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Quantifying ecosystem services of rewetted peatlands – the MoorFutures methodologies

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ABSTRACT

In 2011, MoorFutures® were introduced as the first standard for generating credits from peatland rewetting. We developed methodologies to quantify ecosystem services before and after rewetting with a focus on greenhouse gas emissions, water quality, evaporative cooling and mire-typical biodiversity. Both standard and premium approaches to assess these services were developed, and tested in the rewetted polder Kieve (NE-Germany). The standard approaches are default tier 1 estimation procedures, which require little time and few, mainly vegetation data. Based on the Greenhouse gas Emission Site Type (GEST) approach, emissions decreased from 1,306 t CO_2e in the baseline scenario to 532 t CO_2e in the project scenario, whereas 5 years after rewetting they were assessed to be 543 t CO_2e per year. Nitrate release assessed via Nitrogen Emission Site Types (NEST) was estimated to decrease from 1,088 kg N (baseline) to 359 kg N (project), and appeared to be 309 kg N per year 5 years after rewetting. The heat flux – determined with Evapotranspiration Energy Site Types (EEST) – decreased from 6,691 kW (baseline) to 1,926 kW (project), and was 2,250 kW per year 5 years after rewetting. Mire-specific biodiversity was estimated to increase from very low (baseline) to high (project), but was only low 5 years after rewetting. The premium approaches allow quantifying a particular ecosystem service with higher accuracy by measuring or modelling. The approaches presented here have been elaborated for North-Germany but can be adapted for other regions. We encourage scientists to use our research as a model for assessing peatland ecosystem services including biodiversity in other geographical regions. Using vegetation mapping and indicator values derived from meta-analyses is a cost-efficient and robust approach to inform payment for ecosystem services schemes and to support conservation planning at regional to global scales.

1. Introduction

Intact peatlands provide many important ecosystem services, including climate regulation through carbon sequestration and storage, water regulation, nutrient retention, and provision of wildlife habitat (Joosten & Clarke, 2002, Parish et al., 2008, Tanneberger et al., 2020). Despite their importance, healthy peatlands are worldwide being lost and degraded at the alarming rate of c. 500,000 ha annually (UNEP, 2022). Peatland degradation is releasing about 2.5 gigatonnes of CO_2e per year (incl. peat fires) and causes a loss of many other key ecosystem services. Therefore, international agreements such as the UN Convention on Biological Diversity (CBD), the UNFCCC and the Ramsar Convention have identified peatland conservation and restoration as a priority action and a key contribution towards reaching climate and biodiversity targets (IPCC, 2014, UNEP, 2022).

One approach to tackle the degradation of peatlands are payments

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for ecosystem services (PES). An effective and efficient PES scheme could correct and create markets through capturing benefits of and raising new funds for peatland restoration (Wichmann et al., 2015). Of the many ecosystem services that peatlands provide, until now only their climate regulation function has been put to the market, with the voluntary carbon market actively pursuing emission reduction projects (Tanneberger & Wichtmann, 2011, Joosten et al., 2015, Reed et al., 2022). Since March 2010, peatland projects are possible under the Verra/Verified Carbon Standard (VCS) (Emmer & O'Sullivan, 2011), and in 2011 the regional MoorFutures scheme issued the first carbon credits from peatland rewetting worldwide in Germany (Joosten et al., 2015, COWI et al., 2021).

The commodification of climate services carries the risk of reducing the value of peatlands to their climate services while neglecting or even damaging other ecosystem services. In a review of ten carbon farming standards, five approaches were identified that also claim to safeguard or enhance biodiversity, but none adequately promotes or prevents negative impact on biodiversity (Scheid et al., 2023). Including other ecosystem services including biodiversity would give peatland carbon credits a competitive advantage against (potentially cheaper) other carbon credits (Buck & Palumbo-Compton, 2022).

Quantification and commodification of ecosystem services critically depends on the quality of the underpinning science. While we may understand key ecological processes, quantifying relationships in a format suitable for commodification is challenging (Evans et al., 2014). It is currently being pursued in a wide range of initiatives, including e.g. the EU's work on ecosystem accounting systems (Petersen et al., 2018, La Notte et al., 2017), and the Science-Based Targets for Nature (SBTN), through which companies may determine and address the environmental impacts across their value chains using the best available science. SBTN not only points to which impacts, such as deforestation and pollution, to avoid and reduce but also how to increase positive ones, including watershed restoration and rehabilitation of degraded land (SBTN, 2023).

Methods for quantifying ecosystem services from natural, undrained peatlands have been suggested by e.g. Cusens et al. (2023) for mires in Norway, Vermaat et al. (2020) for Nordic catchments, and Langan et al. (2019) for a tropical peatland in Uganda. Few studies have quantified ecosystem services related to the rewetting of degraded peatlands (e.g. Knieß et al., 2010 for a fen in North Germany, Law et al., 2015 for a tropical peatland, Liu et al., 2023 for Dutch peatlands with dairy farming). In this paper, we have assessed ecosystem services provided by a MoorFutures site before and after rewetting, using criteria and approaches of the Verified Carbon Standard VCS (Bonn et al., 2014a). We focus on three services associated with peatland rewetting: Water quality improvement, evaporative cooling, and enhancement of mire-specific biodiversity (Evans et al., 2014, Bonn et al., 2014b). Other services, e. g. flood control, largely depend on the position of a peatland in the catchment and are therefore not considered. We compare the provision of ecosystem services in a 'business-as-usual' baseline scenario and the project scenario, which describes the assumed condition of the peatland after rewetting. The project scenario is subsequently evaluated with the condition of the peatland five years after rewetting. We present both standard and premium approaches to assess the effects of peatland rewetting on ecosystem functions and the consequent provision of ecosystem services.

