Potential for Greenhouse Gas Emission Savings from Paludiculture

Department for Environment, Food and Rural Affairs

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Executive Summary

Drained agricultural lowland peat accounts for 1.5% of the UKs total greenhouse gas (GHG) emissions while supporting 40% of the country's vegetable production. Paludiculture, the practice of farming on rewetted peatlands to grow wetland-adapted crops, offers a potential alternative to conventional agriculture that combines profitable crop production with reduced environmental impacts. This report identifies paludiculture as a GHG source, releasing an estimated 25.66 t CO_2 e ha^{-1} yr^{-1}. This is a saving of 11.5 t CO_2 e ha^{-1} yr^{-1} compared to conventional cropland on peat. However, substantial uncertainties remain, particularly regarding emissions from individual crops and varying water table depths. Further refinement of these estimates is dependent on additional research and field measurements.

Further actions can be taken to maximise emissions savings from paludiculture including:

- Minimize disturbance by avoiding extensive ground preparation and retain topsoil.
- Reducing the plant export by cultivating crops which are only partially harvested such as berries or *Typha* seed heads
- Prioritise crops which can be incorporated into long-term carbon stores e.g. construction boards.
- Maintaining a high-water table throughout the year
- Reducing the life-cycle emissions associated with paludiculture, for example, through careful machinery, fertiliser and transport use.

Future research directions

To improve the current estimate of a paludiculture emission factor the following research could be carried out:

1. Refine the paludiculture live list to species that are tolerant of high-water levels, economically viable, meet market requirements and require minimal peat disturbance for harvest.
2. Carry out measurements on paludiculture systems in the UK, particularly targeting the most promising species on the live list and those for which there is currently no emission data available. With the aim of generating separate emission factors for individual crops.
3. Develop Tier 2 emission factors for DOC, POC, and Ditch CH_4 enabling any emissions savings between paludiculture and conventional agriculture to be realised and incorporated into national inventories.
4. Improve our understanding of how management interventions in paludiculture influence emissions for example, lowering water levels during harvest or decreasing the areal cover of ditches and causeways.

Acknowledgements

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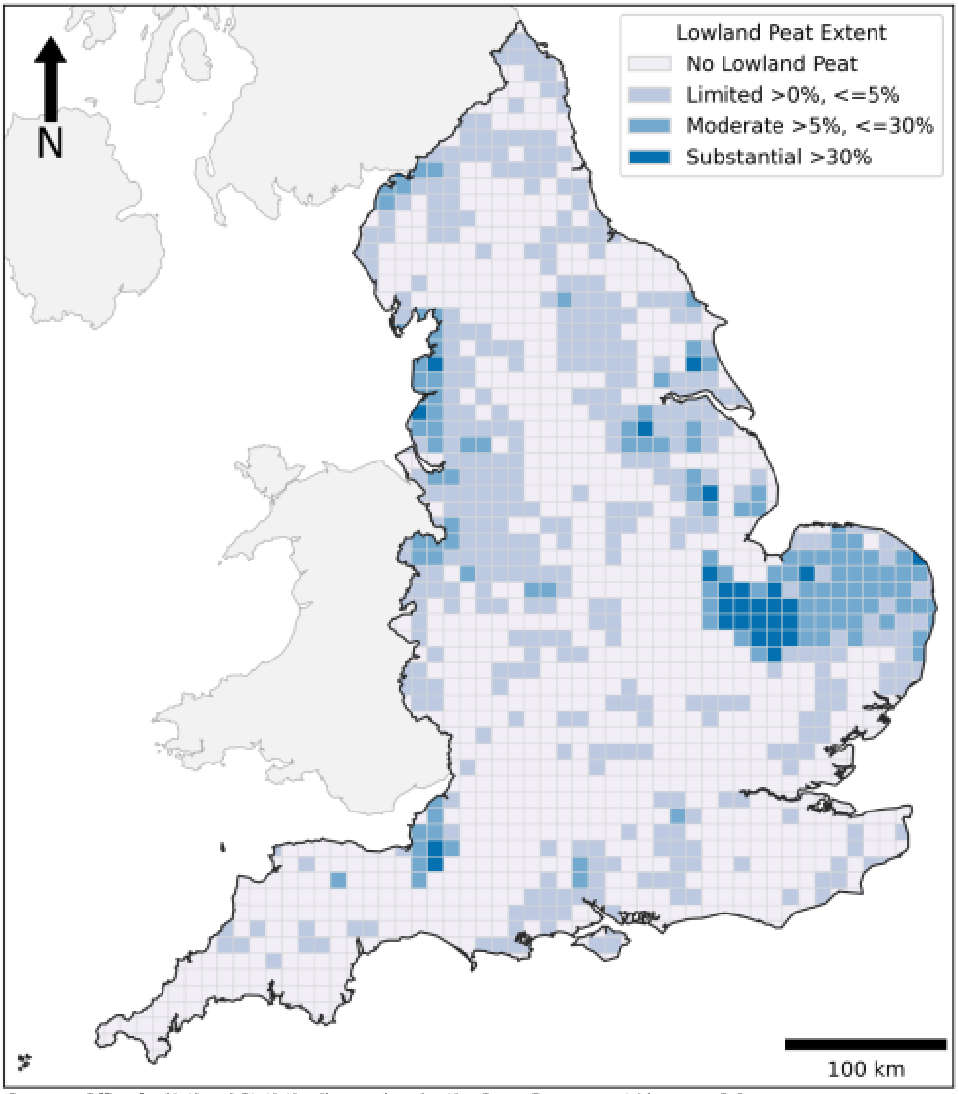
1. Introduction

The raised bogs and fens which make up approximately 465,000 ha of England's lowland peat landscape (1) are spread across the country (Figure 1), from the moors and levels of the South-West and the raised bogs of Lancashire and Cumbria to the Fens and Broads of eastern England. Yet, most of these peatlands, now drained for agriculture, are fast degrading. The carbon losses resulting from subsidence, erosion and microbial breakdown of lowland peat equates to an estimated 6.5 million tonnes of carbon dioxide equivalents lost each year or 1.5% of the UK's total emissions (2).



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BGS, Cranfield University (NSRI) and OS acknowledged for Peaty Soils Location (England) data.

Figure 1: A classified map of approximate lowland peat extent in England with 10km resolution based on the 2008 England peat soils data for deep and shallow peat. Sourced from the Lowland Agricultural Peat Task Force Chair's Report 2023 (2)

With the UK committed to reaching net zero by 2050, lowland peatlands need to be managed in new ways to reduce emissions. A promising pathway is the raising of water levels within agricultural systems. Farming conventional crops at a higher water level is already incentivised through Countryside Stewardship schemes (4) and rewetting these lowland peatlands could prevent substantial further emissions (5). However, these peatlands comprise some of the most economically valuable farmland in the UK, producing 40% of our vegetables and integral for food security (6).

An alternative approach, as recommended by the Lowland Agricultural Peat Task Force is to adopt the roadmap to commercially viable paludiculture (2). Paludiculture, in this context, is the practice of farming on rewetted peat, to grow profitable crops adapted to a wetland environment (7) (Figure 2). While paludiculture is not prescriptive about the water level requirements, paludiculture crops generally require water levels close to the peat surface. The roadmap sets out a 10-year plan for the wide-scale adoption and commercial realisation of paludiculture by 2033. As part of this plan, paludiculture needs to be included in the UK Greenhouse Gas Inventory, so it’s contribution to achieving Net Zero can be calculated, while pathways also need to be developed to secure carbon finance for paludiculture. Central to both is understanding the emissions associated with paludiculture and generating paludiculture emission factors (EFs).

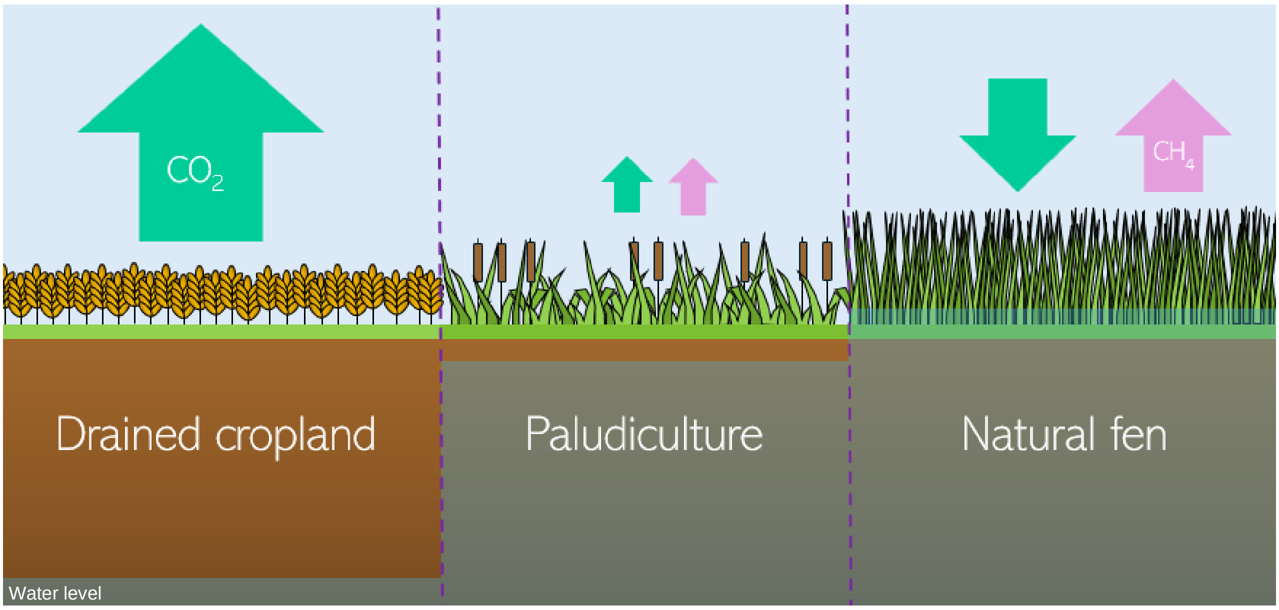

Figure 1 Lowland peat drained to grow crops is a high source of CO_2 emissions. The low water levels allow oxygen into the peat which supports the microbes that break it down and release CO_2. By raising the water level to just below the surface, emissions of CO_2 can be reduced and emissions of CH_4 are still small. Increasing the water level above the surface increases CH_4, but because of the ability of natural fens to take CO_2 out of the atmosphere, they have a net cooling effect on the planet. Arrows are indicative but not to scale, saturation of peat shown in grey/blue.

