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PRODUCTION SOLUTIONS
FOR REWETTED PEATLANDS

PEATLAND ECOSYSTEMS

D3.1 Evaluation report of existing peatland emission estimation tools

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Table of Contents

Abbreviations

CC-SET	Carbon Connects – Site Emissions Tool
CER	Carbon emission reduction
CH_4	Methane
C_{IN}	Carbon import
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CO_{2_AV}	Avoided carbon dioxide emissions
C_{OUT}	Carbon export
DOC	Dissolved organic carbon
DM	Dry matter
EF / EFs	Emission factor(s)
FCT-CC	Farm Carbon Toolkit – Carbon Calculator
GEST	Greenhouse Gas Emission Site Types
GHG / GHGs	Greenhouse gas(es)
GMC-K	Greifswald Moor Centre – Klimaschutzrechner
GMC-KM1	Greifswald Moor Centre Klimaschutzrechner – Method 1
GMC-KM2	Greifswald Moor Centre Klimaschutzrechner – Method 2
GPP	Gross primary productivity
GWP / GWPs	Global warming potential(s)
ha	Hectare
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
KM1 / KM2	Calculation method 1 / method 2 (GMC-K)

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LCA	Life cycle assessment
N_2O	Nitrous oxide
N/a	Not applicable
NECB	Net ecosystem carbon balance
NEE	Net ecosystem exchange
NEP	Net ecosystem production
PC-BOG	IUCN Peatland Code – Bogs emissions calculator
PC-FEN	IUCN Peatland Code – Fens emissions calculator
POC	Particulate organic carbon
SOC	Soil organic carbon
SOM	Soil organic matter
t	Metric tonne
TER	Total ecosystem respiration
Tier 1 / Tier 2	IPCC greenhouse gas reporting tiers
UKCEH	UK Centre for Ecology & Hydrology
VCS	Verified Carbon Standard
WC-CHC	Wilder Carbon – Carbon + Habitat Calculator
WTD	Water table depth
WTDe	Effective water table depth
yr^{-1}	Per year

1 Introduction

Paludiculture has growing interest as a land-use option capable of reducing greenhouse gas (GHG) emissions while maintaining agricultural or biomass-based livelihoods. As interest in paludiculture increases, there is a growing need for robust estimates of the climate impacts of transitioning from drainage-based peatland agriculture to wet-managed production systems. These estimates then need to be available to and usable by policymakers and land managers across a range of scales. Emissions estimation tools represent an important pathway through which information from the scientific evidence base can be used to support land-management planning and decision making.

The aim of this review is therefore to assess the extent to which the currently available peatland emissions estimation tools can be used to estimate both the climate impacts of paludiculture systems and the net climate impacts of land-use change to paludiculture. This includes evaluating whether and where proxy representations (e.g. re-wetted peatlands) are likely to be adequate for screening-level assessment and highlighting key limitations that may constrain their use for paludiculture-specific accounting.

The scope of this review is limited to the evaluation of emissions estimation tools and their usability for assessing the GHG balance of paludiculture systems. Specifically, a comparative assessment of the range of existing emissions estimation methodologies in general is beyond the scope of this review. Differences between underlying methods are discussed only insofar as they influence tool behaviour, transparency, and suitability for paludiculture-related applications.

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2 Peatland emissions estimation tools

2.1 Tool identification approach

We identified six peatland emissions estimation tools (Table 2.1.1). These tools were identified through a combination of web searches and consultation with project partners. Project partners were engaged for input through an online workshop to which all partners were invited. This was supplemented by email communications to allow an opportunity for inputs from those who could not attend the workshop. Only free and publicly available tools were included in this review. There is no evidence to suggest that paywalled, proprietary tools include notably different methods for organic soil emission estimation, as several free tools have been developed by research groups active in this field and include the results of recent research developments.

Table 2.1.1 – Peatland emissions estimation tools identified.

ID	Owner	Name
CC-SET	Carbon Connects	Site Emissions Tool
GMC-K	Greifswald Moor Centre	Klimaschutzrechner
PC-FEN	IUCN Peatland Code	Emissions Calculator (Fens)
PC-BOG	IUCN Peatland Code	Emissions & Carbon Cost Calculator (Bogs)
WC-CHC	Wilder Carbon	Carbon + Habitat Calculator
FCT-CC	Foundation for Common Land	Carbon Calculator

2.2 Tool summaries

2.2.1 Carbon Connects – Site Emissions Tool

This tool was created by Jasper van Belle and Emiel Elferink as part of the Carbon Connects project and can be accessed through the Carbon Connects website (accessed 27/11/25). The project website states that the aim of the Carbon Connects project was, "to reduce the high carbon footprint of peatland soils in Northwest Europe by introducing new bio-based business models developed for sustainable land management practices". Specifically, Carbon Connects aimed to promote alternative practices for wet land management by raising peatland water levels to reduce carbon emissions. Peatland restoration and paludiculture were clear focuses areas for the project. The introductory information within the Site Emissions Tool states that its purpose was, "to support decision making in the context of land management and environmentally sustainable business development in peatlands". It's intended users are described as farmers, public authorities and other stakeholders interested in estimating GHG emissions from managed wetlands. This tool is presented as a Microsoft Excel workbook. Whilst most sheets are hidden, they are not locked, and formulae within cells are also generally visible. Therefore, the mechanics of the tool could be examined in detail.

