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REPORT

Report on model and tool comparison and improvements

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Introduction

Drainage of peatlands releases large amounts of greenhouse gases (GHG), mostly CO_2. Rewetting restores ecological functioning of degraded bogs and mires, at least in part, which reduces GHG emissions. The effect of rewetting on GHG emissions can be measured in the field, but such measurements are very expensive. It is therefore not feasible to measure GHG effects of all rewetting projects and predictive tools and models are needed. There exist several modelling tools to assess effects of rewetting projects on GHG emissions, which are much less demanding in terms of time and capital expenditure. In this report modelled GHG emissions of the pilot sites from the initial Care-Peat project are compared, in order to compare the performance of each model to one another. Three modelling tools (or calculators) are compared: the UK Peatland Code Version 2, the Decision Support Tool developed in the main project of Care-Peat, and the Site Emission Tool (SET) developed in Carbon Connects. Separate reports about the applicability of each model are available on the Care-Peat Interreg website (deliverables D4.1.1, D4.1.2. & D4.1.3).

The aim of this report is to compare the models on their performance to predict GHG fluxes per Care-Peat pilot site. This comparison shows how well the models can predict GHG fluxes compared to one-another or where they might deviate from each other (Chapter 1). Further model improvements are described per model (Chapter 2).

1. Presentation of the models

The models can be useful tools to improve understanding of the interaction between hydrology and greenhouse gas emissions in peatlands. However, many models exist and each function differently to calculate GHG fluxes.

The numerical model (Decision Support Tool) uses conceptual and mathematical equations to estimate GHG and they are mainly based on frequent measurements of relevant parameters. These models can calculate GHG budgets per day, month or annum.

Other statistical models like the SET uses proxies based on vegetation type and water table depth to estimate GHG fluxes using the GEST database of measured emission budgets. Usually, GHG budgets are calculated per annum.

Comparison of the numerical and SET model purely based on their estimations of the GHG budgets per site is not straightforward, as both models produce different outcomes of GHG budgets, in terms of per month/per year.

Therefore, a comparison based on the difference between GHG budget estimations of the control and restored scenarios will results in a more representative view of the models' performances.

1.1. DST model

During the INTERREG CARE-PEAT project, one of our objectives was to simulate carbon balance, especially net ecosystem exchange (NEE), at peatlands scale and according to the main site specificities. Peatlands are complex ecosystems where water, solute and gas fluxes can vary strongly during a year. Therefore, NEE is vulnerable to change according to hydrological, weather and vegetated conditions. Several previous experiments reported that NEE fluxes change drastically according to water table depth. Regressions based on experimental data have been performed to quantify this change but these values are associated with a large uncertainty (Evans et al. 2021). This could be induced because ecosystem respiration, named here RECO, and gross primary production (GPP) are not explicitly described and simulated as well as the effects of change in hydrological conditions on these two parameters.

To overcome this limit, we developed in the INTERREG NWE CARE-PEAT project a numerical model explicitly predicting C-fluxes resulting from RECO and GPP, calibrated and validated against data acquired on several pilot sites (Devau et al., 2021; André et al., 2022, 2023). Concerning GPP, an analytical model describing dependence of these CO_2 fluxes to photosynthetic proton flux density (PPFD) has been developed. A variably saturated flow model and a reactive transport model (RTM) were built using the HPx software (Jacques et al., 2018) to simulate water content at different depths as well as CO_2 fluxes issued from aerobic respiration at the soil-atmosphere interface (Devau el al., 2021).

1.2. SET model

The Site-Emission- Tool (SET) has been developed in the INTERREG Carbon Connects project (van Belle & Elferink, 2021). The SET estimates the C-flux from peat soil, based on proxy measurements of median water table depth in the annual dry summer period (May- October), and selecting an appropriate vegetation type from the Greenhouse Gas Emission Site Types (GEST) (Couwenberg, et al., 2011; Couwenberg, Reichelt, & Jurasinski, in prep.). SET aids the user in selecting the best fitting GEST by limiting the choice of options based on median summer groundwater level. The SET adds standard IPCC Tier 1 calculations for N_2O emissions from soil and CO_2 emissions from fossil fuel use (Eggleston, Buendia, Miwa, Ngara, & Tanabe, 2006), allowing the user to also include emissions and savings from energy use, crop residues and product use. Ultimately, it calculates the GHG emission reduction that is eligible for carbon crediting, taking into account the amount of carbon in the peat layer. For each of the Care-Peat pilot sites, the carbon fluxes from peat soil were estimated based on water table depth (WTD) and (most suitable) GEST-type per control and restored parts of the Care-Peat (see report DT.4.1.2) by the SET. Some sites have multiple GHG collars for which the GHG flux was modelled, as well as multiple GEST-type possibilities per collar. Therefore, multiple modelled GHG fluxes are available for some sites. These results are shown as a range of the minimum and maximum GHG values modelled by the SET per control and restored sites. In the tables showing the modelled restored and control GHG fluxes, the positive values indicate a higher GHG flux (hence, emission of t CO_2/ha/yr), while negative values indicate a lower GHG flux (hence, sequestration). Typically, the SET models GHG fluxes for CO_2 and CH_4 (summed up to total Global Warming Potential in t CO_2/ha/yr) for the restored scenario and control scenario. In this report, only the results for the CO_2 fluxes are shown, as the other models do not take into account the CH_4 flux. Furthermore, for each site the GHG fluxes are calculated per one hectare, and not per actual size of the pilot sites.