Thus far paludiculture has not been included in any national inventories, as too little information is available, and the extent of its practice is limited (8). EFs could potentially be derived from known relationships between water table depth and carbon loss. However this technique is not used for calculating EFs across the other land classes due to the lack of information on water level depth in contributing studies (9). Tier 2 EFs are based on direct measurements of emissions from peatland condition categories. For Lowland peat, this can include categories such as cropland, intensive and extensive grassland, industrial peat extraction and near natural fen.

This report aims to try and develop a Tier 2 EF or EFs for paludiculture based on measured and published emissions from paludiculture crops to support Net Zero policy.

This report, therefore, sets out the current best estimate of a paludiculture emission factor using empirical data and considers the land-management approaches that will influence this.

2. Method

2.1.1 Data Search

The starting point for this project was the UK Paludiculture live list (10), a collection of 88 native species with potential for paludiculture in the UK, adapted from the Database of Potential Paludiculture Plants (11). This list has formerly been used to assess the potential for Paludiculture in England (SP1218) (12) and in scoping for paludiculture food crops (RDE462) (13). Recognising that contemporary agricultural systems in the UK include non-native species, such as crops bred for agronomic properties and, the geographic range of crops is shifting with climate change, the scope of crops considered in this report was widened slightly beyond the live list. Where empirical data was available on greenhouse gas (GHG) fluxes (movements of GHGs between the atmosphere and peat) from peat soils with a raised water table with alternative crops, these were also included. However, this report has a particular focus on paludiculture crops and therefore, for conventional crops cultivated on a higher water level, the UK peatland code carbon calculator should be used to determine emission savings (see section 2.3).

The emissions factors of interest in this report were direct carbon dioxide (CO_2), direct methane (CH_4), nitrous oxide (N2O), dissolved organic carbon (DOC), particulate organic carbon (POC), methane from ditches (Ditch CH_4), carbon lost through the removal of crop biomass and finally carbon lost from topsoil removal (TSR) (Figure 3). In this instance, TSR is considered as peat lost through ground preparation work for the paludiculture site, any loss of material during peat harvest is more likely to be considered within POC but this is rarely quantified. As such an initial data search was carried out on peer-reviewed literature using key terms from the emissions of interest, along with the common and scientific name of each crop and additional keywords such as ‘Paludiculture’. The scope was then widened to include unpublished data and grey literature.

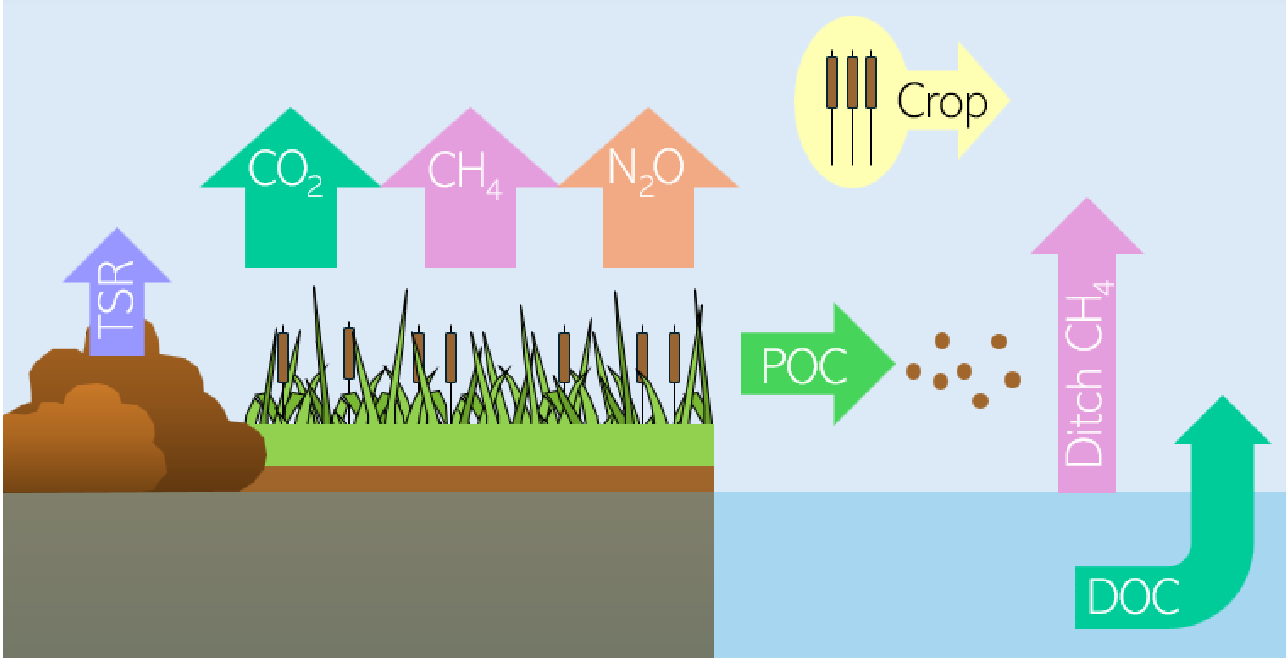

Figure 3. The main pathways of emission and carbon loss in a paludiculture system. CO_2, CH_4, and N_2O can all be lost (or taken up) in a gas form. Erosion can remove particles of carbon (POC), small molecules containing carbon may be dissolved into water and seep out of peatlands before they are broken down and returned to the atmosphere as CO_2 (DOC). CH_4 can also be lost from ditches which are normally hotspots of this type of emission. Carbon is also removed from the system through crop export and any topsoil removal (TSR).

The data on emission factors was compiled in a dataset along with crop type, the former and contemporary land use of the site being studied, the water table depth, information on the paludiculture set-up and management, the duration of the study and the methods used to measure these emissions. All emissions were converted into carbon dioxide equivalents, per hectare per year (CO_2 e ha^{-1} yr^{-1}) following the IPCC methodology (using AR5 without feedback) (14). This makes it possible to compare the warming effects of different GHGs on a common scale. For DOC, POC and TSR it was assumed that this carbon fully re-enters the atmosphere as CO_2.

To ensure that emissions factors from studies outside the UK were relevant in a similar climatic context to England, information included within the database was constrained to locations with the Köppen-Geiger Climate Class of 15 or Cfb (15) (Figure 4) meaning data from sites were only included if they came from temperate areas with no dry season and a warm summer. This meant that for some species the information is limited, such as for forestry species, where the predominant research is within the Boreal zone (16–18). This approach is in line with the UK Tier 2 methodology, which also constrains literature datasets by climate classes relevant to the UK.