Organic soil emissions are predominately calculated using the GEST approach (Couwenberg et al., 2011) in this tool (CO_2 and CH_4 only), which has been approved by the Verified Carbon Standard (VCS) for use on temperate peatlands (Emmer & Couwenberg, 2017). In this tool users are asked to specify a vegetation class and a median summer groundwater level (between 1st April and 30th September), for both baseline and re-wetted conditions. The

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groundwater level is used to allocate a soil moisture class, and this along with the vegetation class is used to assign specific CO_2 and CH_4 EFs to the site. Examination of the tool's mechanics appears to suggest that vegetation class is used to assign pre-defined GHG EFs, whilst the soil moisture class is used to define which vegetation classes are permissible. For example, median summer groundwater levels of +30 cm and -10 cm (above and below the surface respectively[1]), result in soil moisture classes of 6+ (Flooded) and 5+ (Wet). Both permit allocation to the vegetation class 'U17: Very wet tall sedges and Typha', and in both cases the tool predicts identical CO_2 fluxes of -1.1 t CO_2 $ha^{-1}yr^{-1}$ and CH_4 fluxes of 6.8 t CO_2e ha^{-1} yr^{-1}. However, a median summer groundwater level of -50 cm results in a soil moisture class of 2+ (Moderate moist) and allocation to 'U17: Very wet tall sedges and Typha' is no longer permitted. The tool has a wide range of vegetation classes including paludiculture species, and a specific vegetation class for paludiculture ('S5: Simulated harvest (Paludiculture)'), which is applicable under soil moisture class 4+ (Semi Wet; -10 cm > median summer groundwater level ≥ -20 cm). The tool also allows users to specify the crop type and yield, and where the crop produced in the re-wetting scenario substitutes fossil-based products and has a lifetime greater than ten years, the carbon content of the crop is treated as a CO_2 emissions reduction resulting from avoided emissions due to fossil resource depletion (CO_{2_AV}).

This tool assigns a value of 8 kg N_2O ha^{-1} yr^{-1} for direct terrestrial nitrous oxide emissions derived from SOM mineralisation in organic soils, regardless of vegetation class or groundwater level, under both baseline and re-wetted scenarios. This value is cited as the Tier 1 $EF_{2\ CG,\ Temp}$ value for temperate croplands and grasslands on organic soils from Chapter 11 of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). However, it should be noted that whilst the tool cites the value from IPCC (2006) in the same units (8 kg N_2O-N ha^{-1} yr^{-1}), the calculations appear to use the same value with a different unit (8 kg N_2O ha^{-1} yr^{-1}). This tool does not include indirect CO_2 emissions from dissolved and particulate organic carbon (DOC and POC), or CH_4 emissions from ditches. Whilst beyond the scope of this review, this tool also includes options to account for changes in additional agricultural emissions sources including those from fertiliser application, grazing animals, crop residues, and fuel/energy consumption.

2.2.2 Moorwissen – Klimaschutzrechner

This tool was created by the Greifswald Moor Centrum and can be accessed through their Moorwissen website (accessed 01/12/25). The information associated with the Klimaschutzrechner (Climate protection calculator) is provided in German. Our analysis is based on translation implemented using the inbuilt translation tool of the Microsoft Edge web browser. The tool is described as being for the estimation of greenhouse gas emissions, subsidence and climate costs associated with drained peatland sites. The tool does not explicitly account for paludiculture but estimates emissions reductions associated with re-wetting which may act as a proxy. The tool also describes its output as a simplified estimate, signposting users to the GEST approach for more precise site-specific considerations. As this is an online tool, it's internal functions cannot be entirely inferred from its input requirements,

[1] Note that groundwater level becomes increasingly negative with depth below the ground surface, whilst water table depth becomes increasingly positive with depth below the ground surface. Different tools analysed here use different measures to describe drainage conditions. Therefore, when discussing any given tool, we use the measure and sign convention specified for that tool to ensure that inputs are discussed in the same format as used by the relevant tool.

outputs, and the online guidance materials. Therefore, we do not have full visibility for this review.

The tool simultaneously implements two methods to provide separate estimates of organic soil emissions. The first method is based on drainage depth, and is based upon Couwenberg et al. (2011) and an additional unpublished meta-study. The exact functions used to model relationships between GHG fluxes and drainage depth, and the GHG fluxes estimated are not made visible in disaggregated form. Broadly, the relationships describe an increase in GHG emissions from 15 t CO_2e ha^{-1} yr^{-1} to 45 t CO_2e ha^{-1} yr^{-1}, in response to an increase in the magnitude of what we assume to be the mean annual groundwater level (Couwenberg et al., 2011) from -30 cm to -90 cm below the ground surface. At WTDs >-90 cm, emissions do not increase further. The relative savings potential values, indicate that a value of ~12.5 t CO_2e ha^{-1} yr^{-1} is used for re-wetted peatlands.

The second method is described as estimating emissions based on climate zone, form of use and intensity, and is based on Wilson et al. (2016). This method applies appropriate Tier 1 EFs for drained peatlands from IPCC (2014; CO_2, field and ditch CH_4, N_2O and DOC). It also estimates a GHG emissions savings potential associated with raising peatland water tables based on the difference between the aforementioned drained land use EF and the appropriate EF for re-wetted peatlands in the same climate taken from Wilson et al. (2016). The use of Tier 1 EFs means that the tool should have broad applicability under this second method. Whilst beyond the scope of this review, this tool also allows simplistic assessment of the financial effects of rewetting based on approximate carbon prices, and an estimate of the subsidence rate.

2.2.3 IUCN Peatland Code – Emissions Calculator (Fens)

This tool was created by UKCEH staff as part of a project to align the IUCN Peatland Code with the UK Peatland GHG Inventory (Evans et al., 2022), and can be accessed through the IUCN Peatland Code website (v2.1; Last accessed 27/11/25). The IUCN operates the Peatland Code with the intention that it is, “the quality assurance standard for peatland restoration projects in the UK and generates independently verified carbon units” (IUCN, 2024a). The focus of the Peatland Code has primarily been on peatland restoration to date. Implicitly paludiculture would appear to be encouraged where this was associated with peatland re-wetting and a reduction in GHG emissions. However, paludiculture is not explicitly mentioned in either the Peatland Code itself or in the associated guidance (IUCN, 2024a, 2024b). The launch of a dedicated call for paludiculture evidence in 2024 (IUCN, 2024c) indicates an intention to explore paludiculture’s explicit inclusion within the Peatland Code. However, the current absence of explicit inclusion suggests that the existing evidence base may have been deemed insufficient to underpin robust, auditable carbon outcomes.

