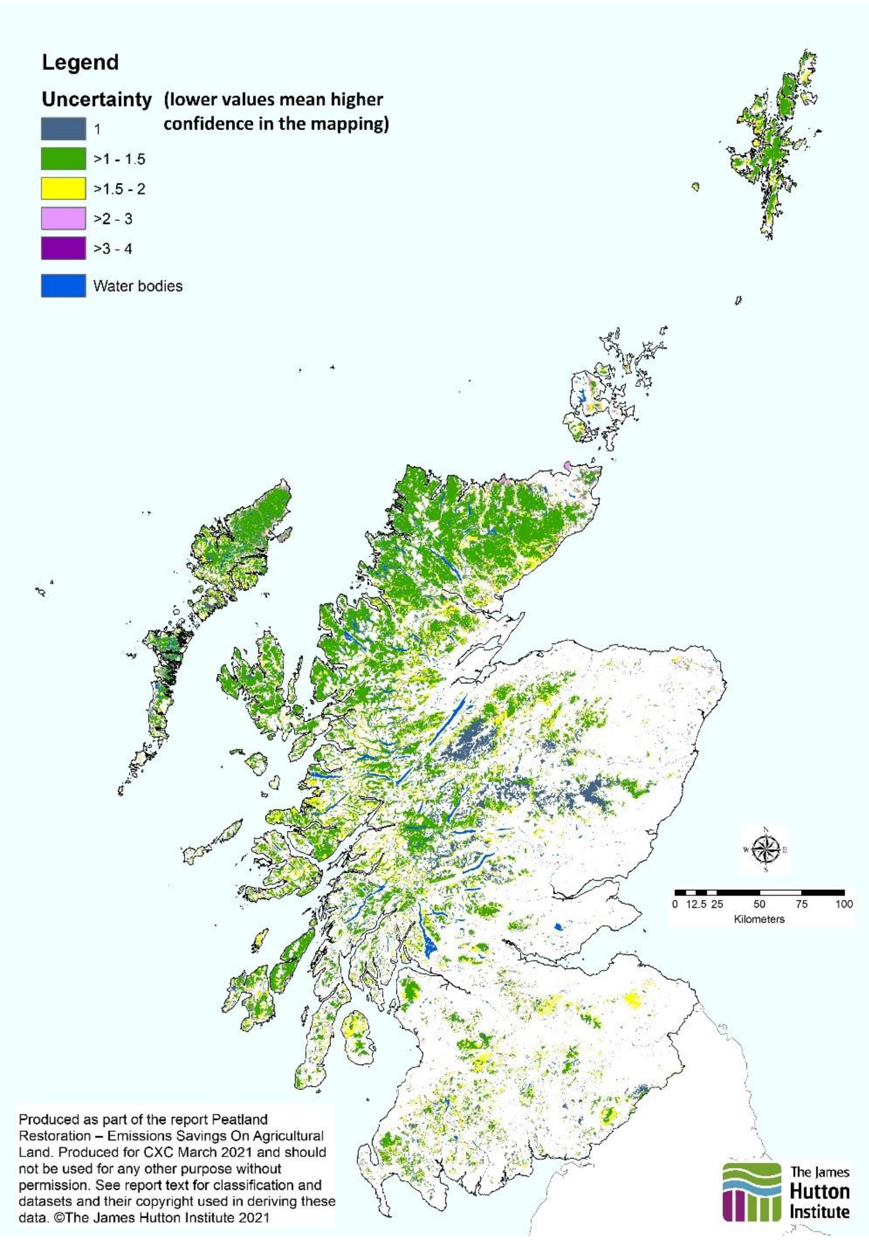

Figure 4. Uncertainty map for categorisation of land use on peatland.

Following on from Figure 4, the uncertainty values calculated for this map were used to produce summary statistics for each peatland emission factor category. This information is shown in Table 2. These number are NOT to be taken as 'error bars' for the range of emission factor values for each category – they are indicative of how confident we are in the mapping of categories themselves.