2. Material and methods

2.1. Study site and hydrological network

The project area covers 54.4 ha with an average peat depth of 3 m and is located in Kieve polder (65 ha) in the southern part of the Müritz district in the upper course of the Elde river, Northeast-Germany (Fig. 1). Mean annual temperature is 8.8 °C, mean annual precipitation 591 mm (DWD, 2023). A small part in the north of the polder is forested with alder and pine (IHU, 2003). Around 49 ha were used for agricultural purposes as grassland prior to rewetting (July 2012). At that time, the water level in the polder was kept at 50–70 cm below ground level during summer by pumping surplus water into the Elde. Due to this long-term drainage, the uppermost peat horizon of the study site is degraded (earthified) (Couwenberg et al., 2015).

The above-ground catchment area of Kieve polder is 366.2 ha large. The catchment is crossed by the Elde river, which flows through the area

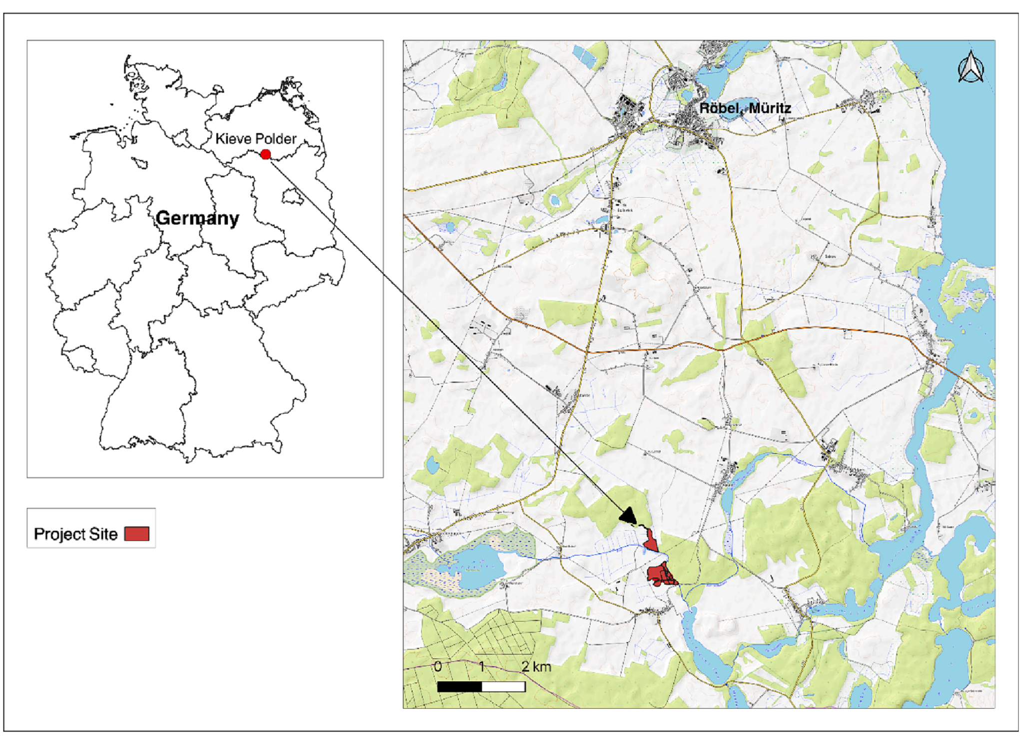

Fig. 1. Location of the study site Kieve polder in Northeast-Germany.

from west to east and turns south with an almost right angle at the eastern border of the catchment. Around 275 ha of the catchment are located north of the Elde and the remaining 91 ha lie to the south. Both parts of the catchment are assumed to be hydrologically connected, even if water exchange can only occur via a culvert under the Elde. Surface elevation of the above-ground catchment ranges from 63 m HN to 68 m HN and was – together with the water surface in ditches and adjacent water-bodies – determined with a levelling device to construct a digital elevation model (IHU, 2004). The catchment is almost entirely under agricultural use, predominantly as grassland. The upstream catchment of the Elde river (13,840 ha) is an undulating ground moraine landscape and is hydrologically separated from the Kieve polder by the river dikes (IHU, 2003, 2004).

2.2. Vegetation mapping

Vegetation was mapped in summer 2010 (Couwenberg et al., 2015). Vegetation units were delineated visually using GPS, and documented by three random 5 x 5 m vegetation relevés each (N = 48) using the Braun-Blanquet scale (Dierschke, 1994). On the basis of the presence or absence of ecological-sociological species groups (Mueller-Dombois & Ellenberg, 1974) and the cover and constancy of species (Dierschke, 1994) with particular regard to aerenchymous 'shunt species', the relevés were manually ordered to non-hierarchical vegetation types (Couwenberg et al., 2011). The vegetation was mapped again using the same method in 2015, i. e. 5 years after rewetting (Couwenberg & Michaelis, 2015).