The introductory information within the Fen calculator tool states that its purpose is, “to help estimate how land-use change may affect greenhouse gas (GHG) emissions from Fen peatlands”. Its intended users include anyone interested in or needing to evaluate the potential GHG benefits of peatland restoration, and the effects of other peatland land-use changes. Specifically, it was intended for use by individuals or organisations engaging with the Peatland Code. As the tool was developed by UKCEH staff we had full information available about its development for this review.

As described in Evans et al. (2022), the tool uses a combination of water table depth (WTD) regressions from Evans et al. (2021; for CO_2 and CH_4 with some modifications) and EFs based on land-use classes (for N_2O) to estimate organic soil emissions. Users are asked to provide the average peat depth and average annual WTD (under both baseline and intervention scenarios) for the site, which allows estimation of the effective WTD (WTDe; the lesser of these values), as this is used for estimation of the site CO_2 balance (Evans et al., 2021). The land-use class for both baseline and intervention scenarios is also requested as this is used to (i) define the permissible range of annual average WTDs that may be specified; (ii) assign the appropriate modifier during the CH_4 emissions calculation; (iii) assign the appropriate N_2O EF. The tool allows users to select any fen appropriate land-use classes from Evans et al. (2022). The tool uses a combination of UK-specific Tier 2 EFs (Evans et al., 2022) and IPCC default Tier 1 EF values (IPCC, 2014) depending on data availability. Where land-use intensity would decrease because of land-use change, a five-year linear transition is used between the relevant N_2O EFs. This tool does not include indirect CO_2 emissions from DOC and POC, or CH_4 emissions from ditches.

The data sets used to fit the CO_2 and CH_4 regressions do not currently include paludiculture sites (Evans et al., 2021), and there are currently no UK Tier 2 EFs for paludiculture systems (Evans et al., 2022). This calculator can estimate emissions from ‘Rewetted Fen’ sites as a proxy for paludiculture sites on fen peatlands within the UK. However, it should be highlighted that biomass export, and the fate of this biomass would not be accounted for. It also focuses exclusively on changes in direct terrestrial GHG emissions from organic soils. Therefore, it does not account for the fate of harvested biomass or any additional (e.g. agricultural) GHG emissions sources. It should also be noted that the tool is UK-specific, based on UK data sets, and application in other contexts would not be directly empirically validated. Whilst beyond the scope of this review, as part of a certification scheme this tool also allows for the inclusion of risk buffers and leakage in line with the Peatland Code guidelines.

2.2.4 IUCN Peatland Code – Emissions Calculator (Bog)

This tool was originally created by the IUCN for the UK Peatland Code. It was subsequently extended by the University of Cumbria and Barker Bland Ltd to calculate the additional carbon footprint of peatland restoration activities (e.g. materials and transport). This tool can be accessed through the IUCN Peatland Code website (v2.1; accessed 27/11/25). In this review we only evaluate the ‘emissions calculator’ component of the tool dedicated to estimating organic soil GHG emissions. The purpose of this tool is similar to the description for the IUCN Peatland Code Emissions Calculator (Fens; see above) but with a specific targeting towards bog peatlands. As with the Peatland Code ‘Fens’ tool, paludiculture is not explicitly included and the validation data do not include paludiculture sites. ‘Rewetted Modified Bog’ could be used as a proxy category for paludiculture on bog peatlands. However, it should be highlighted that biomass export, and the fate of this biomass would not be accounted for.

The available version of this tool is a protected Microsoft Excel workbook. However, the EFs used are cited and visible within the ‘Emissions Lookup Table’ worksheet, and the calculations are relatively simple, so we believe the tool could be fully evaluated for this review.

This tool uses a combination of UK-specific Tier 2 EFs (Evans et al., 2022) and IPCC default Tier 1 EF values (IPCC, 2014) based on land-use classes to estimate organic soil emissions. Users are simply asked to provide pre-restoration and post-restoration land-use classes (condition categories). The tool has only a very limited set of specific permissible combinations are shown in Table 2.1.2. This tool uses the total GHG EFs from Evans et al. (2022), which include indirect CO_2 emissions from DOC and POC, and CH_4 emissions from ditches in addition to direct terrestrial emissions of CO_2, CH_4 and N_2O.

Whilst beyond the scope of this review, as part of a certification scheme this tool also allows for the inclusion of risk buffers and leakage in line with the Peatland Code guidelines.

Table 2.1.2 – Permissible peatland condition category combinations for the Peatland Code calculator for bogs.

Pre-restoration	Post-restoration
Actively Eroding: Hagg/Gully	Revegetated
Actively Eroding: Flat bare	Revegetated
Drained: Hagg/Gully	Rewetted Modified Bog
Drained: Artificial	Rewetted Modified Bog

2.2.5 Wilder Carbon – Carbon + Habitat Tool

This tool was created by the Adonis Blue Consultancy for Wilder Carbon. It is a publicly available online tool that can only be accessed and operated through the Wilder Carbon website (accessed 01/12/25). Wilder Carbon is a not-for-profit carbon standard provider in the UK. The introductory information for the tool describes Wilder Carbon's purpose as being, "to ensure that large-scale restoration of native ecosystems is adopted across the UK as a major weapon in our arsenal for combating climate change". Specifically, the tool is presented as a "resource designed to assess the potential impact of land-use changes or habitat restoration projects in terms of carbon sequestration, carbon emissions reductions, and biodiversity". As an online tool, it's internal functions can only be inferred from its input requirements and outputs, and we do not have full visibility for this review.

Like the IUCN Peatland Code's Bog calculator, this tool appears to use a combination of UK-specific Tier 2 EFs (Evans et al., 2022) and IPCC default Tier 1 EF values (IPCC, 2014) based on land-use classes to estimate organic soil emissions. Users are simply asked to provide pre-restoration and post-restoration land-use classes to estimate organic soil emissions. The tool appears to use the total GHG EFs from Evans et al. (2022), which include indirect CO_2 emissions from DOC and POC, and CH_4 emissions from ditches in addition to direct terrestrial emissions of CO_2, CH_4 and N_2O. The main difference between this tool and the Peatland Code Bog calculator, is that the Peatland Code Bog calculator has a narrow focus on the restoration of less severely modified bogs, whilst the Wilder Carbon tool includes a far wider range of peatland restoration/re-wetting activities and allows estimation for both bog and fen peatlands. However, as this tool relies on the UK total EFs from Evans et al. (2022) it does not include a formal option for paludiculture, though re-wetted land-use categories are included which could be used as proxies for paludiculture.