The relatively high average uncertainty associated with peatland extraction in Table 2 is due to disagreement between the LCS88, LCM2007 and soil map data with the latter two datasets assigning land cover/soil classes that are could not be carried out at the same time as peat extraction (e.g., arable cropping, non-peat soil types). Additionally, peat depth mapping[77] identifies some areas of peat extraction as having organic depth <50 cm, (i.e., less than the technical definition of peat in Scotland).

Table 2. Uncertainty ranges for peatland emission categories.

Peatland emission category	**Min uncertainty score (1=low, 5=high)**	**Max uncertainty score (1=low, 5=high)**	**Average uncertainty score**
Cropland	1	2	1.41
Near natural bog	1	2	1.48
Heather dominated undrained	1	1.5	1.41
Heather dominated drained	1	3	1.54
Grass dominated undrained	1	2	1.34
Grass dominated drained	1	3	1.47
Eroded drained	1	3	1.69
Grassland extensive	1	4	1.68
Grassland intensive	1	4	1.17
Extraction (domestic)	1.5	3	2.95

[77] Aitkenhead & Coull, 2019

Appendix 6: social, economic and political review of paludiculture

Discussion

Given questions over the commercial viability of both energy crops and Sphagnum farming, stimulating a large-scale transition from existing land use would require additional income streams from paludiculture. Payments for ecosystem services may include public funding via future agri-environment schemes and private funding via carbon finance, biodiversity net gain (if adopted in Scotland), water quality benefits (via water utility companies) and green finance where projects can be designed that provide a return on investment[78].

Although payments may be made for climate change mitigation purposes informally provided specific claims are not made about the GHG emission benefits, there is a limited market for "corporate social responsibility" projects of this nature. To access carbon finance, projects would need to be accredited via a wetland agriculture methodology under the voluntary carbon market (a draft methodology including paludiculture has been proposed under Verified Carbon Standard v4.0[79]) or via a national carbon market such as the Peatland Code. However, the costs of validation and verification under the voluntary carbon market are typically prohibitive for peatland projects in the developed world[80], and the Peatland Code does not currently permit lowland peat projects.

Version 2.0 of the Peatland Code is currently under development to include lowland peats for the first time. While not currently planned, this could consider whether there is sufficient evidence to include emissions factors for paludiculture on degraded lowland peat sites. Where farms combine paludiculture with full habitat restoration, the restoration component would be eligible under version 2.0 of the Peatland Code. Alternatively, this could be included in the development of a future Farm Soil Carbon Code (a feasibility study is currently being conducted under the auspices of the Global Food Security Programme Resilient Dairy Landscapes project[81]).

The majority of remaining undrained lowland peatlands in Scotland are designated sites and lowland fens and bogs are priority habitats in the UK Biodiversity Action Plan[82]. Given the biodiversity benefits associated with paludiculture (especially when bundled with habitat restoration), it may be possible to secure additional payments from developers if Biodiversity Net Gain is made mandatory in Scotland in future. Although additionality criteria in the Peatland Code and habitat banking would normally rule out stacking of carbon and biodiversity payments in a single site, the high costs of transitioning from arable agriculture or horticulture to paludiculture or habitat restoration may make payments eligible under "economic alternative" and "barrier" additionality tests (where it can be shown that without both carbon and biodiversity finance, the transition to paludiculture or restoration would not be economically and/or socially viable, and hence would not otherwise happen). As such, it is the high opportunity and other costs associated with paludiculture and habitat restoration that are likely to make payments for both carbon and biodiversity possible in future.

There is also evidence that payments for climate change mitigation and biodiversity may already be possible at scale via regional ecosystem markets, which also have the

78 Reed et al., 2020
79 Verra, 2019
80 Bonn et al., 2014
81 Reed et al., 2020
82 Mulholland et al., 2020

potential to bundle payments for water quality benefits by water companies seeking to reduce water treatment costs at source by reducing nutrient loads from drained peatlands. Landscape Enterprise Networks have already leveraged around £5 million of private investment in sustainable agriculture in the UK and Europe, with limited verification of the ecosystem services provided. By aggregating demand for services across consortia of regional businesses, it is possible to design the procurement of environmental outcomes to minimise trade-offs between ecosystem services or free-riding effects, and deliver outcomes at scale via supply-side aggregators who work with farmers to enter land into the scheme[83].