1.3. Peatland Code

The Peatland Code (IUCN, 2023) is a voluntary peatland certification standard used in the UK. It allows peatland restoration projects to market the bundled benefits of restoration with a focus placed on the carbon benefits. The Peatland Code provides assurances and an audit trail for investors that their investments have produced genuine reductions in carbon emissions and that these emissions are robustly quantifiable, guaranteed for the long term and additional to other reductions.

Early versions of the Peatland Code supported funding on upland peatland restoration projects, however, recent revisions have broadened the peatland types included (Evans et al. 2022; IUCN, 2023). Each project establishes a baseline habitat type and condition, which are then associated with an Emissions Factor. The Emissions Factors used in the peatland code are based on the Emissions Inventory for UK Peatlands (Evans et al., 2017) which produces Tier 2 Emissions Factors based on evidence gained from monitoring projects in the UK and, where UK data doesn't exist, Tier 1 EU Emissions Factors. Only categories where robust data is available are used. The baseline emissions are then compared to the restoration scenario emissions factor and an annual CO_2 equivalent benefit estimated. This CO_2 eq. benefit incorporates gaseous CO_2, CH_4 and N_2O emissions from land and water, alongside fluvial Dissolved and Particulate Organic Carbon (DOC and POC).

In this report, each pilot site's baseline (control) scenario and restoration scenario has been aligned to the most appropriate Peatland Code Version 2 category.

2. Differences between GHG fluxes of restored and control scenario

2.1. Vallei van de Zwarte Beek, Belgium

2.1.1. Estimation with SET model

The data for median water table depth for Zwarte Beek was calculated based on measurements of the piezometer ZWAP361X for 2020. Data for 2021 could not be analyzed in the SET, as the GEST types were not compatible with the median water table depth for the year 2021. Water table depth of the restored sites an stripped control sites were estimated to be 10 cm closer to the surface than at the piezometer's location, resulting from 10 cm topsoil removal. The vegetation of the restored collar sites were classified as GEST *very moist forbs and sedges* and *moist to very moist grassland with shunt species* . The controls sites were classified as GEST *very moist forbs and sedges* and *moist to very moist grassland with shunt species* . The results of the different collars ranged between +12.6 to +13.5 t CO_2 eq./ha/year for both the restored and control sites (Table 1.). These similar results of control and restored C-flux are due to the uniformity of GES between the restored vs. control scenarios and the very small difference in water table depth (10 cm differences).

Table 1 - The minimum and maximum range of modelled GHG fluxes, based on the output of the SET for 2020 – Zwarte Beek

SET Output for CO_2 - 2020	**GHG flux (tCO_2 eq./ha/year)**			**GHG flux (tCO_2 eq./ha/year)**	
Restored	**min**	**max**	**Control**	**min**	**max**
Vegetated	12.6	13.5	Stripped	13.5	
			Non-stripped	12.6	13.5

2.1.2. Estimation with DST model

Several divers were placed in the field to measure the water table depth. The measurements mainly started in 2020. The ZWAP361X piezometer is used for estimating the water table depth in the parcel: its coordinates are: W = 206 908 and Y = 189 575.

The vegetation is monitored with vegetation surveys for the whole of the Zwarte Beek, as well as specific vegetation monitoring inside the collars. The vegetation inside the collars changed significantly over the year. But, it is mainly composed of *Juncus effusus* and *Ranunculus repens*.

PPFD is measured on the site since the end of 2021. From the measurements performed since this date, the mean PPFD is estimated to about 250 µmol/m²/s. This mean value is used to estimate the GPP in 2020 and 2021.The air temperature on the site was not recorded in 2020 and 2021. We used values of air temperature recorded at the Weather station of Diepenbeek (closed to the site).