Whilst beyond the scope of this review, this tool also allows for estimation of wider non-peatland carbon benefits and biodiversity net gain. Additionally, as part of a certification scheme this tool also allows for the inclusion of risk buffers in line with Wilder Carbon guidelines.

2.2.6 Foundation for Common Land – Carbon Calculator

This tool was created by the Foundation for Common Land. It is a publicly available online tool and can only be accessed and operated through the Farm Carbon Toolkit website (accessed

27/11/25). The guidance for the calculator describes it as a "tool which helps farmers and growers measure, understand and take action on their carbon footprint", and the Farm Carbon Toolkit as intended for, "helping farmers and growers to transition to climate-positive practices". As an online tool, it's internal functions can only be inferred from its input requirements, outputs, and the online guidance materials. Therefore, we do not have full visibility for this review.

The guidance for this tool (Parker et al., 2025) indicates that organic soil GHG emissions may be treated differently depending on whether the soil is cultivated or uncultivated. The guidance appears to suggest that values from Taft et al. (2017) are applied based on SOM% to estimate CO_2 and N_2O emissions from cultivated organic soils. In practice, the balances of CO_2, CH_4 and N_2O from Taft et al. (2017; cropped soil values) appear to be applied. If SOM% is not known, then the arithmetic mean of these values is used. It should be noted that the tool refers to SOC% values not SOM% values but this appears to be a naming error. It should also be noted that the evidence base used to produce these values is substantially smaller than the UK EF database. For uncultivated organic soils, the guidance says that emissions are estimated in line with the Peatland Code. For uncultivated soils, the tool appears to function essentially in the same way as the Wilder Carbon tool, applying the total EFs from Evans et al. (2022) on the basis of land-use class. This combination of approaches appears to introduce a slight internal inconsistency, where DOC, POC and ditch CH_4 fluxes are accounted for when assessing uncultivated organic soils but not when assessing cultivated organic soils. Additionally, different 100-year GWP's are applied in each case. As this tool relies on the UK total EFs from Evans et al. (2022) for uncultivated organic soils, it does not include a formal option for paludiculture, though re-wetted land-use categories are included which could be used as proxies for paludiculture. Whilst beyond the scope of this review, this tool also includes a wide range of options to account for changes in additional agricultural GHG emissions sources (e.g. fossil fuel use, materials, nutrient inputs, livestock).

3 Comparative analysis

3.1 Emissions estimates

3.1.1 Approach for comparison

We undertook a simple comparison of the emissions estimates produced by the tools identified, in order to identify any important differences between them. Firstly, to assess how the tools estimate emissions from wet land uses, we collated emissions estimates for paludiculture or proxy re-wetted/wet land-use/vegetation categories. It would not be possible to evaluate all possible land-use change combinations. Therefore, secondly, to allow an assessment of how the tools estimate emissions reductions with land-use change, we produced emissions reductions estimates based on a baseline of deep-drained cropland on thick peat. This land-use change (Deep-drained cropland to Paludiculture or proxy category) was selected as it: (i) would be expected to produce the largest change in net emissions/removals; (ii) therefore might be expected to highlight any differences in the scale of emissions reductions estimated between tools; (iii) the cropland baseline would be relatively internally consistent unlike grassland scenarios which can be extremely variable both between and within regions.

3.1.1.1 Intervention scenario

We used the following tool settings for the paludiculture/re-wetted intervention:

- For the CC-SET tool, we set the median summer groundwater level to -11 cm, in order to produce a soil moisture class of 4+ and allow selection of the vegetation class 'S5: Simulated harvest (Paludiculture)'. We assumed that 100% of harvested biomass would result in biogenic C storage or fossil fuel substitution and used yields of 7.3 t DM ha^{-1} yr^{-1} for *Typha latifolia* from de Jong et al. (2021) and 4.5 t DM ha^{-1} yr^{-1} on average for German *Sphagnum* production from Gaudig et al. (2018). We then set the median summer groundwater level to -5 cm to produce a soil moisture class of 5+ indicating 'Wet' conditions. Vegetation classes of 'U13: Wet sphagnum lawn' and 'U14: Wet tall reeds' were then selected to evaluate 'unmanaged' peatland emissions estimates for bogs and fens respectively under this tool.
- For the PC-FEN tool, we set the mean annual WTD to 11 cm (below the surface; approximately the WTDe implied by the UK Tier 2 EF) and selected the 'Rewetted Fen' land-use category.
- For the PC-BOG tool, we selected 'Rewetted Modified Bog' as the final peat condition category.
- For the WC-CHC tool, we selected 'Creation' as the type of intervention, 'Wetland' as the broad post-intervention habitat, and 'Fens (upland and lowland)' or 'Rewetted lowland raised bog'.
- For the FCT-CC tool, under the 'Sequestration' tab we selected 'Uncultivated Peatland Soils – Modelled' followed by 'Rewetted Fen' or 'Rewetted Bog'.
- Under method 2, the GMC-K tool assigns an intervention scenario of re-wetted nutrient-poor or nutrient-rich peatland by default depending on the baseline land-use entered. For this analysis, we selected only options from the temperate climate zone.
- Under method 1, the GMC-K tool assigns a re-wetted value by default.