2.3. Baseline and project scenarios

Two scenarios were compared for the quantification of ecosystem services:

- The *baseline scenario* describes what the future development of the area would look like during the project crediting period (50 years) if the rewetting project was not carried out. Up until the approval of the rewetting plans, the polder was subject to drainage-based agricultural use with deep drainage (water tables 50–70 cm below surface, soil moisture class 2+/-, Joosten et al., 2015), and it is plausible that this use would have continued (Schroeder, 2012).
- The *project scenario* anticipates that the rewetting project is carried out. This would involve dismantling of the pumping station, dams and pipe culverts, installation of solid trench dams for water retention and several other measures. Based on the digital elevation model (IHU, 2004), a long-term median water table between + 10 cm and -10 cm relative to surface (soil moisture class 5+) is expected to be attained on half of the area (25.5 ha), one of -5 to -20 cm (4+) on 11.7 ha, and one of -15 to -45 cm (3+, Joosten et al., 2015) on 17.3 ha after rewetting. In this scenario, no agricultural use is expected except for peat-preserving (paludiculture) or weakly peat-degrading agricultural use (cf. Tanneberger et al., 2022).

2.4. MoorFutures methodologies – standard approach

MoorFutures employs four vegetation-based methodologies with each two accuracy levels to assess ecosystem services including biodiversity in peatland restoration projects (Table 1). The standard approach requires little time and few data and is – when conservatively used – in most cases sufficient for quantifying ecosystem services and generating credits (Joosten et al., 2015). The premium approach allows quantifying most ecosystem services with higher accuracy, but also with higher costs.

The Greenhouse gas Emission Site Type (GEST) approach allows to assess peatland greenhouse gas fluxes in Central Europe without comprehensive direct on-site gas measurements (Couwenberg et al., 2011, Joosten et al., 2015). GESTs are based on a meta-analysis of measured annual greenhouse gas fluxes in relation to site parameters like water table, trophic level, soil type, acidity and vegetation composition. Of all abiotic parameters, mean annual groundwater table turned out to be the best single explanatory variable for CO_2 and CH_4 fluxes. Therefore, GESTs are based on soil moisture classes with associated mean annual groundwater table and use vegetation as indicators of these classes. Special attention is paid to the occurrence of aerenchymous plants, which may strongly influence CH_4 emissions on wet sites (Joosten et al., 2015). The procedure for assigning greenhouse gas flux values to vegetation types is described in Couwenberg et al. (2011) and Joosten et al. (2015). To ensure conservativeness, N_2O emissions and (often high) CH_4 emissions from ditches are not considered in the baseline scenario. Low best estimates are used for the baseline, high estimates for the project scenario.

Table 1
Standard and premium approaches for quantifying ecosystem services including biodiversity in the MoorFutures methodologies.

Effect	Standard approach	Premium approach
Greenhouse gas emission reduction	GEST approach (Greenhouse gas Emission Site Type) in t CO_2e ha^{-1} y^{-1}	Direct measurements in t CO_2e ha^{-1} y^{-1}
Water quality improvement	NEST approach (N Emission Site Type) in kg N ha^{-1} y^{-1}	Modelling with WETTRANS (in kg N ha^{-1} y^{-1}) and PRisiko in kg P ha^{-1} y^{-1}
Evaporative cooling	EEST approach (Evapotranspiration Energy Site Type) in W m^{-2} or kWh ha^{-1} y^{-1}	Modelling with AKWA-M® in W m^{-2} or kWh ha^{-1} y^{-1}
Increase of mire-typical biodiversity	BEST approach (Biodiversity Evaluation Site Type)	Measuring/assessing based on indicator species/groups

The Nitrogen Emission Site Type (NEST) approach estimates nitrogen (N) *release* of a peatland at the site level. Nitrogen release correlates with drainage depth, either linearly (van Beek et al., 2007) or with deeper drainage exponentially (Behrendt et al., 1993). In peatlands, vegetation indicates water table and land use intensity in an integrated way. The NEST approach thus uses vegetation types as indicator of nitrogen losses for which default values where derived from studies in areas with similar climate conditions (see Joosten et al., 2015 and Annex A). The NEST approach assumes strongly simplified water tables and mean annual N release values and is in our case based on minimum and average values reported for N leaching from fen peatlands in North-western Germany (Scheffer & Blankenburg, 2002, Tiemeyer & Kahle, 2014). This simplification ensures that release in the baseline scenario is not overestimated. For fen peatlands under high intensity use, significantly higher releases have been measured than the default values used here (Joosten et al., 2015). The calculations for Polder Kieve are based on the vegetation mapping for the GEST assessment.

The provision of robust estimates of nitrogen *removal* after rewetting is obstructed by the heterogeneity of site parameters and their relationships. Rate and efficiency of nitrogen removal (by uptake and denitrification) depend on the N concentration and water volume of the input water from the catchment, and on vegetation, soil properties and waterflow pattern in the rewetted site (Land et al., 2016, Walton et al., 2016). The interaction between these and additional properties of the wetland and the catchment area (e.g. history, relief, geographic position, temperature) leads to a complex picture that can hardly be approximated by a simple proxy. Therefore, an additional component (NEST + R) applies a statistical correlation determined in Sweden (Strand & Weisner, 2013) and calculates N removal (R_N) from the N load from the catchment (F_N) using the relation $R_N = -5 \times 10^{-7} F_N^2 + 0.0541F_N$. The calculated values are very conservative, because temperature, which is a key factor in denitrification, is lower in Sweden than in northern Germany. Analysis of a larger dataset (Reichelt, 2019 and Annex B) showed that peatlands on average showed a higher nitrogen removal efficiency (22 %) than found by Strand & Weisner (4 %). A 22 %

removal efficiency for peatlands may be assumed when:

1. water is widely and evenly distributed over the entire peatland area;

2. the entire peatland is covered by productive helophytes (e.g. reeds, sedges), and

3. total N input (atmospheric deposition + direct fertilization + inflow from catchment + all other N-inputs) is below 100 g m^{-2} y^{-1}.