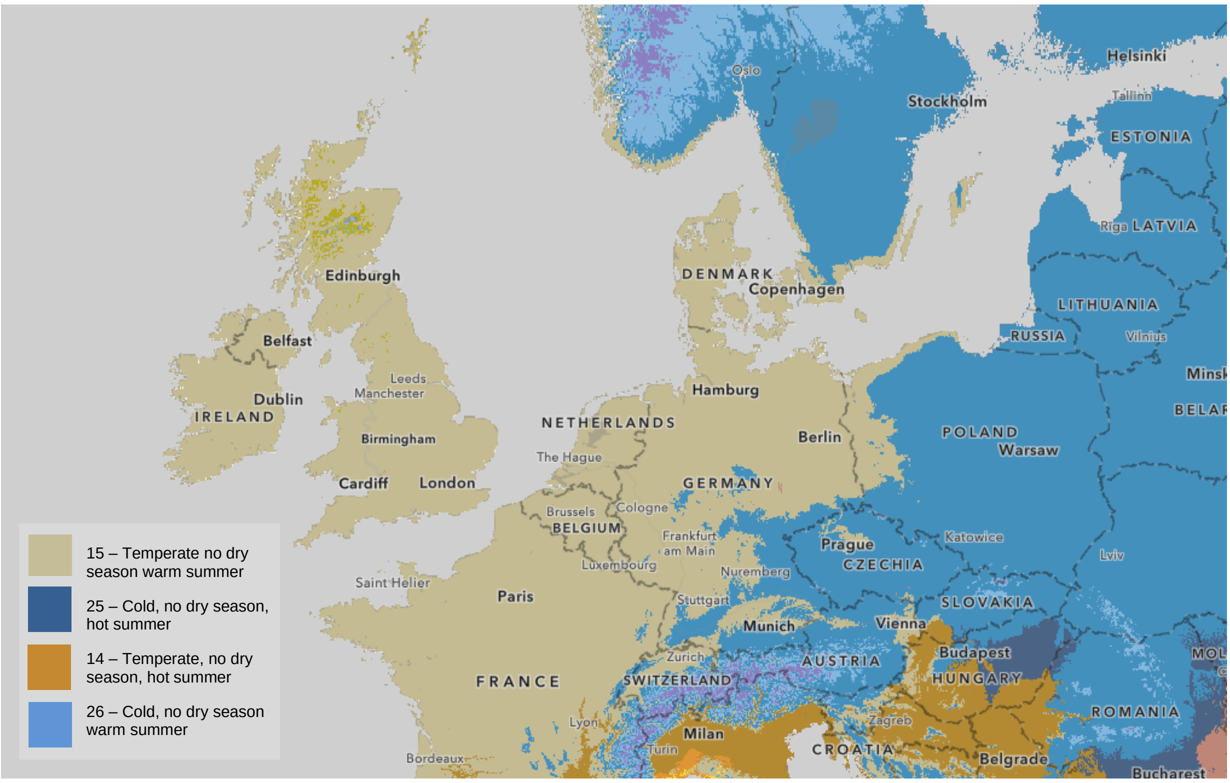

Figure 4: The Koppen-Geiger Climate Class map showing much of the landmass in western Europe with the UK climate class of 15. Map taken from the National Geographic Mapmaker based on the constrained CMIP6 projections by Beck et al., 2023 (15)

Paludiculture is still in its infancy (19) and therefore not all of the measurements included in this review were from a paludiculture system. Likewise, equipment and time constraints mean it is rare to have a full assessment of all the fluxes associated with each crop. Instead, only one or two fluxes are usually reported.

2.1.2 Overview of the data gathered

The final dataset comprised 99 data points from across 42 studies. Just over a third of these results were from a paludiculture system. All fluxes were measured on peatlands with a depth of 40 cm or more (excluding mesocosms) so there were no measurements from wasted peat sites. The most reported crop was *Phalaris arundinacea* (reed canary grass) followed by *Sphagnum* (bog moss) and *Typha* (bulrush) species. However, there were many species on the live list for which there were no recorded emissions, particularly those associated with medicinal, herbal or flavouring end uses. The full dataset of reported emissions can be accessed through the separate database found alongside this report. Studies that were not taken from paludiculture sites were generally former peat extraction sites, drained croplands or drained grasslands which have since been restored or had the water levels raised. There were also a few mesocosm (controlled experimental system) publications included.

CH_4 was the most widely reported on GHG (Figure 5) followed by CO_2 and N_2O, the other pathways of carbon loss were less commonly reported with only one study including an estimate of particulate organic carbon loss.

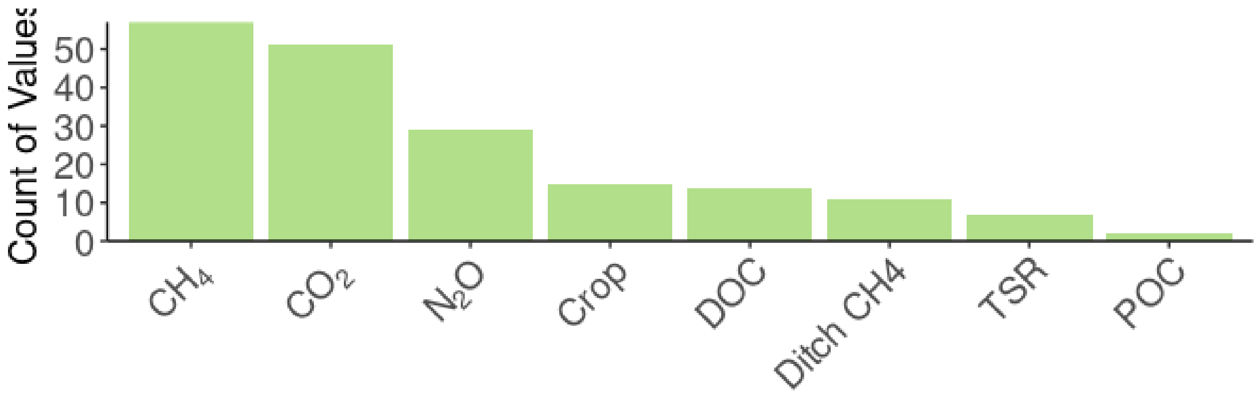

Figure 5: The number of data points within the compiled dataset across all crops for each of the fluxes of interest.

2.2 Data analysis

Once compiled, the dataset was quality assessed and studies were removed if the water table couldn't be managed or measured, if the duration of the study or reporting time covered less than 365 days (to account for seasonal variations in emissions) or from mesocosm studies where the set-up led to artificially extreme fluxes (Table 1). Data from woodland crops were also removed such as Lodgepole pine (*Pinus contorta*), Norway spruce (*Picea abies*) and Black alder (*Alnus glutinosa*) as the National Inventory follows a Tier 3 model-based approach for forestry species. Any data which has not been included in the analysis is highlighted within the dataset.

Table 1. Overview of the total number of data points within the final dataset which were removed from the analysis prior to the calculation of EFs.

Category	Total data points	Justification for removal
Mesocosm	3	Comprised hydrological conditions in mesocosm studies resulting in disproportionately high/low fluxes
Woodland	8	Likely to be reported in the UK emission inventory using a Tier 3 approach based on the CARBINE model
Duration	25	Study is too short to capture the full seasonal variation in emissions

An ordination approach (Principal Component analysis or PCA) was used to see if there were any natural groupings within the data that could be translated into a revised land cover hierarchy for peat within the LULUCF inventory. This method can uncover structures or dissimilarities within a dataset by simplifying lots of variables of interest into two main components. However, this technique didn't reveal any distinct groupings among the data points shown by the high degree of overlap (Figure 6). This was largely due to the small sample size, which reduced the power of this analysis and required many missing values to be filled in using estimates (a process known as 'imputation') which can lead to more uncertainty and overlap, obscuring clear patterns. The clustering of data indicated by dashed lines (whereby 95% of the data for each group is expected to be bounded by this) is predetermined. In figure 6 this is determined by species, but other groupings are included in the appendix (see Additional Figures section). Another ordination approach known as Canonical Variate Analysis was also trialled, but this was no more effective in revealing groupings in the data.

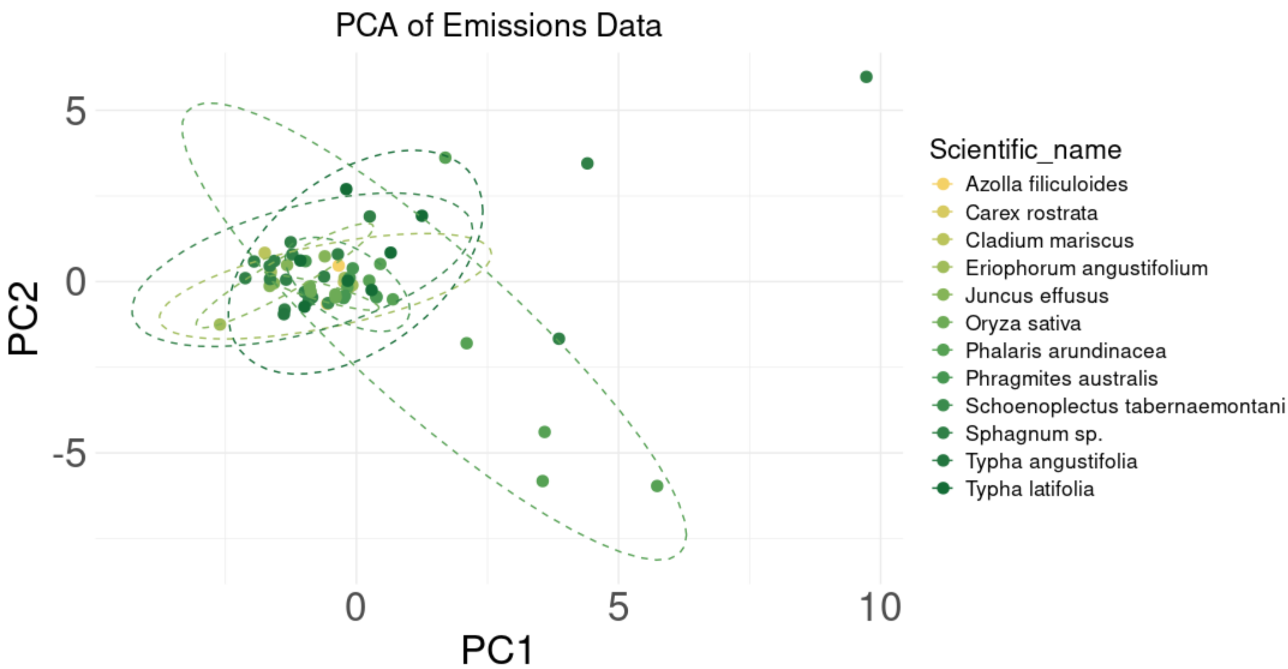

Figure 6: Principal component ordination plot illustrating the relative similarities of the measured fluxes (CO_2, CH_4, and N_2O) for each species in the study, the dashed lines indicate the 95% confidence intervals, and the high degree of overlap suggests there are no obvious clusters or groupings in the dataset. PC1 explains 36% of the variance and PC2 explains 18% of the variance in the dataset. The full set of PCAs can be seen in the Appendix.