3.1.1.2 Baseline scenario

We used the following tool settings for the cropland baseline:

- For the CC-SET tool, we set the median summer groundwater level to -100 cm, in order to allow selection of the vegetation class 'A1: Dry to moderately moist arable land'. In this case we assume no biogenic storage of C exported in crop biomass.
- For the PC-FEN tool, we set the mean annual WTDe to 70 cm (below the surface; approximately the WTDe implied by the UK Tier 2 EF) and selected the 'Cropland' land-use category.
- For the PC-BOG tool, no option is available for a cropland baseline. Therefore, this tool was not used to estimate potential emissions reductions.
- For the WC-CHC tool, we selected 'Creation' as the type of intervention, 'Cropland' as the broad baseline habitat, and 'Cereal crops (on drained peat >40 cm)'.
- For the FCT-CC tool, under the 'Sequestration' tab we selected 'Cultivated Peat Soils – Modelled' followed by 'Peat Soils (Histosols) – high SOC (~70%)'.
- For the GMC-K tool under Method 2, we selected a land use of 'Arable Land', in a temperate climate. Note that the tool defaults to nutrient-rich peatlands when calculating emissions reductions under this selection.
- For the GMC-K tool under method 1, we assigned a drainage depth of -70 cm in line with the value selected for the PC-FEN tool.

3.1.1.3 Calculation details for comparison

The tools that include indirect CO_2 and ditch CH_4 fluxes do so simply by utilising the appropriate IPCC default Tier 1 EF values for these fluxes. In the absence of explicit information, it is assumed that under Method 1, tool GMC-K does not account for these fluxes. Given the low additional information value in this context of this relatively consistent estimation approach, in order to facilitate comparison, we consider only terrestrial emissions of CO_2, CH_4, and N_2O in this analysis. Method 2 of tool GMC-K uses AR4 100-year GWPs, so values from this tool were adjusted to AR5 100-year GWPs to align with the other tools in this analysis. The method for cultivated soils in FCT-CC uses AR2 100-year GWPs, so values for this part of this tool were adjusted to AR5 100-year GWPs to align with the other tools in this analysis. It is unclear which specific fluxes and which GWP values are incorporated in Method 1 of tool GMC-K. Therefore, values from this method are presented unadjusted as total terrestrial GHG emission (or reductions). All estimates were made for a single hectare and are presented as annual values. In the case of PC-FEN the calculator includes a 5-year transition between higher and lower land-use intensities for N_2O emissions. To aid comparisons, we simply provide the difference between annual baseline and intervention scenario emissions estimates as the emissions reduction estimate for this tool. As a result of these various methodological differences, and the necessary adjustments to account for them, not all output values presented here will exactly match the values produced in the tool outputs themselves using the same inputs. However, these adjustments were necessary to allow sensible comparisons to be made without interference from excessive arbitrary differences due to tool reporting and methodologies.

3.1.2 Results of comparison

Several notable features can be seen in the various estimates produced by the tools. Of the thirteen intervention emissions estimates produced for wet land uses, nine sit within the range of -0.4 – 4.4 t CO_2e ha^{-1} yr^{-1}, which shows relatively good agreement (Table 2.2.1). This contains all the UK tool estimates, which is unsurprising as the methodologies in these calculators generally draw on the same data. The other four estimates are in the higher range 8.8 – 12.5 t CO_2e ha^{-1} yr^{-1}, and are all based on methodologies, which draw on data from European sites. However, it should be noted that not all estimates based on wider European data are in this higher range, as three such estimates fall within the lower range. Beyond the observation that high values tend to be derived from European data sets, there is no clear pattern in these differences (e.g. in response to nutrient status or land use). In the case of bog paludiculture (CC-SET tool), the difference from fen paludiculture may well partially be an artefact of the yield value we identified in the literature for *Sphagnum* being lower than that identified for *Typha latifolia*. In the case of the estimates from the CC-SET tool (two of these four higher values), their relatively high values may also represent the application of an EF for direct N_2O emissions from managed organic soils, which inflates estimates from this tool by 2.1 t CO_2e ha^{-1} yr^{-1} relative to the other tools, which do not include this emission for wet sites. The lowest value (for 'Rewetted Modified Bog' in the PC-BOG tool') likely also represents a slight methodological anomaly. This land-use category is reserved in the UK inventory for restoration of less-disturbed peatlands, uses emissions values for near-natural sites, and is probably not an ideal proxy for paludiculture sites. Overall, beyond this handful of methodological artefacts, it is not possible to separate remaining differences from (i) true variation in peatland emissions or (ii) variation in estimates due to methodological or sample composition differences associated with the underlying data.

Of the six unique estimates produced for baseline emissions under deep-drained cropland on thick peat, five, sit within the range of 33.9 – 35.1 t CO_2e ha^{-1} yr^{-1}, which again shows relatively good agreement (Table 2.2.2). As with the intervention estimates, there is good agreement between the estimates for the suite of calculators based on the same underlying UK data. In this case the only notably higher estimate is from the CC-SET tool 43.9 t CO_2e ha^{-1} yr^{-1}, which is based on a wider data set including European data. Notably, it is CO_2 emissions in this case, which result in this much higher overall estimate (they are 43% higher than the Tier 1 EF; IPCC, 2014). If the GMC-K tool were set to its maximum drainage depth effect of <-90 cm under method 1, this would also produce an estimate of 45.0 t CO_2e ha^{-1} yr^{-1}. This suggests that the potential for high emissions estimates from the European tools reflects existing differences between UK and wider European estimates of CO_2 emissions from peatlands (underlying data), more than differences in the tools themselves.

Unsurprisingly the differences in emissions reductions estimates reflect the aforementioned differences in baseline and intervention emissions estimates (Table 2.2.3). The greatest emissions reductions estimates are produced by the CC-SET tool, in cases where the tool estimates relatively low intervention emissions (e.g. where *Typha latifolia* paludiculture is modelled; 39.9 t CO_2e ha^{-1} yr^{-1}). The least emissions reductions estimates are produced by the GMC-K tool under method 1 (22.5 t CO_2e ha^{-1} yr^{-1}). However, this may be an artefact of the drainage depth selected, and greater emissions reductions could be achieved if this input parameter value was increased. The other notably low emissions reductions estimate is from the GMC-K tool under method 2 (24.6 t CO_2e ha^{-1} yr^{-1}) and largely reflects that this tool implements the highest CH_4 emissions estimates under the re-wetted intervention scenario out of all the tools in this analysis. The remaining seven estimates (of eleven total) sit within the relatively consistent range of 31.4 – 35.1 t CO_2e ha^{-1} yr^{-1}. Again, this likely reflects shared underlying data and methodological similarities in most cases. Importantly, there is no clear evidence in this analysis that the tools currently available, produce notably different estimates when evaluating paludiculture as opposed to when evaluating other wet peatland land uses, which might be used as proxies.