If one of the above criteria is not fulfilled, N removal efficiency should conservatively be taken as 4 % (cf. Strand & Weisner, 2013).

A simple approach to assess phosphorous (P) retention (or release) similar to the NEST approach has not yet been developed (see also section on premium approaches).

The Evapotranspiration Energy Site Type (EEST) approach quantifies the net thermal energy (sensible heat flux [H] and soil heat flux [G]) as the difference between net radiation (Rn) and the latent heat flux (L) (cf. Edom, 2001, Edom et al., 2010) in a model-based matrix of vegetation types and specific groundwater table depths (see Joosten et al., 2015 and Annex C). The difference between the energy balance components and their area-weighted averages provides the annual average amount of energy that does no longer contribute to the warming of the lower atmosphere. In order to ensure conservativeness, the dampening effect of wet areas on temperature amplitudes is neglected by using annual averages (neglecting both diurnal and seasonal variation in evaporation,) as well as the better thermal conductivity of moist vs. dry peat. Additionally, heat production due to peat oxidation is neglected in the baseline scenario.

The Biodiversity Evaluation Site Type (BEST) approach uses regionally accepted biodiversity value assessment procedures, which are slightly modified if necessary. Hammerich et al. (2022) developed an indicator-based tool to assess mire-specific biodiversity in Brandenburg (Northeast Germany). By assessing the species, biocoenosis and ecosystem level of mire-specific biodiversity with 5 points each, an overall evaluation ranging from 0 (no mire-specific biodiversity) to 15 points (very high mire-specific biodiversity) is reached (Annex D). The species level biodiversity value is based on the number of mire-specific vascular plants and mosses. Mire-specific and -typical vegetation types and habitats (habitat diversity) and their position in a peatland network (habitat connectivity) are used to assess the biocoenosis level. The ecosystem level is rated on the prevailing degree of degradation of the topsoil peat and on the soil moisture class. The BEST values can be largely determined using the vegetation data collected for the GEST assessment – i.e. no or little additional collection of data is required. To ensure conservativeness, high estimates for the baseline and low estimates for the project scenario are applied, provided that the assignment of category leaves room for interpretation.

2.5. MoorFutures methologies – premium approach

Compared to the standard approaches, the premium approaches require more time and data, but also produce more accurate results (Table 1). The premium approaches are well suited for quantifying services that are central to the offered credits and that allow asking a higher market price to cover the additional costs (bundling; Joosten et al., 2015). Another option is to sell the respective ecosystem services separately (stacking).

Günther et al. (2018) tested the profitability of including direct measurements of *greenhouse gas fluxes* for a range of rewetting costs and vegetation development scenarios based on a hypothetical MoorFutures project. In almost all scenarios, GEST assessments underestimated emission reductions compared to direct measurements. Including direct measurements was lucrative in > 50 % of all vegetation development/rewetting cost combinations; profitability was achieved at rewetting costs of ~ EUR 5,400 ha^{-1} upward. More sophisticated GHG measurements became profitable at twice these rewetting costs. Although the cost of direct gas flux measurements is higher compared to GEST assessments, they may increase reliability and buyer confidence and allow higher prices (Günther et al., 2018).

The premium approach for assessing *water quality improvement* considers peatland nutrient dynamics in their landscape-hydrological context. This may at times result in significantly higher calculated removal rates because denitrification rates are strongly affected by N input from the catchment (e.g. Kieckbusch, 2003 reporting a removal of 132 kg N ha^{-1} y^{-1} in a rewetted, surface flow dominated peatland in NW Germany, Hoffmann & Baattrup-Pedersen, 2007 reporting a removal of 254 kg N ha^{-1} y^{-1} in rewetted river valley peatlands). Accounting for nitrogen removal is only rudimentary in the NEST approach. Models allow taking into account landscape-hydrological aspects next to site-specific internal processes. We used the decision-support models WETTRANS (Trepel & Kluge, 2004) for calculating nitrogen removal and PRisiko (Trepel, 2004) for assessing the risk of an increased phosphorus concentration in the water course downstream of the rewetted area. The WETTRANS model assumes that the water table in areas that are not flooded in the project scenario is about -20 cm. The PRisiko model assumes that the total releasable phosphorus pool of the rewetted site is discharged to the adjacent water course. A default 0.1 mg l^{-1} was used for the current concentration of P in the river Elde, as no direct measurements are available for the studied area.

WETTRANS requires a physical map of the catchment as well as maps of actual and future vegetation, drainage depths and land use and information about peat soil depth of the project site. PRisiko requires information on the size of the basin, the mean drainage depth and the land use intensity, as well as on the size of the catchment area. Such data are usually gathered during the planning stage of rewetting in Germany and have been available for the study site from IHU (2004) and Couwenberg et al. (2015). In order to ensure conservativeness WETTRANS assumes low input of N from outside and is additionally equipped with an error tool for quantifying calculation uncertainties. In PRisiko, P release in the project scenario is estimated at the high end of the range (see above).

The premium approach for assessing *evaporative cooling* is modelling, e.g. with AKWA-M®. The AKWA-M® model (Münch, 2004, Edom et al., 2010) is a modular water balance model, which provides a range of evaporation approaches, both empirical ones, e.g. that of Romanov, which calculates peatland evapotranspiration considering its direct dependency on groundwater table depth (Edom, 2001), and approaches with a stronger physical base, e.g. that of Penman-Monteith. The model calculations result in a range of water level dependent evapotranspiration rates for small peatlands, where latent heat flux L is highly affected by advection, to large peatlands where advection only influences L at the boundaries. Similar to the standard approach, also the premium approach neglects the dampening effect of wet areas on temperature amplitudes, the better thermal conductivity of moist vs. dry peat, and heat production by peat oxidation in order to ensure conservativeness.