If there was sufficient data to have multiple paludiculture emission factors these would likely be developed on a crop basis in the first instance. There is also potential to group emissions based on other factors such as the plant functional type (a group of plants with similar traits or functions) or the water level. Water level groupings based on the countryside stewardship options (i.e. 10-30cm and 31-50cm) could be a sensible future approach as this is a likely framework under which paludiculture may develop.

Several statistical tests were used to see if there were differences in the most common fluxes (CO_2, CH_4 and N_2O) between potential emission factor groupings. However, significant differences between groups couldn't be established, likely because the dataset was too small to facilitate this.

The dataset was then explored to see if there were underlying drivers of the main emission factors that could guide future efforts into the development of multiple emission factors. The full list of statistical methods and techniques used for differentiating groups and establishing relationships can be seen in the statistical approaches section of the appendix. While there were relationships with water table depth, as is widely known to be an overriding control on emissions from managed peatlands (9) (Figure 7) with a trend towards increasing CO_2 emission with water table depth, these were not significant, likely due to the small sample size.

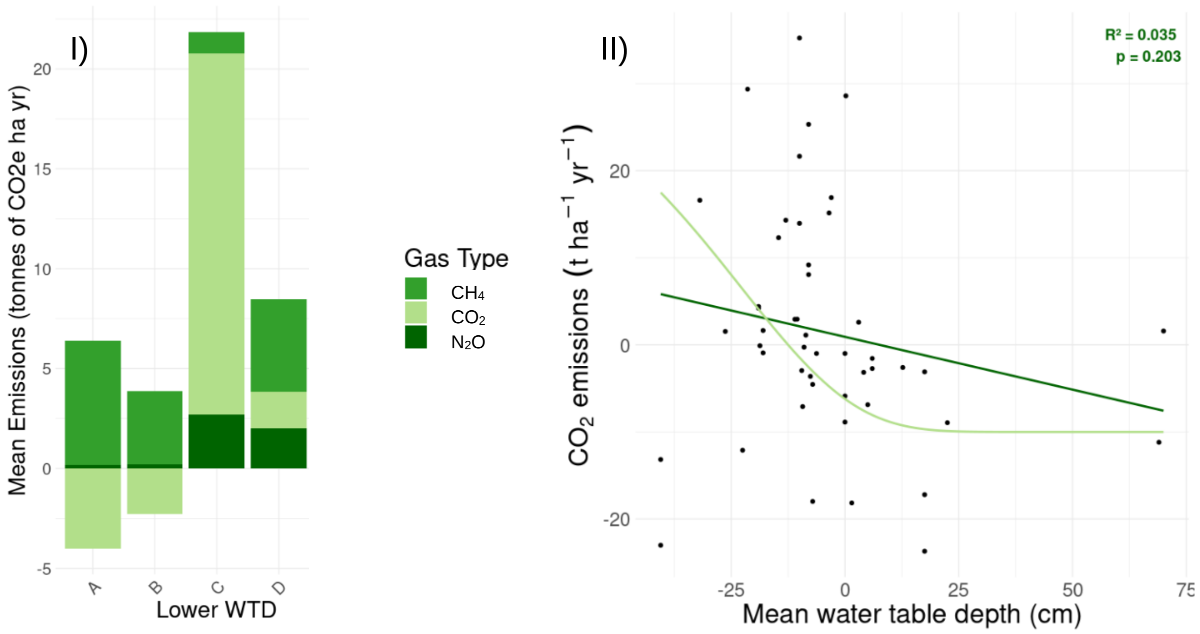

Figure 7: I) A stacked bar plot of mean fluxes (CO_2, CH_4 and N_2O) from paludiculture crops based on the lowest water table across groups based on countryside stewardship payments whereby A is above the surface, B is 0-10cm subsurface, C is 10-30cm, D is 30-50cm and E is <50 cm below the peat surface. II) A scatterplot of CO_2 emission against mean water table depth with the linear regression between the two variables (dark green) and the Gompertz function for water table depth proposed by (Evans et al., 2023)

Instead, when trying to model the variables that affect emission, the plant species was found the best predictor. While including the species improved estimates of CO_2 emissions there remained huge variation around this with estimates varying by around 11 t CO_2 e ha^{-1} yr^{-1} from the actual values. Despite this, *Typha sp.* and *Cladium mariscus* came out as particularly good sinks of CO_2 (NEE) in a wetland system. Effective models couldn't be developed for CH_4 or N_2O. This in part may be due to the data set being small and the complexity of the processes affecting these peatland fluxes (20), (21).

Before filtering the data, the application of fertiliser seemed to significantly increase N_2O emission, while this pattern is still visible, it is no longer significant after filtering (Figure 8). This relationship may become clearer as more studies on paludiculture emissions are carried out.

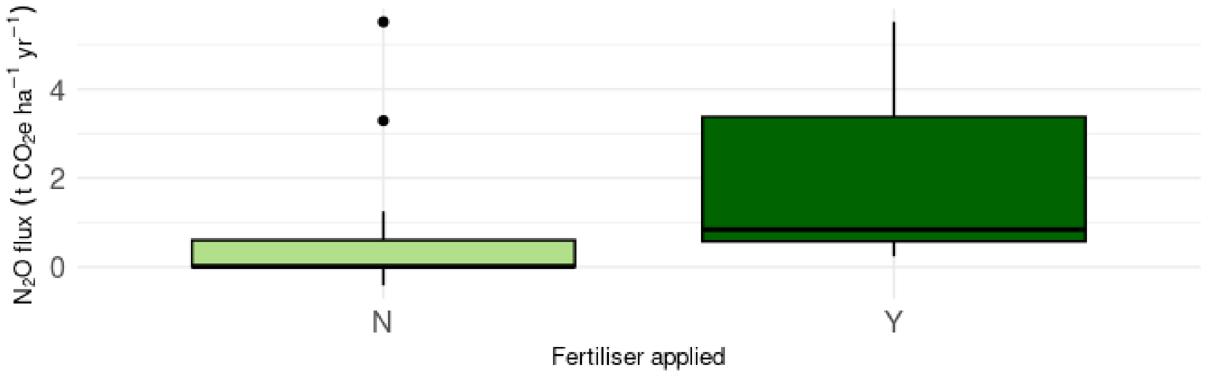

Figure 8: A box plot of the N_2O emissions associated with fertiliser application (Y) or absence (N), while fertiliser application does seem to increase the N_2O flux, this is not significant.

The other pathways of carbon loss, POC, DOC, Ditch CH_4, TSR and Crop removal were rarely included in the studies that made up this dataset and therefore the information wasn't available to try grouping these or generate emission factors and the default IPCC Tier 1 emission factors have been used.

2.3 Developing a paludiculture emission factor

Based on the information currently available it was not possible to develop multiple paludiculture emission factors for each crop or even coarser groupings such as water table because there were not significant differences between these. Therefore, a single 'best estimate' emission factor has been determined using the mean values across all of the studies for each of the main fluxes (Table 2).

However, there is added complexity when calculating an EF on crop system as the carbon removed in crop harvest must also be accounted for. The Direct CO_2 EF involves 3 fluxes or movements of CO_2. The first, Gross Primary Productivity (GPP) is the uptake of CO_2 by the plants and photosynthesising organisms within the peat, using light to convert the carbon in CO_2 to organic matter. The second, Ecosystem Respiration (R_{ECO}) is the opposite of this where organic matter is broken down by plants and microorganisms in the peat and released back into the atmosphere as CO_2. The balance between these two fluxes is known as the Net Ecosystem Exchange (NEE) with positive numbers generally indicating there is more CO_2 entering the atmosphere than being taken up while negative numbers mean the peatland is storing more carbon than it is releasing. The third flux is the carbon stored within the plant material which, when harvested, is also considered a loss (crop export).

In total, only 14 studies in the dataset reported on all three of the CO_2 fluxes. Therefore, to calculate the Direct CO_2 emissions only these 14 have been used. The CO_2 balance was calculated for each study and then the overall mean and 95% confidence interval was calculated and reported as the CO_2 (including harvest) emission factor (Table 2). The set of 14 is too small to separate out significant differences in emissions based on paludiculture crop type or other factors so a single value is reported. This also neglects many studies where crop harvest was not included. Therefore, another measure of CO_2 (CO_2 excluding harvest) has also been reported based on the balance between GPP and R_{ECO} for each study (NEE). This number may be used preferentially as a baseline in paludiculture systems which carbon export through crop harvest is known and can be added to this figure.

Table 2. Estimated direct emission factors and NEE calculated as the mean of the fluxes from the database of paludiculture crops in t CO_2 e ha^{-1} yr^{-1} based on IPCC AR5 100-year global warming potentials. In brackets are the 95% confidence intervals associated with these estimates.

CO_2 including harvest	CO_2 excluding harvest (NEE)	CH_4	N_2O
18.82 (8.04)	1.43 (5.73)	3.40 (2.07)	0.93 (1.15)

To see if there was a benefit to using a new paludiculture emission factor, these emission factor estimates were compared to the existing lowland peat categories within the LULUCF inventory. This revealed that when the harvest value was included, Direct CO_2 was most similar to intensive or extensive grassland while is crop harvest is not considered this is most similar to the rewetted fen category (Figure 9). CH_4 is most similar to a rewetted fen, while N_2O was most similar to extensive grassland on peat. As the volume of data on emissions in paludiculture grows there may need to be distinctions between fen and bog peat systems. However, at this stage the data is not available to make this separation.