Year 2020 is dry which involves a high production of CO_2. The estimation of the fluxes corresponds to a production of about 2,400 g CO_2/m^2/year. At the opposite, the fluxes in 2021 are lower mainly because of the increase of the water table depth during this year. Indeed, the fluxes are estimated to a release of about 670 g CO_2/m^2/year. In 2022, the estimation is based on the half of the year since we only have water table depths up to June 2022. From the measurements during the first 6 months, the CO_2 fluxes are estimated to 470 g CO_2/m^2 which can be approximated to 1,100 g CO_2/m^2/year. This value can be refined by integrating the water table depths of the last 6 months.

Table 2 - The modelled GHG fluxes with DST tool between 2020 and 2022 – Zwarte Beek (positive value = emissions)

	C-emissions from soil (tCO_2/ha/year)
2020	+ 24.00
2021	+ 6.70
2022	+ 11.00*

* Estimated from the water table depth and weather conditions from 01/01/2022 to 31/05/2022.

2.1.3. Aligning the Peatland Code to the site

The baseline habitat of De Zwarte Beek is an iron-rich fen peatland that has been drained, it is a fen but dominated by grassland vegetation. As such, it could fit in either the 'Grassland – extensive drained' category in the peatland code with an EF of 15.88 tCO_2 eq./ha/year or Modified Fen sitting over a low water table. The 2020 mean water table was -19 cm with a low 0f -38.9, these sit below typical fen water tables and closer to 'Grassland – extensive drained' so this category was chosen. Its target habitat following rewetting and restoration is quaking bog/transition mire and this most closely corresponds to the Peatland Code category of 'Rewetted Fen'. The restoration is forecast to bring an overall CO_2e benefit of 13.87 tCO_2 eq./ha/year.

Table 3 - The Peatland Code categories and Emissions Factors associated with the Starting and Restored Habitat Type – Zwarte Beek

Control plots			Restored plots		
Starting habitat	**Peatland Code condition category**	**Peatland Code Emissions Factor tCO2 eq./ha/year**	**Target habitat**	**Peatland Code condition category**	**Peatland Code Emissions Factor tCO2 eq./ha/year**
Iron Rich Fen Peatland (Drained)	Grassland - extensive drained	15.88	Quaking bog/Transition Mire	Rewetted Fen	3.19

2.2. La Guette, France

2.2.1. Estimation with SET model

The median water table depth data for SET is based on data from one piezometer for 2021. The appropriate GEST types were chosen for the control/restored scenarios based on the different collar vegetation. The restored collars containing *Sphagnum* were classified as *wet to very wet Sphagnum lawn* and *wet bare peat*. The control sites were classified as *very moist* to *moist bog heath* and *moist to very moist Molinia meadows*. The GEST types chosen for the restored bare peat collars were not compatible with the corresponding water table depth, therefore no SET results could be obtained for these collars. The results of the SET for the *Sphagnum* scenarios and control scenarios yielded a range for the SET results between -3.0 to -4.6 and -4.3 to +4.7 respectively (Table 4).

Table 4 - Results for modelled CO_2 flux for the control and restored site of La Guette 2021.

SET Output for CO_2 - 2021	**GHG flux (tCO_2 eq./ha/year)**			**GHG flux (tCO_2 eq./ha/year)**	
Restored	**min**	**max**	**Control**	**min**	**max**
Sphagnum	-3.0	-4.6		-4.3	+4.7
Bare peat	x	x			

2.2.2. Estimation with DST model

The respiration fluxes are only estimated according to the water table depth (WTD) recorded between 2018 and 2021 on three piezometers set-up in three different part of the peatland. Daily WTD measurements allows calculating daily CO_2 fluxes. Then all the daily calculations are summed on one year to calculate the global carbon budget related to ecosystem respiration. The daily mean value of air temperature is also integrated in the calculations.

For the Gross Primary Production, we consider that La Guette peatland is fully invaded by a vegetation composed of *Molini* and *Sphagnum*. The GPP estimation is based on the PPFD measurements done on the site.

The daily NEE is then calculated according to daily estimations of RECO and GPP. La Guette peatland is emitting about 900 g CO_2/m^2/year (mean value calculated from estimations of CO_2 emissions between 2018 and 2020).