The premium approach for assessing *mire-typical biodiversity* measures the number of indicator species and evaluates them using an indicator species model. In northeastern Germany, indicator species models for evaluating peatlands are currently available only for birds and selected groups of arthropods (Görn & Fischer, 2011). To ensure conservativeness, the gain in indicator species is underestimated in the project scenario except when colonisation is highly likely (e.g. because the species is present in adjacent areas).

3. Results

3.1. Greenhouse gas emission reduction

The GHG emissions in the *baseline scenario* are estimated conservatively at 24 t CO_2e ha^{-1} y^{-1}, resulting in total emissions of 1,306 t CO_2e y^{-1} (Table 2, Fig. 2). The value of 24 t CO_2e ha^{-1} y^{-1} lies at the lower end of the range for intensively used 2+/- sites, and the actual flux is likely to be significantly higher (~35 t CO_2e ha^{-1} y^{-1}; Drösler et al., 2013, Tiemeyer et al., 2020). The difference of about 600 t CO_2e y^{-1} (>45 % of total emissions) highlights the conservativeness of the approach

Table 2
Ecosystem services in the baseline and project scenarios (Couwenberg et al., 2015), and 5 years after rewetting (Couwenberg & Michaelis, 2015), based on site types and their respective areas in Kieve polder. Site types, Greenhouse gas emission site type (GEST), Nitrogen emission site type (NEST) and Evapotranspiration energy site type (EEST) after Joosten et al. (2015).

Scenario	Area (ha)	Site type			GEST	NEST	EEST
		Soil moisture class		Vegetation type	t CO_2e ha^{-1} y^{-1}	kg N/ha y^{-1}	kW ha^{-1} **
Baseline	54.4	moderately moist	2+/-	High intensity grassland	24.0	20	123
Total	**54.4**				**1,306 t CO_2e y^{-1}**	**1,088 kg N y^{-1}**	**6,691 kW**
Project	17.3	moist	3+	Tall forb meadows	15.0	10	79
	11.6	very moist	4+	Meadows (Carex)	3.5	5	46
	25.5	wet	5+	Reeds	8.5	5	1
Total	**54.4**				**532 t CO_2e y^{-1} ***	**359 kg N y^{-1}**	**1,926 kW**
5y after rewetting	7.3	moist	3+	Forb meadows	15	10	79
	14.2	very moist/moist	4+/3+	Meadows	12.5	5	46
	12.3	very moist	4+	Meadows	7.5	5	46
	5.8	very moist	4+	Meadows (Carex)	4	5	46
	12.1	very wet/wet	6+, 5+	Reeds	9.5	5	1
	2.7	very wet	6+	Relict ditches	9.5	5	65
Total	**54.4**				**543 t CO2e y^{-1} ***	**309 kg N y^{-1}**	**2,250 kW**

*Total emissions (incl. 10 t CO_2e ha^{-1} y^{-1} methane peak emissions in the first three years after rewetting on 5 + sites).
** Total heat flux to the atmosphere.

(Table 2, Fig. 2).

In the *project scenario*, half of the area (25.5 ha) is expected to have a soil moisture class 5+ (Table 2, Fig. 2). For this area, next to the regular GEST value for 5+ sites of 8.5 t CO_2e ha^{-1} y^{-1}, additional methane emissions of 10 t CO_2e ha^{-1} y^{-1} are assumed for the first three years following rewetting ('initial methane peak', Couwenberg et al., 2015). The resulting figure of 18.5 t CO_2e ha^{-1} y^{-1} (740 kg CH_4 ha^{-1} y^{-1}) is at the upper end of the range of measured values for wet, eutrophic fen sites (cf. Couwenberg & Fritz, 2012). Significantly higher values were measured on strongly eutrophic sites with ~ 40 cm inundation (Glatzel et al., 2011, Drösler et al., 2013), which are, however, not expected here. In total, an average annual emission of 532 t CO_2e y^{-1} over the 50 years project period is assumed for the entire project area following rewetting (without the initial post-rewetting methane peak: 517 t CO_2e y^{-1}).

The corresponding emission reduction amounts to 789 t CO_2e y^{-1} or 39,438 t CO_2e over the 50-year project period (Table 3).

The vegetation types present 5 years after rewetting, when equally assigned to the GESTs as in Couwenberg et al. (2011), indicate a GHG emission of 543 t CO_2e y^{-1} for the entire project area (Table 2). This value deviates only slightly from the project scenario estimates. When extrapolated over 50-year project duration, the total emission reduction of 39,265 t CO_2e is consequently also very similar to the ex-ante (project) estimate of 39,438 t CO_2e (Table 3). Using updated GEST values results in a similarly small difference (Couwenberg & Michaelis, 2015).

3.2. Water quality improvement

The NEST approach indicates that in the *baseline scenario* 1,088 kg N y^{-1} will be discharged from the study site against 359 kg N y^{-1} in the *project scenario* (Table 2). Rewetting is thus envisaged to result in a reduction of 730 kg N y^{-1} (Table 3). In case of water inflow from the catchment in the project scenario, N removal may be assumed. For the area of soil moisture class 5+ (25.5 ha) and the 340.7 ha large catchment (total catchment 366.2 ha minus 25.5 ha) with an average N release of 10 kg ha^{-1} y^{-1} (i.e. a total load of 3,407 kg N y^{-1}), a removal of 185 kg N y^{-1} is estimated. Thus, on the basis of the NEST approach, rewetting results in a reduced N discharge of 915 kg N y^{-1} or 45,725 kg N over the 50 years project period (Table 3). Discharge 5 years after rewetting is slightly lower than in the project scenario (309 vs. 359 kg N y^{-1}; Table 2).