In addition to avoiding GHG emissions and the loss of future carbon sink capacity, enhancing biodiversity and improving water quality, which may attract private investment, a range of indirect cost savings and wider benefits associated with no longer maintaining drainage systems provide a strong case for public funding for paludiculture. These include:

- Reducing the rapid and progressive loss of high value agricultural soils;
- Releasing funds currently invested in maintaining drainage systems;
- Reducing impacts on infrastructure due to subsidence; and
- Avoiding loss of archaeological, historical and geological features (that are currently protected by peat deposits), cultural values and sense of place.

Given the wide range of negative impacts and externalities created by arable agriculture and horticulture on lowland peats (e.g. GHG emissions, soil erosion, flood risk increase, biodiversity impacts), and the public goods (notable GHG emission reduction and biodiversity gains) associated with paludiculture, several studies have advocated for publicly funded paludiculture options in agri-environment or other types of Government-funded schemes (e.g.[84] [85] [86] [87]). It has been estimated[88] that the negative externalities associated with agriculture on lowland peat in Germany equated to £13 ha^{-1} yr^{-1}.

Although it is not advisable to apply such findings to the very different Scottish context, it is likely that externalities may run into the tens of millions. Further research would inform the potential in a Scottish context. Although there were widespread concerns among EU member states that paludiculture was not eligible for payments under the EU Common Agricultural Policy[89], Scotland's departure from the EU represents an opportunity to consider paludiculture in any future agri-environment scheme.

However, the design of any such mechanism would need to consider how it could help leverage rather than compete with private investment. For example, Finance Earth have proposed a Peatland Carbon Guarantee, similar to the Woodland Carbon Guarantee in England and Wales, which could leverage impact investment on the basis of repayable loans for the capital works necessary to convert land for habitat restoration or paludiculture (if included in version 2.0 of the Code), repayable over 30 year or longer contracts at the five-yearly verification points of the Peatland Code, with landowners either accepting the floor price from the Government for their carbon (reached via reverse auction to ensure this covers the cost of the loans) or accepting higher prices if available via the carbon market. Where carbon is sold via the market, very limited public

[83] Reed et al., 2020
[84] Korn et al., 2012
[85] Appulo et al., 2020
[86] Grieswald Moor Centrum, 2020
[87] Ziegler; 2020
[88] Schafer (2011)
[89] Greifswald Moor Centrum, 2020

finance would be required to create the necessary confidence to scale peatland carbon markets.

High intensity Sphagnum moss farming

A constant high water table (where the water level is 2-5 cm from the surface during establishment and close to the top of the plant during production phase) is needed for rapid Sphagnum growth[90]. Precise control of the water table level is thus essential for the commercial viability of Sphagnum farming. Flat topography is therefore necessary to retain water in dry summers and reduce water table variation (so bogs with degradation features would be problematic). This often requires topsoil removal, especially if carried out on hydrophobic peat or nutrient rich former agricultural land. Irrigation through open ditches, or pipes, preferably connected to nearby water bodies, or artificially created reservoirs, is needed. Due to the potential need for on-site personnel to monitor water levels, as well as to use heavy machinery for farm establishment and harvesting, and to be able to transport the dry matter product to market, distance to the nearest road is an important factor for transport, in terms of cost, practicality, and additional carbon emissions from vehicles running on fossil fuels.

Figure 5 shows the areas of peat in Scotland that are within 1 km of a road, and also within 1 km of a freshwater body. This map indicates that only a small fraction of peatland areas in Scotland would be suitable for sphagnum farming without construction of a water reservoir nearby. The map does not take into account other factors that influence sphagnum growth (e.g., temperature, local ecological interactions).