During the project, parcels of 600 m² are restored. The restoration consists of removing the first 5 to 10 cm of the peatland (including vegetation) and to spread *Sphagnum* patches. In these restored parcels, the calculations estimates that peatland sequesters carbon (about 3 tCO2 eq./ha/year**).**

Table 5 - Results for modelled CO_2 flux for the control and restored site of La Guette 2021 (negative value=uptake / positive value = emissions)

Restored scenario: C-emissions from soil (tCO_2/ha/year)		**Control scenario: C-emissions from soil (tCO_2/ha/year)**	
Restored area (= *Sphagnum*)	Between –2.9 and -3.3	Control area (= *Sphagnum + Molini)*	+ 9.00

2.2.3. Aligning the Peatland Code to the site

The baseline habitat of La Guette, France is degraded poor fen peatland that has been drained, it is dominated by sedge vegetation with Sphagnum moss in wetter areas. Fens have not been incorporated into previous Peatland Code versions due to limited Tier 2 Emissions data from the UK. However, revisions have been made that enable adaption of the Near Natural Fen category to allow variation in water table below Natural Fens in a new category called 'Modified Fen' (Evans et al., 2023). There have been small changes in the water table during the project, from a mean of around 10 cm below the surface at the start to around 5 cm below cm following drain blocking. The first figure generates an EF of 0.16 tCO_2 eq./ha/year. As such has been assigned the 'Modified Fen' category in the peatland code.

The target habitat following rewetting and restoration is rewetted fen, which matched the Peatland Code category of 'Rewetted Fen'. The EF for this category is 3.19, this is higher than the start category. Given this, it was decided to continue with the same Modified Fen category as the baseline, but with a modified water table. Using a water table based approach in the modified fen category an EF of -0.43 tCO_2 eq./ha/year is produced. The restoration is forecast to bring an overall CO_2e benefit of 0.59 tCO_2 eq./ha/year. No N_20 emissions are predicted for Fen habitats in the UK Tier 1 Emissions Factors, the figures below represent the sum of CO_2 and CH_4 fluxes only.

Table 6 - The Peatland Code categories and Emissions Factors associated with the Starting and Restored Habitat Type – La Guette

Control plots			Restored plots		
Starting habitat	**Peatland Code condition category**	**Peatland Code Emissions Factor tCO_2 eq./ha/year**	**Target habitat**	**Peatland Code condition category**	**Peatland Code Emissions Factor tCO_2 eq./ha/year**
Degraded fen	Modified Fen	0.16	Rewetted Fen	Modified Fen	-0.43

2.3. Winmarleigh Moss, UK

2.3.1. Estimation with SET model

The water table depth for Winmarleigh was obtained from two dip wells, corresponding to the Carbon farm (restored) and Grazed pasture (control). The carbon farm was planted with *Sphagnum*, therefore it has been classified as *very moist Sphagnum lawn* (GEST-type). The grazed pasture was classified as *Dry to moderately moist grassland on peaty soil*. The restored scenario resulted in –4.3 tCO_2 eq./ha/year, while the control scenario resulted in + 46.1 tCO_2 eq./ha/year (Table 7).

Table 7 - The output of the SET for the minimum and maximum values of CO_2 flux, based on the present GEST-types for restored and control for Winmarleigh Moss

SET Output for CO_2 2021	**GHG flux (tCO_2 eq./ha/year)**		**GHG flux (tCO_2 eq./ha/year)**
Restored		**Control**	
Carbon Farm	-4.3	Grazed Pasture	+46.1

2.3.2. Estimation with DST model

The water table depth is followed on this site since the end of 2020. Two parcels are monitored: the control area which is a grazed pasture and the restored area (= the carbon farm). The evolution of the vegetated cover is also a crucial parameter, which is followed since this date.

In the following calculations, fluxes for this site are calculated in 2021 i.e. during the establishment year of the vegetation. First respiration fluxes are calculated according to the respiration model using the water table depth. Since the water table depths of the control area are lower than the ones of the restored area, the respiration fluxes are drastically different: they are estimated to about 42.08 tCO_2 eq./ha/year for the grazed pasture against 13.89 tCO_2 eq./ha/year for the carbon farm.

About the Gross Primary Production (GPP), fluxes are also very different. They are about -37.93 tCO_2 eq./ha/year for the grazed pasture against -5.92 tCO_2 eq./ha/year for the carbon farm. These values are determined according to the relationships established in André et al. (2022, 2023). It is to note that this calibration of the GPP model was made from chamber measurements mainly recorded during the end of 2020 and the beginning of 2021. During this period, the S*phagnum* cover was still low (around 10 %). By the end of 2021 and 2022, this percentage of coverage drastically increase and this factor must be considered if calculations are performed in 2022 and the following years.