Table 2.2.1 – Comparison of emissions estimates for paludiculture and re-wetted peatland proxies.

Type	Tool	Category/Class	Terrestrial GHG emissions				
			CO_2	CH_4	N_2O	CO_{2_AV}	Total
Fen	CC-SET	S5: Paludiculture [Typha]	11.5	3.1	2.1	-12.7	4.0
	CC-SET	U14: Wet tall reeds	0.2	6.5	2.1		8.8
	PC-FEN	Rewetted Fen	-0.9	3.3	0.0		2.4
	WC-CHC	Fens (upland and lowland)	-0.7	3.1	0.0		2.4
	FCT-CC	Rewetted Fen	-0.7	3.1	0.0		2.4
	GMC-K^{M2}	Re-wetted nutrient rich	1.0	8.8	0.0		9.8
Bog	CC-SET	S5: Paludiculture [Sphagnum]	11.5	3.1	2.1	-7.8	8.9
	CC-SET	U13: Wet sphagnum lawn	-3.0	5.3	2.1		4.4
	PC-BOG	Rewetted Modified Bog	-3.5	3.2	0.0		-0.4
	WC-CHC	Rewetted lowland raised bog	-0.6	3.1	0.0		2.5
	FCT-CC	Rewetted Bog	-0.6	3.1	0.0		2.5
	GMC-K^{M2}	Re-wetted nutrient poor	-1.2	3.4	0.0		2.2
N/a	GMC-K^{M1}	Re-wetted					12.5

GHG: Greenhouse gas; CO_2: Carbon dioxide; CH_4: Methane; N_2O: Nitrous oxide; CO_{2_AV}: Avoided carbon dioxide emissions.

Table 2.2.2 – Comparison of emissions estimates for baseline of deep-drained cropland on thick peat.

Type	Tool	Category/Class	Terrestrial GHG emissions			
			CO_2	CH_4	N_2O	Total
Fen	CC-SET	A1: Dry arable land	41.7	0.1	2.1	43.9
	PC-FEN	Cropland	28.1	0.0	6.8	34.9
	WC-CHC	Cereals (on drained peat >40 cm)	27.1	0.1	6.8	33.9
	FCT-CC	Cultivated Peat – high SOM	28.3	0.0	6.8	35.1
	GMC-K[M2]	Arable land	29.0	0.0	5.4	34.4
Bog	CC-SET	A1: Dry arable land	41.7	0.1	2.1	43.9
	WC-CHC	Cereals (on drained peat >40 cm)	27.1	0.1	6.8	33.9
	FCT-CC	Cultivated Peat – high SOM	28.3	0.0	6.8	35.1
N/a	GMC-K[M1]	Drained				35.0

GHG: Greenhouse gas; CO_2: Carbon dioxide; CH_4: Methane; N_2O: Nitrous oxide.

Table 2.2.3 – Comparison of emissions reductions estimates with land-use change from cropland to paludiculture (or re-wetted proxy conditions).

Type	Tool	Final Category/Class	GHG emissions reductions			
			CO_2	CH_4	N_2O	Total
Fen	CC-SET	S5: Paludiculture [Typha]	42.9	-3.0	0.0	39.9
	CC-SET	U14: Wet tall reeds	41.5	-6.4	0.0	35.1
	PC-FEN	Rewetted Fen	29.0	-3.3	6.8	32.5
	WC-CHC	Fens (upland and lowland)	27.8	-3.1	6.8	31.5
	FCT-CC	Rewetted Fen	29.0	-3.1	6.8	32.6
	GMC-K[M2]	Re-wetted nutrient rich	28.0	-8.8	5.4	24.6
Bog	CC-SET	S5: Paludiculture [Sphagnum]	38.0	-3.0	0.0	35.0
	CC-SET	U13: Wet sphagnum lawn	44.7	-5.2	0.0	39.5
	WC-CHC	Rewetted lowland raised bog	27.6	-3.1	6.8	31.4
	FCT-CC	Rewetted Bog	28.9	-3.1	6.7	32.5
N/a	GMC-K[M1]	Re-wetted				22.5

GHG: Greenhouse gas; CO_2: Carbon dioxide; CH_4: Methane; N_2O: Nitrous oxide.

3.2 Discussion of tool features

The main differences between the tools lie in their (i) core organic soil emissions estimation methodologies (and underlying data sets); (ii) additional emissions estimation functionality; (iii) presentation of results. These are discussed in turn in the following sub-sections.

3.2.1 Core emissions estimation methodologies

The main methodologies involve the use of GEST, WTD-based regressions and category-based EFs. The methods used within the various tools are summarised in Table 2.2.4. All of these methods are consistently updated, and are applied and developed differently by different organisations. Therefore, for example, WTD-based regression estimates of GHG emissions from UK and European tools would not necessarily be expected to be identical. Similarly, a range of Tier 1 and Tier 2 EFs are available, and are applied across a range of contexts by organisations based on their relative suitability. In this analysis, we only identified tools using Tier 2 EFs for the UK, but this does not mean that Tier 2 EFs from other nations might not be used in tools we could not access for example. An in-depth evaluation of the relative merits of

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national data sets and different estimation methods is beyond the scope of this review. However, as can be seen in Table 2.2.4, several of the tools share underlying methodologies and are based on the same or similar underlying data. Therefore, it is important to highlight that agreement between the estimates produced by these tools – specifically the UK tools in this case – should not be misinterpreted as agreement between independently derived estimates. Consequently, this agreement between estimates should also not be treated as evidence that these tools produce superior estimates when compared with other tools.

Table 2.2.4 – Comparison of tool calculation methodologies.