[90] Gaudig et al., 2020

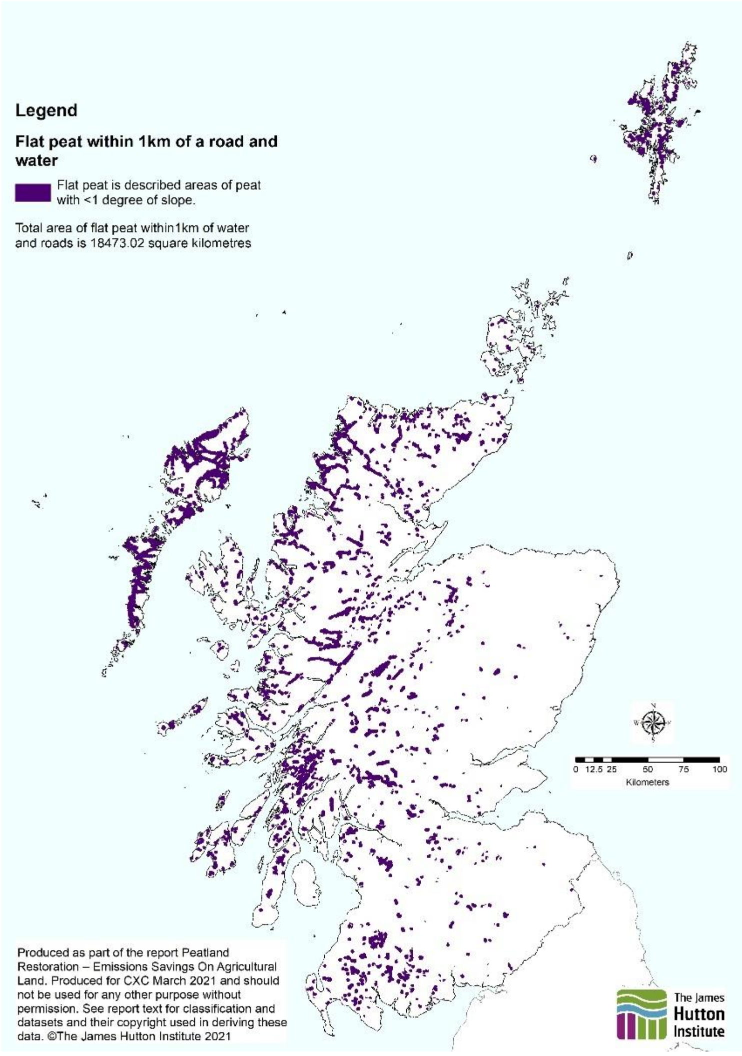

Figure 5. Peat areas that are within one kilometre of both roads and freshwater bodies.

It could take more than 7 years between the establishment of a sphagnum farm and the first harvest, although a harvesting frequency thereafter of once every 3–5 years seems to be feasible[91]. An average harvesting depth of 30 cm has been demonstrated to work in field trials in Germany. To prevent damage to peatland, allowing mechanical sphagnum harvesting from a central ditch would allow scraping of the biomass without risk of ditch filling but is less easy to maintain than edge ditches. Different production systems for bioenergy cropping also have different overall carbon budgets. For example, mowing of sphagnum biomass appears better than more destructive mechanical harvesting approaches[92].

Costs and barriers

Financial costs

While the private and public benefits of paludiculture covered in the previous section appear clear, it is important to balance these against the costs and unintended negative consequences of this land use change. These include the direct costs of changing land use including changes to drainage systems (i.e. ditch blocking/filling to allow rewetting) and the specific costs associated with irrigation control systems that are required to control water table depth for these crops. These costs are not trivial because significant

[91] Gaudig et al., 2018b
[92] Rodzkin et al., 2017

understanding is required of the soils, topography and hydrology to target rewetting, and not all sites can be effectively rewetted, depending on their location in the drainage system. Changes to one part of the system can have negative unintended consequences for other neighbouring land, leading to flooding of land and property not intended in a rewetting programme.

Significant investment is also needed in new machinery, equipment and skills to manage paludiculture crops. The specialist nature of this equipment means machinery rings or co-operatives may be necessary to pool labour and machinery specialised for paludiculture activities[93]. Indirect costs of paludiculture can be substantial and include opportunity costs associated with losing existing profitable land uses, and loss of food security (and potential displacement of emissions, depending on where food crops previous grown on lowland peat soils are sourced from).