Table 8 – Estimations of the CO_2 fluxes for the Winmarleigh site in 2021 with the DST model (positive value = emissions)

DST Output for CO_2 in 2021	GHG flux (tCO_2 eq./ha/year)		GHG flux (tCO_2 eq./ha/year)
Restored		**Control**	
Carbon Farm	+ 7.97	Grazed Pasture	+ 4.15

2.3.3. Aligning the Peatland Code to the site

The baseline habitat of Winmarleigh Moss is drained and grazed pasture, it is dominated by grassland vegetation. It is fertilised to promote growth as food for sheep and cattle farming, as such has been assigned the 'Grassland - intensive drained' category in the peatland code. It's target habitat following rewetting and restoration is Carbon Farm, dominated by *Sphagnum* moss. There is no direct fit for this in the peatland code, however, as the target is a highly *Sphagnum* rich bog the most closely matched category of 'Rewetted modified bog' was applied. This currently uses the same emissions factors as 'Near Natural Bog'. The restoration is forecast to bring an overall CO_2e benefit of 21.68 tCO_2 eq./ha/year.

Table 9 - The Peatland Code categories and Emissions Factors associated with the Starting and Restored Habitat Type – Winmarleigh Moss

Control plots			Restored plots		
Starting habitat	**Peatland Code condition category**	**Peatland Code Emissions Factor tCO_2 eq./ha/year**	**Target habitat**	**Peatland Code condition category**	**Peatland Code Emissions Factor tCO_2 eq./ha/year**
Grazed pasture – drained	Grassland - intensive drained	22.00	Carbon Farm (*Sphagnum*)	Rewetted Modified Bog	0.32

2.4. Little Woolden Moss, UK

2.4.1. Estimation with SET model

Little Woolden Moss is divided into six measuring plots, and each plot has bare peat (control) and vegetated (restored) parts. Each plot is fitted with a dip well to measure water table depths. The vegetation of the six collars in the restored site were classified as wet to *very wet Sphagnum hollows* and *very moist* to *moist bog heath*. The control collars were classified as *wet* to *moist bare peat*. The SET results for the restored gave a range between –4.6 to +12.3 tCO_2 eq./ha/year, for the control the range was +1.3 to +9.0 tCO_2 eq./ha/year (Table 10).

Table 10 – The output of the SET for the minimum and maximum values of CO_2 flux, based on the present GEST-types for restored and control for Little Woolden Moss 2021

SET Output for CO_2 - 2021	GHG flux (tCO_2 eq./ha/year)			GHG flux (tCO_2 eq./ha/year)	
Restored	**min**	**max**	**Control**	**min**	**max**
Vegetated	-4.6	12.3	Bare	1.3	+9.0

2.4.2. Estimation with DST model

The water table depth is recorded from 6 dip wells in the control area and 6 dip wells in the restored area. Water table is measured in each dipwell fortnightly and in one location on the site an automated piezometer is measuring water table depth every 15 minutes. The two areas are showing similar variations of WTD with lower values during the summer and values close to the surface during winters, falls and springs. The respiration fluxes (RECO) are estimated from the model for both areas. The control areas emit about + 1,100 g CO_2 / m^2/year against 1,400 g CO_2 / m^2/year for the restored areas in 2021.

Concerning the GPP, we are considering that it is nil for the control areas (bare-peat). For the cotton grass areas, we are applying the model determined from chamber measurements for calculating GPP fluxes. However, by using the parameters estimated in the previous report (see André et al., 2022, 2023) , the obtained values of CO_2 uptakes are very high, this could be because the plant materials was fast developing from plug plants, planted at high density. I. The results are supported by a very high vegetation volume in the first year. During the second year, the plants have matured and the vegetation volume decreases.

Since all the calibrations are done on plant volume of the first year (i.e. during the maximum vegetation volume), we probably overestimate the uptake. Consequently, we decided to include a vegetation factor in the calculation of the GPP which is based on the variation of vegetation volume. The Table shows that the restored area mainly behaves as a carbon sink with the absorption of about 10.00 t CO_2 / m^2/year.