ID	Method					
	CO_2	CH_4	N_2O	DOC	POC	Ditch CH_4
CC-SET	GEST	GEST	T1 EF	-	-	-
GMC-K^{M1}	← Regression/s and possibly EFs* →					
GMC-K^{M2}	T1 EF†	T1 EF†	T1 EF†	T1 EF	-	T1 EF
PC-FEN	Regression	Regression	T1/T2 EFs	-	-	-
PC-BOG	T2 EFs	T2 EFs	T1/T2 EFs	T1 EF	T1 EF	T1 EF
WC-CHC	T2 EFs	T2 EFs	T1/T2 EFs	T1 EF	T1 EF	T1 EF
FCT-CC	T2 EFs‡	T2 EFs	T1/T2 EFs	T1 EF	T1 EF	T1 EF

Note that for tool GMC-K, superscripts indicate the two different calculation methods available. *It is not specified exactly which GHG's are accounted for by this method. †Updated Tier 1 values from Wilson et al. (2016). ‡Uses single study values from Taft et al. (2017) for cultivated land and Tier 2 EFs for uncultivated land. GHG: Greenhouse gas; CO_2: Carbon dioxide; CH_4: Methane; N_2O: Nitrous oxide; DOC: Dissolved organic carbon; POC: Particulate organic carbon.

It is still reasonable to suggest that where data and methods have been developed based on nationally or regionally specific data, these could be argued to be preferable for application within the relevant area/s. Therefore, by extension, it could be argued that where Tier 2 EFs are available and assessed to be suitably robust, then these should be preferred to Tier 1 EFs. In the context of the UK (see Evans et al., 2022), there is evidence that WTD-based approaches can currently offer a more nuanced estimate of peatland GHG emissions than category-based EFs. The information associated with the tools identified in this analysis (see GMC-K), would appear to suggest that GEST is the preferred emissions estimate in temperate European contexts (see also Emmer & Couwenberg, 2017), although WTD-based methods are also available (e.g. Couwenberg et al., 2011). Both GEST and the WTD-based regressions of Evans et al. (2021, 2022) have been approved by credible carbon standards for regional use (VCS and IUCN UK Peatland Code respectively), indicating that both can be considered acceptably robust methods for peatland emissions estimation in the appropriate context, based on current standards. GEST does contain a vegetation class explicitly for paludiculture, though the emissions estimate produced by tools using this approach appears to be highly dependent on crop yield and biomass fate (see CC-SET). In contrast, the UK approach is not based on data from paludiculture sites and UK methods do not explicitly include paludiculture. Nonetheless, our analysis of calculator estimates suggests that any differences between paludiculture estimates and those for re-wetted peatlands as a proxy are currently indistinguishable given estimation error and the noise introduced by methodological artefacts. It therefore seems reasonable to suggest that the use of regionally specific methods currently remains best practice even where paludiculture-specific options are available. However, this may change as the available data and methods are updated and refined. Notably, UK calculator methods are currently based solely on UK data and extrapolation of these specific methods beyond this region would not be empirically validated.

Currently, indirect CO_2 fluxes from DOC and POC, and ditch CH_4 emissions are inconsistently included in these calculators. However, this reflects relative data-scarcity for these fluxes and the direct consequence of this, that relatively less robust Tier 1 EFs are unlikely to give accurate or precise estimates of within-site changes for these fluxes.

3.2.2 Additional emissions estimation functionality

The CC-SET tool (see Section 2.2.1) has a unique feature among the calculators evaluated, in that it includes a function to account for the fate of carbon exported in paludiculture crop biomass. Specifically, this tool allows users to specify the crop type and yield. If the crop produced in the re-wetting scenario substitutes fossil-based products and has a lifetime greater than ten years, then the carbon content of the harvested crop is treated as avoided fossil emissions. These then represent an emissions reduction which is applied when estimating the carbon balance of the paludiculture system (see CO_{2_AV} term in Table 2.2.1). This is a potentially useful function and future calculators for paludiculture systems should ideally contain functionality to factor in the effects of biomass harvest and use. However, caution will be required around implementation of this function.

The estimation of carbon and CO_2 balances is often a source of confusion. Net ecosystem exchange (NEE) is the vertical CO_2 balance. It is calculated as the sum of CO_2 uptake by plants through gross primary productivity (GPP) and CO_2 loss through total ecosystem respiration (TER), which includes organic soil emissions from microbial respiration. The net ecosystem production (NEP) also accounts for lateral CO_2 gains/losses from a site resulting from imported (C_{IN}) and exported (C_{OUT}) biomass carbon. Therefore, at the site/ecosystem level, exported biomass represents a loss of carbon from the system, and thus is treated as a CO_2 emissions source. This remains true when CH_4 emissions and indirect CO_2 emissions from aquatic fluxes are included, in order to calculate the site's net ecosystem carbon balance (NECB). It is therefore, only if any exported biomass subsequently substitutes or avoids upstream fossil resource depletion, that avoided emissions can be subtracted from the CO_2 balance of the site or product. It should also be noted that future, direct terrestrial organic soil CO_2 EFs for paludiculture sites, should already account for carbon lost from the site through biomass harvest; these EFs should be derived from NEP. Therefore, it is essential during tool development, to take care that any CO_2 emissions or emissions reductions, resulting from biomass harvest and substitution of fossil products, are not repeatedly counted at multiple stages. This is true both within projects and within wider certification processes. It is also essential that any assumptions about biomass fate accurately reflect real-world outcomes if appropriate estimates are to be produced.

We should also highlight that for national GHG inventory reporting of land use or land-use change emissions, the organic soil EFs used must represent the emissions of the land and not of subsequent upstream processes and supply chains. Therefore, calculators which are intended to support or be used directly for national GHG inventory calculations/reporting should include the option to exclude downstream avoided emissions from the calculations of CO_2 balances for paludiculture sites. The best approach for implementing this function within any specific tool development case will depend on the data available for methodology development, the information likely to be available to end users, and the specific needs and use case of end users. However, in all cases, care should be taken to ensure appropriate implementation.