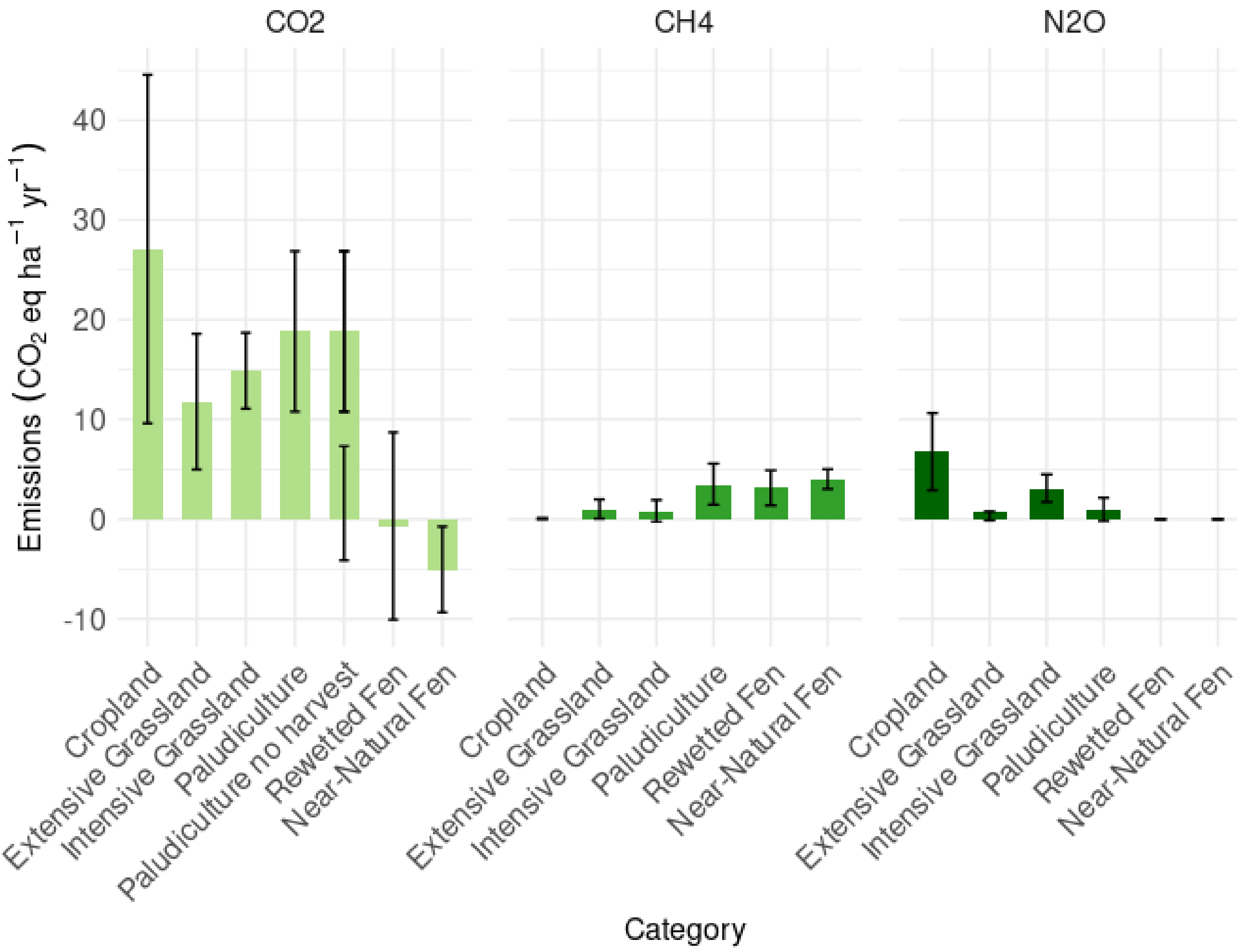

Figure 9: Mean emissions in CO_2e ha^{-1} yr^{-1} for each of the main condition categories associated with peatlands. The black error bars indicate the upper and lower 95% confidence intervals. These are based on the direct Tier 2 emission factors from the LULUCF inventory with the mean and confidence intervals for the data synthesised in this study included in the Paludiculture bar.

For consistency, the same approach, calculating the mean for direct CO_2, can also be used to estimate direct CH_4 and N_2O for paludiculture, calculating the mean across the dataset. However, there is too little data for this to be appropriate for the other fluxes (Ditch CH_4, DOC and POC). In this case, it may be most appropriate to use the existing values for rewetted fen due to the potential similarity in species present and the non-significant differences between rewetted fen and the other calculated fluxes. For CH_4 emissions from ditches, the higher Tier 1 emission factor of 1.63 has been chosen, as there is not yet evidence to suggest there are emission reductions in ditch CH_4 after conversion from traditional crop to paludiculture systems (Table 3).

Table 3. Emission factors for peat condition categories in t CO_2e ha^{-1} yr^{-1} based on IPCC AR5 100-year global warming potentials. Emission factors from IPCC Tier 1 defaults are italicised. It is important to note that for paludiculture this includes two values one for when the crop biomass export has been included (Paludiculture) and one where the loss of carbon through harvest has not been accounted for (Paludiculture no harvest). The final crop yield should be added onto this value as carbon loss from the system.

Peat condition	Direct CO_2	Direct CH_4	Direct N_2O	CO_2 from DOC	CO_2 from POC	CH_4 from ditches	Total (± SE)
Cropland (peat > 40 cm)	27.06	0.05	6.78	*1.14*	*0.51*	*1.63*	37.17 (±8.18)
Intensive grassland	14.87	0.77	3.08	*1.14*	*0.51*	*1.63*	22.00 (±2.08)
Extensive grassland	11.78	0.96	0.76	*1.14*	*0.51*	*0.74*	15.88 (±3.38)
Paludiculture	**18.82**	**3.40**	**0.93**	***0.88***	***0***	***1.63***	**25.66 (±4.19)**
Paludiculture no harvest	**1.43**	**3.40**	**0.93**	***0.88***	***0***	***1.63***	**8.27 (±3.10)**
Rewetted fen	-0.69	3.12	0	*0.88*	*0*	*0*	3.31 (±4.61)
Near natural fen	-5.06	4.01	0	*0.69*	*0*	*0*	-0.36 (±1.98)

It is important to note that these emission factors do not account for carbon lost in other pathways such as topsoil removal, and for the ‘Paludiculture no harvest’ category, crop removal has not been included. As paludiculture is based on the profitable production of wetland crops, carbon will inevitably be exported from the system during harvest. As a starting point the Paludiculture EF can be used, but this is likely to vary depending on the crop, harvesting interval and paludiculture system. Hence the Paludiculture no harvest category has also been included as a start point for which on farm values for crop harvest can be added to.

Given these numbers, Paludiculture could offer emissions savings of 11.5 t CO_2 e ha^{-1} yr^{-1} compared to conventional cropland on peat. However, this number could vary greatly based on how much of the crop is harvested and the end use of the Paludiculture crop. While carbon lost from crop harvest should be considered as a loss from the system, if the crop is converted into a product with a long lifespan there is the potential to reduce this emission. Using *Typha* as an example, for every 5 tonnes of dry matter harvested, 2 tonnes could effectively be stored if processed into insulation panels (22).

Topsoil removal can also lead to huge emissions of CO_2 as the carbon within the topsoil decomposes. The depth to which the topsoil is removed and the density of the organic matter within the topsoil will greatly influence the total carbon lost. Huth *et al.,* 2022 (26) reported 1426 t CO_2 e ha^{-1} lost for 60 cm depth of topsoil removal before *Sphagnum* paludiculture while Van Den Berg *et al.,* 2024 (27) found 557 t CO_2 e ha^{-1} loss with 20 cm depth removal for *Typha* paludiculture. If topsoil is removed as part of a paludiculture project, this should be accounted for in the total emission factor (see section 3.2 Topsoil Removal).

When considering a final GWP of paludiculture, the estimated value of 25.66 t CO_2 e ha^{-1} should be used as a start point. However, if there is suitable understanding of the carbon lost through crop removal during harvest, this exported emission could be added to the baseline of 8.27 t CO_2 e ha^{-1} to get a site-specific EF. It is noted in this report that these values are high for a paludiculture system, particularly when looking at life cycle emissions estimates from other countries and it is expected that over time, as the data and paludiculture techniques improve, these emissions estimates will decrease (31).

If the preference is to raise the water level on a lowland peat site but continue to grow conventional crops (farming on rewetted peat), the UK Peatland Carbon Calculator should be used with the effective water table depth and any land-use change.

3. Approaches within paludiculture which influence emissions

3.1 Biomass

The crop that is grown, and the end use of the paludiculture product has huge potential to influence the carbon balance of a paludiculture system. For example, harvests of *Sphagnum* could be equivalent to 6.6 t CO_2 e ha^{-1} yr^{-1}, *Drosera* (sundew) could be closer to 3.8 t CO_2 e ha^{-1} yr^{-1} (11) while *Glyceria* has been found to range from 15.2 to 50.4 t CO_2 e ha^{-1} yr^{-1} if the whole plant is harvested (11,28,29). There is also a huge increase in the production of bioenergy crops such as *Miscanthus* in the UK (Figure 10), while not yet considered a paludiculture crop on the live list, this has estimated biomass harvest of 24.6 to 29.4 t CO_2 e ha^{-1} yr^{-1} (30).