According to the WETTRANS model, rewetting the study site with water from the catchment reduces the N release to the surface water (i.e. the Elde river) with 6,029 kg N y^{-1}, which amounts to about 300 t N over the 50-year project period in the project scenario (Joosten et al., 2015).

According to the PRisiko model, the total project area may release 4.4 t P after rewetting (Joosten et al., 2015). As a result, the P concentration in downstream water courses will increase by less than 0.02 mg l^{-1} in the third year after rewetting and pollution risk is therefore regarded as being very low.

3.3. Evaporative cooling

The total heat flux to soil and atmosphere (H + G) in the *baseline scenario* is 6,691 kW. In the *project scenario*, due to wetter conditions and different vegetation, the total heat flux is only 1,926 kW. The total envisaged cooling effect as a result of rewetting is thus 4,765 kW (Table 2). Five years after rewetting, a total heat flux of 2,250 kW was assessed, i.e. a reduction compared to the baseline scenario of 4,441 kW (Table 3).

The AKWA-M® model shows a decrease of 37.7 GWh y^{-1} of energy as a result of rewetting with a mean cooling effect of 7.9 W m^{-2} (=79 kW ha^{-1} or 4,275 kW on 54.4 ha) in the project scenario (calculated 1997–2020 following the approach in Joosten et al., 2015).

3.4. Mire-specific biodiversity

The initial site assessment (Couwenberg et al., 2015) resulted in a very low mire-specific biodiversity value in the baseline scenario of 3 out of 15 points (Table 4). The value in the project scenario is 11 (high mire-specific biodiversity) and includes peat-forming conditions. In the verification 5 years after rewetting, the mire-specific biodiversity had increased by 4 points compared to the baseline scenario, resulting in 7 out of 15 points, which is, however, still low.

An evaluation of Kieve polder using indicator species is currently not possible because lack of data for the drained situation. For vascular plants and mosses, only the mapping data from 2010 are available, when water tables were already somewhat elevated. If a vegetation map of the polder in its drained condition were available, it could be used as a baseline scenario. Then, the difference in vegetation compared with the project scenario could be assessed using an indicator species model. However, an indicator species model for plants/mosses is also not available. Such a model does exist for birds and arthropods for the region, as well as unsystematic observations from the years 2012 and 2013 (Joosten et al., 2015). For the most part, these observations reflect a state of transition with high water levels in the first years following rewetting.