Table 11 – The Calculation of the mean NEE for all the piezometers of the control and restored areas (negative value=uptake / positive value = emissions)

Restored scenario: C-emissions from soil (tCO_2/ha/year)		Control scenario: C-emissions from soil (tCO_2/ha/year)	
R1	- 8.68	C1	+13.69
R2	+ 1.00	C2	+12.55
R3	- 5.37	C3	+7.20
R4	- 9.05	C4	+8.89
R5	+ 11.64	C5	+16.86
R6	- 11.34	C6	+9.28

2.4.3. Aligning the Peatland Code to the site

The baseline habitat of Little Woolden Moss is drained and commercially extracted peatland, it is dominated by bare peat. This category exists in UK Tier 2 Emissions Factors but is not mirrored directly in the peatland code. The closest match in the Peatland Code is 'Actively Eroding Bog (Modified bog - eroding drained)' category in the peatland code. It's target habitat following rewetting and restoration is Active Raised Bog, dominated by Sedges and *Sphagnum* moss and this corresponds most closely to the Peatland Code category of 'Rewetted modified bog'. The restoration is forecast to bring an overall CO_2e benefit of 17.70 tCO_2 eq./ha/year.

Table 12 - The Peatland Code categories and Emissions Factors associated with the Starting and Restored Habitat Type – Little Woolden Moss

Control plots			Restored plots		
Starting habitat	**Peatland Code condition category**	**Peatland Code Emissions Factor tCO_2 eq./ha/year**	**Target habitat**	**Peatland Code condition category**	**Peatland Code Emissions Factor tCO_2 eq./ha/year**

Bare Peat - extracted	Modified bog - eroding drained	17.72	Active Raised Bog (Sedge Dominated)	Rewetted Modified Bog	0.32

2.5. Cloncrow Bog, Ireland

2.5.1. Estimation with SET model

Two dip wells in the Submarginal ecotope of Cloncrow measure the water table depth in the restored and control part of this ecotope. The data used for the SET is from 2021. The water table depth of the Facebank is not yet available for the SET analysis. The Submarginal vegetation for the restored part was classified as Wet bog heath and Wet to very wet Sphagnum hollows, the control part was classified as Very moist bog heath. The results of the SET show a range of –4.6 to 0.0 tCO_2 eq./ha/year and 4.7 tCO_2 eq./ha/year for the restored and control part, respectively (Table 13).

Table 13 – The output of the SET for the minimum and maximum values of CO_2 flux, based on the present GEST-types for restored and control sites of the Submarginal ecotope Cloncrow Bog 2021

SET Output for CO_2 - 2021	**GHG flux (tCO_2 eq./ha/year)**	**GHG flux (tCO_2 eq./ha/year)**		**GHG flux (tCO_2 eq./ha/year)**	**GHG flux (tCO_2 eq./ha/year)**
Restored	**min**	**max**	**Control**	**min**	**max**
Submarginal	-4.6	0	Submarginal	4.7	

2.5.2. Estimation with DST model

The control and restored areas are monitored in 2021. Water Table Depth (WTD) was recorded from piezometers set-up in the control and rewetted areas. Measurements are done every 10 minutes. Measurements show that the rewetting involves an important increase of the water table depth which is close to the surface most of the year. WTD only decreases during the summer.

The solar radiation (PPFD) is also recorded from a weather station set-up on the site.

Fluxes of carbon (NEE) are both calculated for the control and the rewetted submarginal areas. These calculations include the estimation of the respiration fluxes (RECO) according to water table depth and air temperature, whereas GPP is calculated according to the PPFD monitored on the site.

For the control area, the peatland behaves as a carbon source with the emission of about + 486 g CO_2/m^2/year . Peatland emits all along the year, with only short exceptions during the summer period. For the rewetted area, the peatland generally behaves as a carbon sink. The fluxes are negative and about 300 g CO_2/m^2/year are absorbed.

Table 14 – The output of the DST for the CO_2 fluxes, for the restored and control sites of the Submarginal ecotope Cloncrow Bog 2021 (negative value=uptake / positive value = emissions)

	Restored scenario: C-emissions from soil (tCO_2/ha/year)	**Control scenario: C-emissions from soil (tCO_2/ha/year)**
Submarginal ecotype (From year 2021)	-3.00	+4.86

2.5.3. Aligning the Peatland Code to the site

The baseline habitat of Cloncrow Bog is a drained lowland raised bog dominated by Calluna vulgaris, sedges and *Sphagnum* mosses in wetter areas, as such has been assigned the 'Drained bog

(Grass/heather)' category in the peatland code. It's target habitat following rewetting and restoration is Active Raised Bog and this corresponds most closely to the Peatland Code category of 'Rewetted modified bog. The restoration is forecast to bring an overall CO_2e benefit of 3 tCO_2 eq./ha/year.