The extent to which these costs are a barrier to entry to paludiculture will depend on a range of external and internal factors. External factors include[94] [95] [96] [97] [98] [99] [100] [101]:

- Land tenure
- Farm characteristics (e.g. farm size, farm infrastructure and availability of relevant equipment)
- Characteristics of paludiculture itself (for example the difficulty of trialling paludiculture and the relative irreversibility of the land use change) compared to existing land uses (and their relative profitability compared to paludiculture).

Internal factors include[102] [103] [104] [105] [106] [107]:

- Availability of resources, including financial capital, social capital (e.g. access to expertise, credit and other support, and levels of connectedness and trust in social networks) and time
- Personal capabilities and related demographic factors (e.g. knowledge and skills, formal educational status, disabilities, age, gender and succession status), especially as these influence risk perception
- Risk perception itself, which is influenced by the type of risks perceived and cognitive biases
- Levels of perceived self-efficacy and agency
- Individual land manager attitudes towards and preferences for paludiculture, as they are shaped by their values, beliefs and norms about the natural environment and other people compared to more self-interested ‘egoistic’ values, beliefs and norms.

<u>*Social and cultural barriers*</u>

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[93] Johnson et al. 2017
[94] Reed, 2007
[95] Siebert et al., 2006
[96] Ruto and Garrod, 2009
[97] Wilson and Hart, 2000
[98] Emery and Franks, 2012
[99] Proctor et al., 2012;
[100] Kusmanoff et al., 2016
[101] Mills et al., 2017
[102] De Groot and Steg 2007, 2008
[103] Burton et al., 2008
[104] Mills et al., 2017
[105] Sutherland et al., 2012
[106] Wynne-Jones, 2013
[107] Kenter et al., 2015

Interviews with farmers[108] [109] in lowland peat settings in Germany and England and identified four important psychological factors reinforcing the status quo of current land use. First, land drainage is seen as an engineering achievement enabling economic progress by making previously unproductive land profitable for agriculture. Second, many inhabitants of drained landscapes derive a strong sense of place identity from the "straight and ordered landscape" that is created by drainage. Third, because the transition from semi-natural to agricultural landscape did not occur within the lifetime of most people living in drained peatlands, they are unable to perceive the scale of biodiversity loss and often point to habitat remnants and generalist species that are able to co-exist with current land uses as evidence that nature has adapted and can thrive in the current land use.

Finally, farmers interviewed in both projects emphasised their credentials as small business owners, making economically rational decisions to secure their own livelihoods and those of others in the rural economy. While recognising the importance of climate change and biodiversity loss, and their potential role, their agency was limited by the economic reality of maintaining their businesses. This in turn led to the perception among many farmers that they were unfairly held responsible for habitat degradation and GHG emissions.

Having said this, farmers interviewed in England expressed a strong sense of place attachment and place identity as they spoke about themselves as custodians of the land and its heritage[110]. Land managers who were interviewed had a strong sense of control, but this often felt threatened by policy change, with specific concerns expressed about the extent to which the future peatland policy might constrain management options and freedom of action. A strong component of the identities expressed by land managers focused on their freedom of action, openness to change and adaptability as decision-makers in the landscapes they managed.

There was a feeling that some of this sense of control had to be given up if farmers adopted land management prescriptions from Government. While many land managers had a strong sense of self-efficacy around their skills and capacity to deliver public goods, others expressed doubts about the extent to which they could change their practices, and the level of support that would be available if things went wrong. This suggests advisory services may need to play a stronger role in supporting those who wish to adopt paludiculture and emphasizes the need for demonstration sites to enable land managers to evaluate the risks and benefits more effectively for themselves.

Gaps in knowledge and evidence

Barriers to the implementation of commercial, low-emission sphagnum harvesting include a lack of research findings about biophysical and economic impacts, and a lack of evidence of the practicalities in large-scale implementation. Very few field investigations have been carried out, with 900-1500 square metres needed for a full-scale trial. Economic studies of setting up sphagnum farming sites in Germany have also shown that investment costs are high.