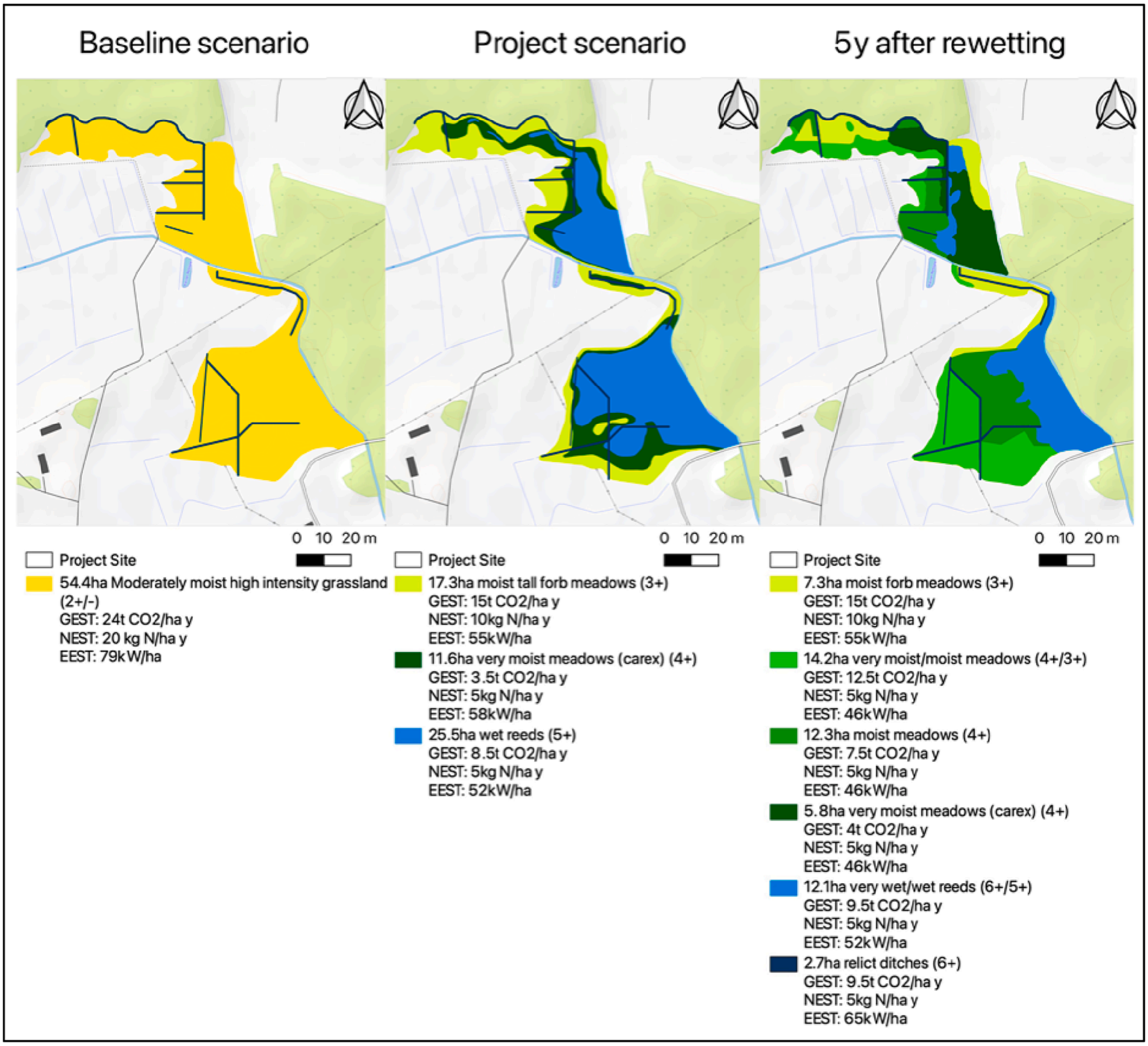

Fig. 2. Site types in Kieve polder and corresponding values used in the GEST, NEST and EEST approaches in the baseline scenario, in the project scenario, and in reality 5 years after rewetting.

Table 3
Difference between baseline (B) and project (P) scenarios and between baseline scenario (B) and 5 years after rewetting (R) for ecosystem services per year and over the entire project period of 50 years (rounded numbers, values derived from Table 2).

Difference		GHG emission reduction (GEST) t CO_2e	N release reduction (NEST) kg N	N release reduction (NEST + R) * kg N	Evaporative cooling (EEST) kW
B-P	Per year	789	730	915	4,765
B-P	Per 50 years	39,438	36,475	45,725	238,270
B-R	Per year	785	780	965	4,441
B-R	Per 50 years	39,265	38,975	48,225	222,055

* Total reduction after rewetting plus retention of 185 kg N y^{-1} in the project scenario (after Strand & Weisner, 2013).

4. Discussion

4.1. Overall rewetting outcome and comparison to other peatland types

In this study, the vegetation-based indicator approach and criteria for GHG emission reduction projects were transferred to other ecosystem services including biodiversity, and applied in the Kieve polder MoorFutures project area in NE-Germany. At Kieve polder, rewetting has worked out positively for all considered ecosystem services – GHG emission reduction, water quality improvement and cooling. Five years after rewetting, the assumptions made in the project scenario could be confirmed and the achievements proved to be either

Table 4
Mire-specific biodiversity for the baseline and project scenario and 5 years after rewetting based on Hammerich et al. (2022). See Annex D1 for classes and colour code.

	Baseline scenario	Value	Project scenario	Value	5 years after rewetting	Value
Species level						
Number of mire-specific vascular plants	0	0/5	≥ 4	2/5	1	1/5
Number of mire-specific mosses	0		0		0	
Biocoenosis level						
Plant formations	None	1/5	Tall sedge swamp (with creeping sedges); Tall sedge swamp (with caespitose sedges); Freshwater reed swamps; Reed swamps on riverbanks	4/5	Tall sedge swamp (with creeping sedges) Freshwater reed swamps	3/5
Special habitats	Solitary trees		Solitary trees; Hummocks; Hollows; Open water body; Areas without vegetation		Solitary trees: Open water body; Areas with no vegetation	
Integration into biotope network	yes		yes		yes	
Ecosystem level						
Soil moisture class (dominating)	2+/- (54,4 ha)	2/5	Mainly 5+	5/5	Mainly 4+	3/5
Degree of peat degradation (dominating)	Moderately degraded peat (earthified peat)		Non-degraded peat (currently forming)		Moderately degraded peat (earthified peat)	
Overall assessment	Value: 3/15 Very low mire-specific biodiversity		Value 11/15 High mire-specific biodiversity		Value 7/15 Low mire-specific biodiversity	

better or close to what was envisaged in the project scenario. Only with respect to mire-specific biodiversity, the value assumed for the project scenario had by far not been achieved, although a clear trend towards a higher value was observed.

Using vegetation and land use as key indicators, the GEST approach allows assessing GHG fluxes consistently and in a transparent manner. The approach is based on the conditions before rewetting, and on the potential of plant species to establish in the project area after rewetting. Further research on vegetation succession in drained and rewetted peatlands, in particular *meta*-analyses such as Klimkowska et al. (2019) and Kreyling et al. (2021), will help improving the prediction of vegetation development and associated GHG fluxes, both in the baseline and in the project scenario.

For water quality improvement, the NEST + R approach offers very conservative numbers and is adequate when this ecosystem service is addressed as a co-benefit. In case of selling specific nitrogen emission reduction or nitrogen removal credits, more elaborated models should be considered. Wetlands are known to have a high potential of denitrification (Strand & Weisner, 2013, Land et al., 2016, Walton et al., 2016, Cheng et al., 2020). As a general rule, promising sites for large reduction in nitrogen release have either a large catchment that is hydrologically connected with the rewetted site or low water tables in combination with high fertilizer application in the project area. A market for selling reduced nitrogen release to surface waters may develop to reach local targets derived from the EU Water Framework and Marine Strategy Framework directives (Trepel & Fischer, 2014, Joosten et al., 2015). Harvesting of vegetation will probably minimise potential P loss and plant biomass yield may promote circular economy value chains (Walton et al., 2016).