Table 15 - The Peatland Code categories and Emissions Factors associated with the Starting and Restored Habitat Type – Cloncrow Bog

Control plots			**Restored plots**		
Starting habitat	**Peatland Code condition category**	**Peatland Code Emissions Factor tCO_2 eq./ha/year**	**Target habitat**	**Peatland Code condition category**	**Peatland Code Emissions Factor tCO_2 eq./ha/year**
Raised bog (drained)	Drained bog (Grass/heather)	3.32	Active Raised Bog	Rewetted Modified Bog	0.32

2.6. De Wieden, the Netherlands

Data on water table depth and vegetation is not measured in De Wieden. Therefore, the SET could not be applied to this site.

2.6.1. Aligning the Peatland Code to the site

The baseline habitat of De Wieden is a terrestrialized former peat pits that have naturally forested with the surface layer above the water table, as such has been assigned the 'Modified fen' category in the peatland code with a water table of 13 cm below (the maximum in this category). There is also open water area where the foreshore is being constructed, this has no emissions factor category. The target habitats following rewetting are Quaking Mire/Rich Fen in the former terrestrialized peat pits and naturally recolonized reed beds in the foreshore. The peat pits correspond most closely to the Peatland Code category of 'Modified fen', this is the same as the baseline category but the maximum water table of -5 (5 cm above the peat surface) has been used. although no category exists for the reed bed habitat. The restoration is forecast to bring an overall CO_2e benefit of 1.73 tCO_2 eq./ha/year

Table 16 - The Peatland Code categories and Emissions Factors associated with the Starting and Restored Habitat Type – De Wieden

Control plots			**Restored plots**		
Starting habitat	**Peatland Code condition category**	**Peatland Code Emissions Factor tCO_2 eq./ha/year**	**Target habitat**	**Peatland Code condition category**	**Peatland Code Emissions Factor tCO2 eq./ha/year**
Forested fen	Modified fen	1.19	Rewetted fen	Rewetted fen	-0.54
Open water	N/A	-	Reed beds	N/A	-

2.7. Performance of models

The models and tools are used to describe the carbon fluxes at the interface between peatland and atmosphere in the case of the SET tool and DST. The emission values used in the Peatland Code also include fluvial carbon losses. The simulations concern both the control and the restored areas. As discussed in Chapter 1, each approach uses different inputs to estimate carbon fluxes. The equations or the approaches are also drastically different. It is not then surprising to have gaps between results.

However, these numerical results and their comparison with flux measurements raise several comments:

- At Little Wooden Moss, the control area is a bare peat. The SET and the DST are estimating that the ecosystem releases carbon in the atmosphere and the calculated values are quite similar. For 3 plots (C3, C4 and C6), the emissions range between 7 to 9 t CO_2 ha^{-2} $year^{-1}$, which is close to the SET estimations (between 1.3 and 9 t CO_2/ha/year). For the 3 other plots, the DST estimations are a little bit higher, but always in the same magnitude. These fluxes are mainly dependent on the water table depths and the air temperature. Indeed, for this ecosystem, the contribution of the GPP to the Net Ecosystem Exchange can be considered as negligible. The fluxes are mainly due to respiration fluxes and in this specific case, the two models are consistent. The Peatland Code suggests a larger value of 17.72 t CO_2eq./ha/year, however, this value includes fluvial fluxes and examination of the direct CO_2 losses that site behind this (see Evans et al., 2022) indicates a gas flux of 5.44 t CO_2/ha/year which is close to the values predicted by SET and the DST.
- At Little Wooden Moss, the carbon fluxes estimated by the SET for the restored area are quite large, with a potential uptake but also a release of carbon in the atmosphere. The same tendency is observed with the DST since some areas behaves as carbon source (R2 and R5), whereas the other behave as carbon sink (R1, R3, R4, R6). Most of the DST estimations for each area are in the range of carbon flux proposed by the SET. The Peatland Code suggests a much smaller emission for the restored area of 0.32.
- The SET results for the control and restored areas of Cloncrow bog show similar predictions as the results of the DST. The same tendency is observed: the control area releases about 4.7-4.8 t CO_2/ha/year, whereas the restored area is storing carbon. The DST estimation is in the uptake range proposed by the SET. The Peatland Code is close to the other tools with a value of 3.32 tCO_2eq./ha/year for control but predicts a small loss of 0.32 tCO_2eq./ha/year, both of these include fluvial fluxes.
- The SET results for the control and restored areas of La Guette site show similar predictions as the results of the DST. The same tendency is observed: the restored area sequesters about 3 tCO_2/ha/year, whereas the control area is releasing carbon. The DST estimation for the control area is a little bit higher than the one proposed by the SET. The Peatland Code predicts a net C loss for the Modified Fen control of 0.16 and an uptake of -0.43 for the raised water table Modified Fen restored situation, again this includes fluvial C losses. However, inspection of the UK emissions factors behind the total value suggests a small CO_2 sink of 0.69 tCO_2eq./ha/year. For this site, high-frequency measurements are also carried out by an Eddy-covariance tower set-up on the site. These measurements show that the site behaves as a Carbon source releasing in the atmosphere between 1.83 to 11 tCO_2/ha/year. DST and SET estimations are consistent with measurements.
- For the Belgium site (Vallei van Zwarte Beek), the fluxes are mainly influenced by the vegetation type and the calibration of the DST model was complex due to the difficulty to link to chamber measurements. With DST, the fluxes are ranging between + 6.7 tCO_2/ha/year (estimated in 2021, a wet year) and + 24 tCO_2/ha/year, (estimated in 2020, a dry year). In 2022, based on calculations on the first half year, the estimation is about 11 tCO_2/ha/year. The SET