The end use of the harvested crop is also important. If crops are used to produce energy, the stored carbon is re-emitted, however, if the crops are replacing fossil fuels this can reduce carbon emissions from energy production (31). However, as the net balance of emissions is still positive in paludiculture, growing crops to produce energy still has detrimental impacts on the non-renewable peat resource due to the net losses of carbon over time. Incorporating harvested biomass into building materials has the potential to contribute to mid to long-term carbon storage (22) while returning the biomass to the soil in unreactive forms such as biochar can contribute to long-term carbon storage (32).

Not all biomass will be exported from the system. As plants grow, they develop below surface structures which have the potential to store carbon as underground biomass if water levels are high enough. If leaf drop and litter doesn't decompose, this can also contribute to soil carbon. The total underground biomass associated with paludiculture crops is not well known and again varies from crop to crop, it could also be broken down and remineralised back to CO_2 rapidly. However, *Miscanthus* is thought to contribute almost 1 tonne of soil carbon per hectare each year while *Alnus* (alder) has been found to increase carbon in the top 10 cm of soil by 1.2 t ha^{-1} yr^{-1} (30,33). The contribution of these crops to increasing belowground biomass should also be considered as more information develops in the future. While for other crops such as *Vaccinium sp.* most of the plant material remains in the paludiculture system while only the carbon in the berries is exported as a loss. *Typha sp., Juncus sp., Cladium mariscus, Carex sp., Sphagnum sp., and Schoenoplectus sp.,* are all known to be peat forming plants so provided not all of the plant is removed and conditions are right, any remaining biomass from these plants could contribute to the long-term peat carbon store (11).

Figure 10: The flux of greenhouse gasses being measured by UKCEH in a Miscanthus trial (left). There are a huge number of potential end uses for paludiculture crops and while some products are in development lots more work is being done to understand the post-harvest processing required to make products like insulation boards (right).

3.2 Topsoil removal

Topsoil is regularly removed during the construction of paludiculture systems with the material often repurposed on site into causeways, to create bunds and block ditches or to construct separate planting cells. As sites developed for paludiculture are commonly on former crop or agricultural grasslands the topsoil often has a high nutrient content from a history of fertiliser addition. This can make it difficult to establish some of the low-nutrient paludiculture crops (26). However, if crops are selected carefully, they can be used to remediate the soil and reduce the nutrient content allowing other crops to establish (34).

Topsoil removal is purported to have certain benefits. This includes reduced methane emissions due to the removal of easily degradable carbon and reduced phosphorus and salinity of the soil supporting crop establishment (27,35,36). However, it is generally assumed all the carbon in removed topsoil is remineralised back into CO_2 and released into the atmosphere (27). This number may reduce in the future, with the Greater Manchester peat pilot finding less than 10% of topsoil being remineralised in the first year, particularly when used to build subsurface structures (76). If water tables are maintained at or 10 cm below the surface CH_4 emissions will be relatively low, regardless of if the topsoil is removed or maintained. If the topsoil is reused in the paludiculture system as causeways, these are major contributors to total GHG emissions with some studies reporting up to 39.1 tn CO_2 e ha^{-1} yr^{-1} (37). Future best practices from paludiculture studies suggest causeways should be limited as much as possible with no more than 15% total cover and minimal depth of topsoil removal. Topsoil removal should be avoided (37). Planning permission has so far not been required by paludiculture projects in the UK as there is generally not a change of land use and any topsoil is reused within the site. However dependent on the planning authority and the extent of operations planning consent may be required and therefore adherence to the best practice for soil management in construction guidance (77).

3.3 Water management throughout the year

Managing water at near-surface levels is essential for reducing the Global Warming Potential (GWP) of peatlands (9). However, landowners are limited in their capacity to do this due to existing infrastructure and policy designed to drain the peat. This is further hampered by limited water storage capacity and resulting low supply in the drier months and technical knowledge of paludiculture rewetting in its infancy in the UK (2). Farmers can decide to go down the route of machinery development, investing in automated, soft track or drone-based harvesting and planting systems. Or they can decide to increase the infrastructure and causeways associated with paludiculture or lower the water levels during harvest/planting time, allowing access to heavy machinery (38).

Dropping the water levels can increase weed burden and CO_2 emissions will also rise as the peat is exposed to the air; this can be higher if fertilisers are applied at the same time, with available nitrogen enabling more organic matter decomposition. These emissions associated with dropping the water table can reduce or even negate the GHG reduction potential of paludiculture. It can also be difficult to rewet these soils when reservoir supplies are scarce during the summer (Figure 11). Combined with the warmer temperatures stimulating microbial activity, this can lead to large losses in CO_2 during the summer. Therefore, lowering the water tables, particularly during the summer should be avoided (40). This in turn may influence crop choice dependent on the optimum harvest times and machinery available to harvest with.

Figure 11: Being able to manage and store water on site is essential for the success of a paludiculture system. The farm scale reservoir system (left) has been combined with floating solar panels to reduce farm energy demand from the grid and reduce evaporation. The field scale reservoir (right) has a solar pump to raise water levels in the Typha paludiculture system when required.

Ditches are commonplace across the lowland peat landscape and are often included in paludiculture sites, to maintain higher water levels. Ditches are generally a source of CO_2 and N_2O but a hotspot of CH_4 emission (41). Ditch emissions can increase if nutrients and easy-to-break down organic matter enter the ditches from surrounding peatlands or if temperatures increase. As ditches are sources of emissions, reducing their area in a paludiculture system may seem like the best way to reduce emissions. However, several studies have found it more effective to reduce causeway area, as this will reduce the easily degradable organic matter entering water courses from the degrading causeways. Similarly, an essential step for reducing GHGs from ditches is reducing the nutrient supply in the wider landscape. This will prevent excessive plant and algal growth and will also reduce the emissions associated with ditches by constraining the nutrients available for microbes converting organic matter to GHGs (41). This seems to have a greater impact on reducing emissions (37). While the evidence can be contradictory, deeper ditch water levels appear to result in lower CH_4 emissions, with more time for the CH_4 to be converted into CO_2 in the water column (methanotrophy). Deeper water is also generally cooler and therefore less methane production (methanogenesis) occurs as it is limited by temperature (41).

3.4 Fertiliser application

In current paludiculture systems, fertiliser is applied to increase yield and plant quality (22,42). While fertiliser application is not well associated with changes in CH_4 or CO_2 fluxes, N_2O application often peaks immediately after fertiliser application, especially if it coincides with a rainfall event or higher water tables (43,44). These peaks are generally short-lived, being less than 2 weeks in duration. Outside of this period, fluxes from N_2O are negligible (45,46). There is also increasing evidence that paludiculture crops compete with microorganisms for mineral nitrogen and in the case of *Phalaris arundinacea* could potentially reduce the N_2O flux by 70% (43). The increase in biomass associated with fertiliser addition may also increase the carbon sequestration potential of paludiculture crops. Therefore, if fertilisers are applied with consideration for the wetland system once the growth of plants has been observed, the current information suggests this won't negatively impact carbon balance.

However particular care with fertilisers in paludiculture needs to be taken regarding The Reduction and Prevention of Agricultural Diffuse Pollution (England) Regulations 2018. As part of these regulations land managers must not apply fertiliser to agricultural land if the soil is waterlogged. Likewise, the proximity of the site to wetlands and inland freshwaters must be taken into account during planning to ensure there is no significant risk from agricultural diffuse pollution (47). The use of foliar fertilisers could have reduced environmental impacts compared to soil-based fertilisers (78) and several UK paludiculture trials are developing these alongside overhead irrigation systems (79). Many paludiculture systems are already high-nutrient environments compared to their near-natural counterparts, understanding the condition of the peat can guide crop choice in favour of species that will benefit from these nutrients, after which, the more targeted application could be used if required. There may also the potential to use existing high nutrient water from the surrounding agricultural landscape to meet the needs of the paludiculture crop with the co benefit of improving downstream water quality (34).

While not a conventional fertiliser, biochar, a charcoal-like substance created when biomass is heated at high temperatures without oxygen, also offers the potential for emission reduction and further carbon sequestration in a paludiculture system (48). Biochar itself is high in carbon and resistant to decomposition, if made from crops grown in a paludiculture system, these become a long-term store of carbon and the biochar can also adsorb or remove additional CO_2 (49). Biochar can also have additional benefits through removing excess nutrients from water and soil, although the duration for which pollutants can be retained in biochar within waterlogged peat is unknown (80). Likewise, there remain questions on how biochar application may influence peatland biodiversity and function. Studies into the cost-effectiveness and suitability of biochar application are ongoing in the UK (50). The application of biochar looks to be an additional technique which could further reduce emissions from paludiculture systems. However, care should be given to the crop, an application on short-growing vegetation could limit photosynthesis and carbon uptake. There can also be concerns around the origin of biomass and whether it has come from regenerative sources. Likewise, biochar is considered low-risk waste so spreading has similar regulation to the other fertilisers discussed above (47) and is limited to 1 tonne per hectare per year (51). This may be too small to be effective in a carbon removal context and we also have a limited understanding of the behaviour of biochar in paludiculture and its effects on water quality.