Large-scale commercial implementation is still lacking. Further research is needed to evaluate the long-term effects of sphagnum farming and to assess profitability and environmental benefits in countries other than Germany. The effect of growing and

[108] Ziegler (2020)
[109] Reed et al. (2020b)
[110] Reed et al. (2020b)

harvesting conditions during sphagnum farming on the properties of the sphagnum biomass is also insufficiently clear[111].

Other barriers

Other barriers to sphagnum farming include:

- Access to, and high cost of, donor material for sphagnum: in the EU, sphagnum species and their habitats are protected by EC Directive 92/43/EEC, which prevents the collection of material. Furthermore, established commercial farming of sphagnum requires material that is 'fit for purpose'[112] and free from biological contamination from other sources. A UK company that produces Sphagnum for such purposes exists but is relatively small in its annual output at present.
- Control of nutrients: sphagnum requires careful management of nutrient and pH levels. It is also very intolerant to nutrient levels outside an accepted range. This nutrient balance would be hard for commercial plantations to maintain.
- Sensitivity to climate extremes: sphagnum growth is affected not only by drought, but also flooding and extreme heat. Model simulations suggest that increasing temperatures under climate change will reduce carbon sequestration rates for sphagnum moss. This impact on sequestration will increase towards the end of the 21st Century[113].
- Institutional & socio-cultural environments: changes to how peatland is used for agricultural purposes would require modifications to the political and legal frameworks linked to both farming and peatland[114]. Recognition of sphagnum as an agricultural crop would be needed, to allow subsidies to be linked to its growth for harvesting.
- Specialised machinery: no harvesting machinery currently exists that can drive on very wet peat surfaces without sinking or damaging the surface, while also harvesting material in sufficient quantities.

Impact on income of potential agricultural changes

High intensity Sphagnum moss farming

Initial estimates suggest that while there may be a profitable niche market for direct use of Sphagnum for floristry and pets, prices for use in growing media are likely to be around £25-50 per cubic meter (compared to £20-22 for peat). Current demand for peat in growing media in the UK is around 2.5 million m^3, suggesting that it may be possible to develop a multi-million-pound market for Sphagnum if peat-based growing media were phased out and the very significant barriers mentioned above could be overcome. However, without significant research and development or income from the sale of ecosystem services arising from Sphagnum farming (see below), current production costs result in anything from a loss of £12,500 to a break-even point[115].

Sphagnum farming is a high-precision agricultural activity that needs to be carried out on specially modified land with specialist machinery, implying high start-up costs. Estimates have been given of 98,000 EUR per hectare for establishment, more than 3,000 EUR per hectare per year for management and more than 12,000 EUR per year for harvesting. Sphagnum often grows in low nutrient peat and wet fen habitats[116]. Potential

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[111] Günther et al., 2017
[112] Heck et al., 2021
[113] Gong et al., 2014
[114] Wichmann, 2017
[115115] Mulholland et al., 2020
[116] Temmink et al., 2017

sites for farming this crop are degraded bogs and acidic water bodies[117], or cutover peatland where extraction is no longer carried out. To date, the majority of sphagnum moss farms have been set up on cutover bogs whose setup costs can be lower.

As a growing media, farmed sphagnum moss competes directly with peat-based media. The price of the latter for general horticultural use is about 25 EUR per cubic metre, whilst for growing orchids it is 165 EUR per cubic metre and for sale as high-quality donor material for paludiculture the price is about 750 EUR per cubic metre. Research based on five years of data on the establishment of a farm in Germany indicates that the price required to break-even commercially can range from 93 – 423 EUR per cubic metre depending on the farm operation. This suggests that only the production of niche products is currently commercially viable.

Again, gaining market access is also necessary. For orchid production, for example, there is an existing competitive global market including China, New Zealand, Australia and Chile as the main players. If competitive advantage could be achieved and the entire import demand, for example, of the Netherlands, France and Germany could be won by Scottish producers, this would represent 9,000 cubic metres of sales per annum, for which up to 167 hectares of sphagnum farming would be needed. This figure indicates the limited number of hectares that could be profitably turned over to sphagnum moss farming for export in this case.

[117] Wichmann et al., 2017

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