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Another potentially large influence on the CO_2 balance of paludiculture sites is topsoil removal prior to re-wetting. The size of any effect on CO_2 balance will be highly dependent on the fate of exported topsoil and currently this would likely have to be estimated based on simple modelling assumptions. However, where topsoil is ultimately exported to be stored in aerobic conditions, sizeable CO_2 emissions could be expected to result (see van den Berg et al., 2024). Therefore, this must be accounted for within the aforementioned C_{OUT} term of the ecosystem CO_2 balance, if accurate overall assessments of the climate change impact of land-use change to wet peatland systems are to be made. For biomass export, where the NEE and C_{OUT} terms are intrinsically linked, NEP including C_{OUT} from biomass harvest must be used to estimate direct terrestrial organic soil CO_2 EFs for paludiculture sites. However, emissions associated with topsoil removal represent a relatively independent term. Therefore, it seems reasonable to suggest that the emissions could remain external to the direct terrestrial organic soil CO_2 EF for paludiculture and re-wetted sites, being treated instead as an indirect CO_2 emissions source, with emissions estimation methodologies based upon the mass and fate of the topsoil being exported.

Some calculators also have capacity to consider additional emissions sources associated with land-use change to paludiculture (or peatland re-wetting and restoration). For example, the CC-SET and FCT-CC can be used to characterise selected additional agricultural emissions sources, whilst the PC-BOG tool contains capacity to account for additional emissions associated with peatland restoration activities. However, as the functionality of emissions calculation tools to incorporate additional emissions sources is increased, so is the risk that emissions abatement is claimed which is not reflective of real-world changes in total anthropogenic GHG emissions. Currently, for example, the Peatland Code includes provisions to account for leakage resulting from *intended* changes in management elsewhere. However, the Peatland Code calculators themselves do not and none of the calculators evaluated account for the effects of *unintended*, indirect land-use and management changes resulting from peatland re-wetting. These effects are likely to be regionally variable and complex, and could only be robustly handled within consequential life cycle analyses. This creates a risk that the more easily accessible tools could present misleading representations of true real-world land-use change climate outcomes if results are not presented with care. Consequently, developers of peatland emissions estimation tools should be cautious in their presentation of estimated emissions reductions and how these are contextualised for end users.

3.2.3 Presentation of results

There is substantial variation in the detail and format of results presentation among tools. This largely reflects their different purposes. If a tool were being developed to help users understand the potential impacts of land-use change on the climate impacts of paludiculture adoption, then it is likely that a combination of both (i) a detailed breakdown of individual emissions/removals under baseline and intervention scenarios and (ii) a high-level summary of overall changes, would be of value. This would allow users both to quickly identify key high-level conclusions but also explore detailed effects of management actions as required.

Where calculators are associated with specific carbon standards it makes sense that results presentation might focus on the details relevant in that context. The focus may be more on presenting results for individual assessment units or project durations, with a breakdown of how leakage and risk buffers might be accounted for under scheme processes (e.g. see PC-FEN tool).

Consideration could also be given to presenting calculation results in financial terms (based on carbon commodity prices) as in the GMC-K tool, in order to provide end users with additional context. However, we note that carbon commodity prices can vary, and that any financial outcomes are likely to be strongly influenced by market conditions and monetisation scheme regulations. Therefore, presentation of results in financial terms should be considered additional and should be handled with care, to ensure that end users would be aware of the potential for substantial differences between estimated and real-world outcomes.

In all cases, the specific GHG fluxes considered and included in any estimates should be made explicit, as should the 100-year GWP values used (where applicable), and any carbon commodity prices used. Tool developers should also seek to provide sufficient context and clarity about underlying methods, so that end users are aware of the limitations of any estimates produced. This is especially important where: (i) tools attempt to account for processes outside the system of interest (e.g. biomass/topsoil fate); (ii) tools attempt to account for wider effects of land-use change or leakage (e.g. changes in agricultural inputs); (iii) tools are explicitly recommended for contexts not supported by underlying data (e.g. using proxy categories to represent paludiculture). These reporting diligence steps are essential to ensure that end users are not put at risk through the provision of misleading or simply confusing outputs.

Conclusions

This review demonstrates that a range of publicly available peatland emissions estimation tools can be used to approximate the climate change implications of converting drained cropland on peat to wetter land uses (including those relevant to and including paludiculture). Across tools, estimated emissions reductions are broadly consistent once methodological differences are accounted for, and there is no clear evidence that paludiculture-specific estimates differ systematically from those derived using re-wetted proxy categories under current data constraints.

However, the usability of existing tools for paludiculture does remain limited by the way paludiculture is represented. Most tools were developed to support peatland restoration or re-wetting and only have limited capacity to include paludiculture implicitly as a re-wetted peatland, without accounting for managed biomass production, export, or the fate of harvested material. While one tool explicitly includes paludiculture-related options, outputs are highly sensitive to assumptions about yield and carbon storage or substitution pathways, which are often uncertain or site-specific.

As a result, existing tools are well suited to screening-level assessment of the emissions benefits of re-wetting peatlands and for benchmarking paludiculture against drained agricultural baselines. However, robust accounting of paludiculture as a managed production system is inherently challenging and cannot be achieved through peatland emissions calculators alone. Net climate outcomes depend not only on changes in on-site soil GHG fluxes, but also on management practices, harvested biomass yields, product lifetimes, substitution effects, and wider system-level responses, which are more appropriately addressed within life cycle assessment frameworks.

That said, improvements to emissions estimation tools – such as clearer treatment of biomass fate and better representation of paludiculture sites in the underlying empirical data – would enhance their usefulness. Tool-based estimates should not be viewed as a substitute for full system-level analyses where these are required. However, due to their relatively lower costs and greater accessibility, emissions estimation tools will continue to have an important role to play in knowledge exchange and decision-making support for policymakers and land managers. This means that there will need to be a balance struck between ongoing empirical research and detailed life cycle assessments to ensure the robustness of tool methods/assumptions, and continued emissions estimation tool development to ensure efficient delivery of practically useful pathways to produce real-world impact from the aforementioned research. Nonetheless, in closing, we will reiterate our caution that careful interpretation and presentation of emissions estimation tool results will remain essential to ensure positive impacts are achieved.

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