model results for the control and restored sites of Zwarte Beek are over a more restricted range, between 12 and 14 tCO_2/ha/year. The Peatland Code suggests overall CO_2eq. losses of 15.88 tCO_2 eq./ha/year for the control and 3.31 tCO_2 eq./ha/year for the restored area.

- Large differences between the two models are observed for the Winmarleigh site. For the control pasture area, a carbon release of 4 tCO_2/ha/year for DST against 46 tCO_2/ha/year for the SET). For the restored Carbon Farm area, the DST predicts carbon release whereas SET predicts carbon uptake. The reason could be that the DST model was calibrated during the establishment year of the vegetation. Some adjustments can be made in order to improve the calculations. The Peatland Code suggests an overall C loss of 22.00 tCO_2 eq./ha/year for the pasture and a small loss of 0.32 tCO_2 eq./ha/year for the restored Carbon Farm.

3. Model improvements

The SET showed lower CO_2 fluxes for two sites (La Guette and Zwarte Beek), this might be due to the small difference in median water table depth between control and restored sites. In these sites, the difference of median water table depth was estimated to be 10 cm, which does not yield different results when using the SET. Differences between control and restored are more likely seen when a different vegetation type is present in control/restored and when the water table depth correspond to these vegetation types (and thus GEST types). The SET would be applied easier if water table depths were measured independently for both control and restored sites.

The difference in results of the models for Little Woolden Moss might be due to the companion planting. Planting can lead to a mismatch between vegetation present and soil and water conditions, which violates the GEST's underlying ideas that vegetation reflects soil and water conditions. Also the vegetation created with companion planting does not fit very well with vegetation types in the GEST. Therefore, these predictions paint a skewed picture of the GHG flux situation. Adding a new GEST type for Carbon farms or companion planting (based on field data) might improve the model results for this site.

The DST was developed with the goal to predict the carbon fluxes at the interface between peatland and atmosphere. It is based on the estimation of CO_2 fluxes due to the respiration of the ecosystem and to the vegetation. According to these first results, the respiration of the ecosystem based on the water table depth seems to be well simulated by the code. One limitation today corresponds to flooded conditions. Indeed, our model was mainly developed for a water table depth lower than the surface. The model could be improved by extrapolating to flooded conditions. It could be then used for open water systems like for the Dutch site.

The second part of the calculations with the DST corresponds to the estimation of the gross primary production (GPP). Two limitations can be identified concerning these calculations:

- A vegetation index: the GPP calculations are mainly based on two parameters i.e. the Photosynthetic Photon Flux Density (PPFD) and the air temperature. These two parameters are included in the equations and they have been calibrated thanks to chamber measurements performed during the project. However, in some cases, this calibration occurs during the establishment period of the vegetation. Since this period, the vegetation grows and the percentage of coverage or the vegetation volume drastically change. A vegetation index could be suitable for some vegetation types.

- The number of vegetation types: the model was developed in priority for the sites of the CARE-PEAT project. Therefore, we mainly have equations and defined parameters to calculate GPP fluxes related to the vegetation of these specific sites. On this topic, the DST offers less opportunities than the SET. But, it could be easy to add other vegetation types.

The Peatland Code categories are broad and, in some cases, don't closely fit the specific peatland and vegetation type. Further disaggregation of peatland types may be possible as more field data becomes available with greater clarification between categories, for example: Rewetted Fen vs Modified Fen. Paludiculture options are not yet available in the Peatland Code due to a lack of UK data in that category.

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