3.5 Crop choice

The crop choice will directly influence carbon balances through the total biomass and end-use as discussed previously. Different paludiculture species also have unique mechanisms which can influence the movement of carbon in and out of a peatland and the resulting fluxes. Aerenchymatous species are those which contain tissues with large gas spaces to help them survive in wet conditions by enabling gas exchange to occur between roots and shoots. This also enables methane produced deeper in the anoxic peat layers to be transported out of the peatland (52). This plant-mediated transport is the main CH_4 emission pathway in wetlands (53), estimated in some cases to be over 90% (54). However, the gas exchange occurs both ways with oxygen being transported into the usually anoxic sediment which can increase CH_4 oxidation or the conversion of CH_4 into CO_2. In addition to aerenchyma *Typha* (Figure 12) and *Phragmites* also have a pressurised gas flow, which during high temperatures and low humidity can lead to very high fluxes of CH_4 from peat (53). This is particularly significant when compared to species such as *Cladium mariscus* or *Juncus sp*. which rely on diffusion rather than an having internal transport system for CH_4 (55,56). Conversely, *Sphagnum* species have methanotrophic (methane-consuming) bacteria in close association with them (57). So, the presence of Sphagnum as a crop or understorey layer e.g. in *Vaccinium* paludiculture can reduce methane emissions from the system. Similarly, pools and ditches with sphagnum cover have lower emissions than those without, encouraging their growth in ditches could therefore have a positive effect on emissions (58, 81).

Figure 12. Typha beds were developed as part of a paludiculture trial by Lancashire Wildlife Trust. Greenhouse gas emission measurements from the Typha plots and the surrounding causeways are being made at this site.

3.6 Phase of development

The stage of development or age of a paludiculture system is also important when considering the carbon balance. There is generally a decline in emissions over time as crops become established and the emissions associated with intervention and site preparation decline. This does vary between crops though with some slowing in their carbon uptake as they age (30), while others increase as they occupy a larger area (26).

Crop rotation should also be considered. Crops on a short rotation generally need more mechanical preparation due to the regular planting and harvest. This disturbs the peat, increasing the likelihood of carbon loss while longer-lived plants generally also contribute more to the belowground biomass as touched on previously. Crop rotations can vary too meaning the contribution of crop yield as a carbon export pathway can be very different depending on the year. For example, some species on the live list such as *Alnus glutinosa* operating on 20 to 40-year cycles while *Echinochloa sp.* are cultivated annually. This all has implications for the carbon exported as biomass and emissions associated with water-table management if machinery needs more access as well as the lifecycle emissions of the paludiculture site (11).

3.7 Additional lifecycle emissions

So far emissions have focussed directly on the paludiculture system however this neglects the emissions associated with the rest of the system. Lifecycle assessments are now being carried out for different systems and are finding lower emissions from paludiculture compared to ‘business as usual’ agriculture systems on peat by up to 35% (31,59). However, these will vary depending on the paludiculture system. Using infrastructure with lower fabrication emissions and minimising machinery running times can reduce construction emissions (59). Generally, all crops excluding *Sphagnum* may require fertilisation and there are emissions associated with the production of these (17). These can be reduced using controlled-release fertilisers, low-carbon alternatives and improving on-farm nitrogen use efficiency (60). There will also be further emissions associated with the harvest, material processing and transport. These will be unique to each end-use and better calculated on a case-by-case basis by pre-existing farm carbon calculators.

4. External factors which influence emissions

4.1 Time of year

Paludiculture emissions throughout the year will vary depending on some of the factors explored above, such as a fluctuating water table with winter flooding and summer droughts. High temperatures are also key for driving biological processes (61). When high temperatures coincide with a drop in the water table during summer, CO_2 production is stimulated. This occurs at the same time as high levels of plant respiration due to the large biomass at this time of year while easy to break down material from roots enters the soil. This results in large emissions of CO_2, from ecosystem respiration. These summer fluxes can dominate the annual total, with total respiration measured to be at least 50 times higher in the summer than winter. (27,62).

While CH_4 should be higher in winter due to the elevated water table, the colder temperatures often limit CH_4 production and emission (63). With rising global temperatures the strength of this methane suppression in winter will weaken (64). However, as water levels aim to be just below the surface in paludiculture these emissions will still be low.

N_2O fluxes are generally low throughout the year and are mainly affected by fertiliser input, however, the system can switch from a source to a sink during the growing season as plants compete with microorganisms for available nitrogen (43).

While the data from paludiculture systems is limited, based on other peatland systems DOC concentration is also driven by water table and temperature. Generally, the highest concentrations are in Autumn and the lowest in Spring. Warmer temperatures in the summer enhance microbial breakdown of the peat and the production of DOC locally, however, water level increases into the end of Summer and Autumn allow DOC to discharge from the peat and be exported from the system (65,66). Moreover, it is important to note that DOC concentrations are lower in better-condition peat so, over time, switching from conventional agriculture to paludiculture could reduce DOC concentrations (67).

The loss of particulate organic carbon from lowland peat is more episodic, occurring during erosion events. In lowland agricultural peat, ‘fen blows’ where the wind blows clouds of peat dust from fields is a big source of POC. This is particularly common during the spring when fields are freshly ploughed and bare. Ensuring continual cover of vegetation and keeping the soil wet in a paludiculture system is key to reducing this wind-driven peat loss (68).

4.3 Peat quality

The quality of organic matter in peatlands can strongly influence the amount of CO_2 and CH_4 released into the atmosphere. Peat varies in how labile (readily broken down) or recalcitrant (resistant to break down) it is. The recalcitrance of peat depends on a variety of things from the organic structures within the plants that make the peat to the latitude the peat is forming (69). Generally, though, the deeper down the peat profile the greater the recalcitrance (or lower organic matter quality) because the easy to decay labile parts have already been broken down and re-entered the atmosphere as CO_2 or CH_4. This means that some of the most degraded or wasted peatlands may have the lowest emissions if put into a paludiculture system because most of the carbon for respiration or methane production has already been lost (70).

5. Considerations and constraints

The paludiculture emission factors in this report are ‘best estimates’ based on the existing data. Therefore, they represent the start points in the process of generating a paludiculture emission factor. As more paludiculture systems are trialled and monitored in the UK including in LowlandPeat3 (71), the projects funded by the Paludiculture Exploration Fund (PEF) (50) and the Horizon projects on large-scale paludiculture demonstrations (72), the evidence base for paludiculture will grow. This will bring with it improved estimates of emissions. While many of the studies that went into this estimate were from paludiculture, for some crops, estimates were made based on their emissions in rewetted sites and not a cropping system. There are many more crops for which there are no reported measured emissions and others which may not have yet been considered for paludiculture. This dataset is, therefore, not representative of all paludiculture crops. There are also differences between crops for which unique emission factors can’t be calculated at this stage. However, the size, cropping rotation and ecology will ultimately lead to differences in emissions, for example, between biomass, forestry, sphagnum and grass paludiculture systems. Increasing innovation and demonstrators in this space will help to determine more appropriate emissions estimates and develop the agronomy and markets for these crops.

As the knowledge of these systems grows, the data on emission factors will expand allowing further refinements of emission factors to be made based on crop, cropping system or water table depth. More novel species such as rice being successfully trialled in the Netherlands could begin appearing in UK trials, offering a more diverse range of crops to landowners (73). There will also be increasing opportunities to trial different paludiculture setups, which along with advances in machinery could reduce the number of ditches or sizes of causeways. In turn, this will reduce the areas where there are ‘hot spots’ of higher emissions.

There remain large challenges to paludiculture. High and maintained water levels, essential for reducing emissions, are still difficult and costly to achieve. Plastic sheeting has been successfully used to segregate paludiculture trials from the wider landscape and to allow for more targeted water control. However, this is an expensive approach that reduces the effectiveness of paludiculture if it is to be used as a buffer zone in a mosaic between restored and agricultural peat. There have been further innovations in the construction of bunded cells, reservoirs and solar-powered pumps for water management, but this is again a smaller-scale and expensive approach. For large emissions savings to be realised paludiculture needs to be implemented across much larger areas and central to this is an understanding of how to effectively raise and control water levels (2).

Landscape-scale approaches will allow for better water management across the system and the costs are also more likely to go down on a per-area basis. A landscape view can more easily guide the mosaic approach that is increasingly being proposed in the Lowlands (6). An understanding of chemistry, ecology and water behaviour at a larger scale can guide which sites are most suitable for paludiculture and specific crops. By looking at the whole landscape, paludiculture can be in the best place that also supports raised water levels, continued food production and areas of restoration essential to meet the UK’s climate commitments (17).

Paludiculture, as a lower-emission land use, has potential in climate change mitigation, slowing peat loss, sequestering carbon and reducing emissions (21). However, with climate change warmer soils will release more greenhouse gases as organic matter is broken down more quickly (27). Changing rainfall patterns will make water storage and infrastructure increasingly vital to avoid drought and flooding (74). Different crops will become more or less suitable in different regions (75). Therefore, to develop paludiculture successfully in England the impacts of climate change, as well as the potential climate adaptation offered by paludiculture need to be considered.

6. Conclusions

This review found paludiculture to be a net source of emissions in the region of 25.66 t CO_2 e ha^{-1}. While this is still an emissions source, it still offers savings of over 10 t CO_2 e ha^{-1} compared to traditional croplands on drained agriculture lowland peat. This estimate is conservative with the extent of savings dependant on several factors such as the crop, paludiculture systems and management approach. The emissions found in this report represent a ‘best estimate’ of emissions with the information to date. With further development of paludiculture and monitoring of greenhouse gases, these estimates will improve and are likely to reduced. While paludiculture offers direct carbon benefits through a reduction in emissions, it will also likely reduce further emissions through indirect pathways, reducing subsidence and erosive loss. All while maintaining a profitable use of lowland peat and securing a just transition for farmers.

Appendices

Glossary

Anoxic	Deficient in oxygen, saturated peat is considered anoxic because the water prevents oxygen from getting in and allowing it to be broken down.
Biochar	A type of charcoal made by heating organic materials in a low or no-oxygen environment. It is rich in carbon and can be added to soil to improve its quality and locks away carbon for a long time. It is not made to be burnt for energy generation.
Biomass	The total mass of a living organism, often given as dry mass, excluding the water content.
Emission factor (EF)	The amount of greenhouse gases (GHGs) released per unit of peatland area due to specific activities or natural processes.
Enhanced rock weathering (ERW)	A process that accelerates the natural weathering processes by adding rock dust to soils which through chemical reactions capture and remove carbon dioxide from the atmosphere.
Flux	The rate at which gases like carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) move into or out of the peat.
Global Warming Potential	A measure used to compare the impact of different greenhouse gases on global warming over a specific time.
Greenhouse gas (GHG)	Greenhouse gases (GHGs) are gases in the Earth's atmosphere that trap heat and keep the planet warm. However, human activities have increased the amount of these gases, which contributes to global warming and climate change. The key ones mentioned in this report are carbon dioxide (CO_2), methane (CH_4) and Nitrous oxide (N_2O)
Labile	Something that can be easily broken down, in this case, organic material.
Mesocosm	An experimental system that simulates natural environmental conditions on a smaller, controlled scale.
Methanogenesis	The microbial process by which methane (CH_4) is produced in waterlogged, anaerobic conditions in peatlands, as microbes decompose organic matter without oxygen.
Methanotrophy	The process by which bacteria break down methane, using it as their energy source.
Organic matter	Material that comes from living things that contains carbon.
Paludiculture	The practice of farming on rewetted peat, to grow profitable crops adapted to a wetland environment. There is no specific water table requirement for paludiculture

	however paludiculture crops generally require a water table close to the surface to grow successfully. It is anticipated that Paludiculture in the UK will be eligible for countryside stewardship options with a minimum mean water level of 30 cm below the surface.
Photosynthesis	The process by which plants, algae, and some bacteria convert sunlight, carbon dioxide (CO_2), and water into glucose (a form of sugar) and oxygen, using energy from sunlight to fuel the reaction.
Recalcitrant	Something resistant to decomposition or breakdown.
Respiration	The process by which microorganisms and plants in peatlands break down organic matter, releasing carbon dioxide (CO_2)
Subsidence	The gradual sinking or lowering of the ground surface as peat soils lose volume. This is mainly due to decomposition and compaction.
Tier 1	Default or general values used in greenhouse gas (GHG) inventories to estimate emissions. These values are typically based on global averages or simplified assumptions.
Tier 2	More detailed and region-specific estimates which are used to calculate greenhouse gas (GHG) emissions. Tier 2 factors are tailored to specific countries or regions often calculated from direct measurements.
Topsoil	The uppermost layer of soil that is generally rich in nutrients, organic matter, and microorganisms.
Wasted peat	Wasted peat is degraded peatland that has become shallow, usually due to drainage and cultivation. In England, peat is considered wasted when thinner than 40 cm.

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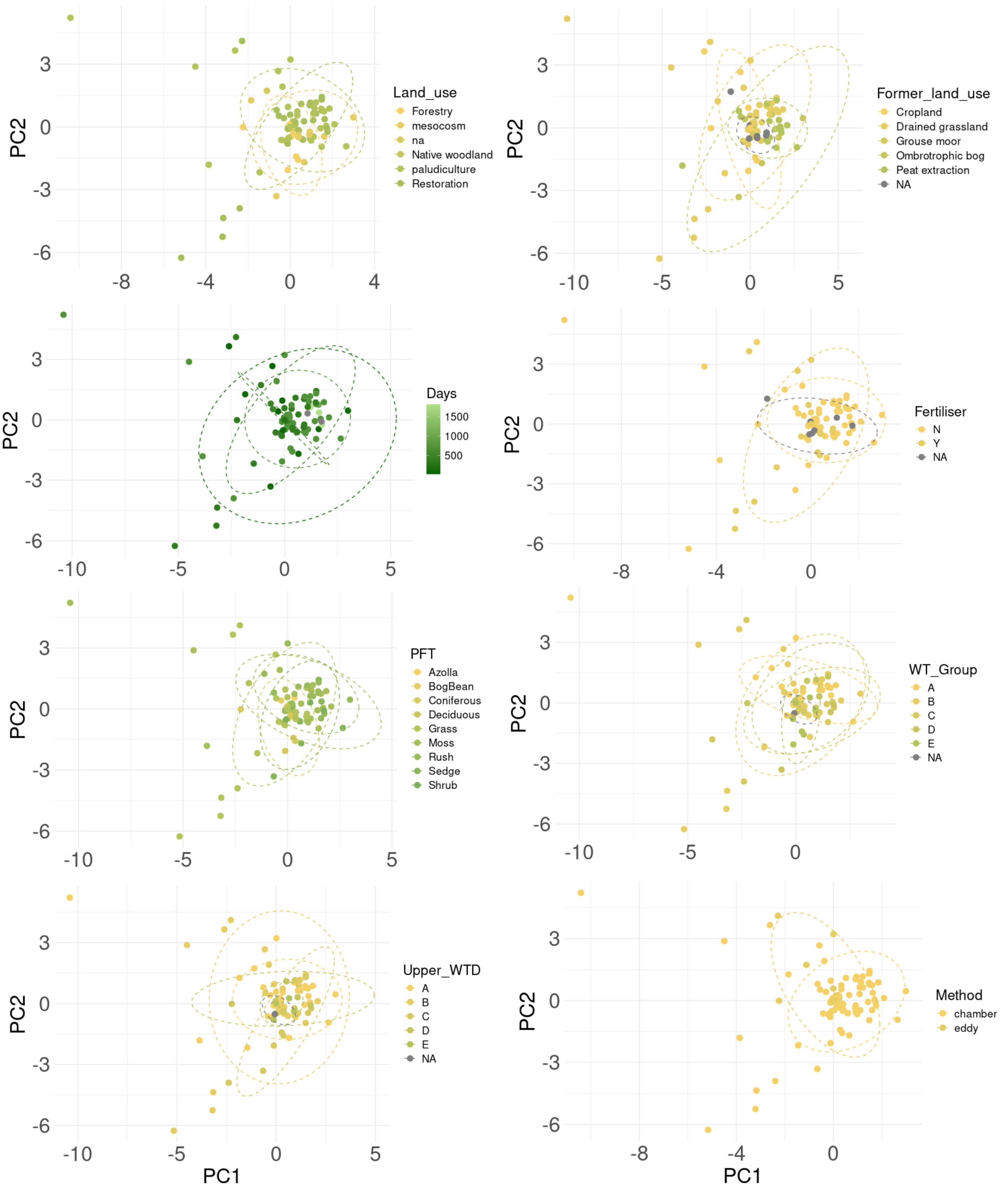
Supplementary Material

Additional figures

Results of the principal component analysis based on different categories within the collected data including former and current land use, duration of experiment, method of data collection, water table (grouped based on Countryside Stewardship options), plant functional types and method of collection.



Results of the Principal Component Analysis used to look for natural groupings in the fluxes from the data, the 95% confidence intervals for groupings based on each variable of interest are largely overlapping suggesting there are no clear clusterings within the dataset which could be used when developing multiple emission factors

Statistical approaches

All analysis was carried out in R 4.4.1 *(R Core Team (2024). R: A Language and Environment for Statistical Computing_. R Foundation for Statistical Computing, Vienna, Austria. <https://www.R-project.org/>.)*

Missing values were imputed prior to PCA. NA's were left in the dataset for the other tests. Welch's ANOVA was used to test for significant differences based on groups due to the assumptions of unequal variance. Games Howell post-hoc tests were then used to establish if there were significant differences in fluxes within these groups.

Multiple regressions were used to look for relationships between environmental parameters and fluxes. When developing models, they were regularly checked for multicollinearity using the variance inflation factor, homogeneity and normality of residuals and good model fits.

Significant differences between the paludiculture emission factors and Tier 2 emission factors were assessed using a standard t test the results of which can be viewed in the table below.

Table: *Results of the t-test carried out between the paludiculture emission factors and the Tier 2 factors within the UK's Emission Inventory. The Tier 2 emission factor for each of the emission categories is included alongside the P-value and T-test statistic. Where there is a significant difference between the Tier 2 emission factor and the paludiculture emission factor these are highlighted in pink.*

Category	Tier 2 value CO2	P value CO2 crop removed	T statistic CO2 no crop removal	P value CO2 no crop removal	T statistic CO2 no crop removal	Tier 2 value CH4	P value CH4	T statistic CH4	Tier 2 value N2O	P value N2O	T statistic N2O
Cropland	27.06	0.045	-2.22	0.000	-16.33	44.54	0.000	-19.95	9.58	0.000	-6.68
Intensive Grassland	14.87	0.308	1.06	0.000	-8.61	18.68	0.000	-6.23	11.07	0.000	-7.38
Extensive Grassland	11.78	0.081	1.89	0.000	-6.66	18.58	0.000	-6.17	4.98	0.000	-4.50
Rewetted Fen	-0.69	0.000	5.24	0.219	1.24	8.69	0.358	-0.93	-10.07	0.012	2.60
Near-Natural Fen	-5.06	0.000	6.41	0.000	3.92	-0.77	0.000	4.06	-9.35	0.025	2.32