The cooling effect at a rewetted peatland can be compared with the anthropogenically caused radiative forcing by the emission of greenhouse gases. Globally, human-caused emissions have warmed the climate system with 2.72 (1.96 to 3.48) W m^{-2} in 2019 relative to 1750 (IPCC, 2021). Rewetting thus more than compensates for this change on the polder area (but only there). The evaporative cooling brought about by rewetting can therefore be considered high. This has also been shown by Worrall et al. (2019) for a bog 16 years after rewetting (2016). The rewetted peatland was 0.5 K cooler than the surrounding agricultural land on mineral soils, whereas it was 0.7 K warmer in 2000. This study has shown that anthropogenic land use change may cool a landscape and that functioning peatlands act as cool, humid islands within a warmer, drier landscape (Hemes et al., 2018, Hesslerová et al., 2019, Worrall et al., 2022).

The biodiversity value of the rewetted site deviates substantially from the project scenario 5 years after rewetting. MoorFutures aims to increase mire-typical biodiversity, i.e. the particular biodiversity that would occur without drainage, spontaneously, or under adapted land use. At all levels (species, biocoenosis, ecosystem), the mire-specific biodiversity value had increased 5 years after rewetting compared to the baseline scenario, but was still below the envisaged project values. This is consistent with studies assessing the development of rewetted fens over time: After rewetting the recovery towards the original fen vegetation is slow (Mälson et al., 2008) and helophytisation leads to a rather species-poor, tall-growing vegetation in many rewetted fens across temperate Europe (Kreyling et al., 2021).

In order to establish a standard integrating various ecological and social aspects, the approach developed for Kieve polder must be tested at other sites and adapted where necessary. Whereas GHG emission reduction is already strongly formalised (via the Global Warming Potential) and independent of location (GHG mix rapidly in the atmosphere), for other ecosystem services more formalisation towards a standardised metric is needed. Their value will, in contrast to that of GHG emissions, remain largely dependent on their spatio-temporal context (Joosten et al., 2015).

4.2. *Improvement and regional transfer of the MoorFutures methodologies*

MoorFutures successfully introduced the concept of carbon credits from peatland rewetting as a regional product. From this perspective, MoorFutures has provided the groundwork for the establishment of similar products in other regions. If the MoorFutures standard is transferred, the legal and administrative framework should be checked, and, where necessary, additional requirements should be integrated into the standard. The significance of particular peatland ecosystem services does not only depend on biophysical features, but also on their significance for society, at local, regional, and national levels. For example, Evans et al. (2014) identified three regulating services in a UK bog as having greatest value in this region (namely climate regulation, water quality regulation and flood regulation). By choosing appropriate methods, regional/national, scientifically accepted and well-established approaches to ecosystem service assessment should be used. The approaches presented here have been elaborated for North Germany but can be adapted for other regions.

In future carbon credit projects, both project duration and baseline selection should be critically discussed and carefully determined. A project duration beyond legally binding climate neutrality target years is at least questionable. The forward-looking baseline makes forward selling projects, such as those under the MoorFutures standard, and the allowances they generate very sensitive to unforeseen developments, e.g. binding prescriptions for peatland management in the EU Common Agricultural Policy (Good Agricultural and Ecological Condition GAEC2) or new regulations limiting ditch deepening leading to 'self-rewetting' of the sites. Therefore, ex-post remuneration of ecosystem services should be preferred.

The GEST approach was developed for the lowlands of Northwest Europe, and must be calibrated for other biogeographical and climatic zones. Calibration has been attempted for Belarus (Tanneberger & Wichtmann, 2011) and recently also the Baltic States (Jarašius et al., 2022). The key challenges for transferring the approach to other regions are the use of other vegetation typologies often not equally sharp in indication of site conditions and often a lack of direct flux measurements to calibrate vegetation indication. Generally, few targeted flux measurements suffice for calibration and filling gaps in the GEST matrix. Furthermore, the available flux data are growing rapidly. Research in the framework of carbon projects should improve the data underlying GHG assessments in a targeted fashion (Joosten et al., 2015).

The NEST approach was developed for the vegetation types of the Kieve polder, and can be applied to peatlands with moderate land use intensity across the north German lowlands. Nitrogen release from very intensively used land, which is common in the west, will be higher and, accordingly, NEST values would be higher. In the Netherlands, land use intensity is generally higher for sites with similar drainage depth, in Poland much lower (Joosten et al., 2015).

The EEST is essentially transferable to other regions, when climatic gradients are taken into account. Like net radiation, temperature and precipitation show a west-to-east gradient across Germany, which results in a similar gradient in evaporation, and thus in evaporative cooling. The lowest values are found for climate stations in the west, and the highest (and thus the largest cooling effect) in the east (Joosten et al., 2015).

The BEST approach can be applied elsewhere, by defining the mire-specific components (species, plant formations, special habitats, biotope networks) of the region addressed and analysing data from degraded to natural peatlands occurring within that region. A precondition is the availability of reference systems, which are in a (near-)natural state. The list of mire-specific plants and mosses provided in Hammerich et al. (2022) is valid for north-east Germany and could be used for the rest of Germany with slight modifications. A good basis for determining mire-typical and mire-specific species is provided by Joosten et al. (2017), who present the characteristic vascular plant and moss species of mires and peatlands in various European countries. Similarly, other levels can be transferred (Hammerich et al., 2022).

4.3. *Ecosystem services and biodiversity in current VCM and EU climate policies*

Globally, the voluntary carbon market (VCM) has experienced a significant growth in the past five years with an increase of around 252 % since 2017 (South Pole, 2022), while the demand for carbon credits could increase by a factor 5 to 15 by 2030, being worth up to 50 billion US dollar in 2030 (South Pole, 2022, McKinsey, 2021) and potentially reducing and removing 2.6 Gt of GHG emissions by then (World Economic Forum, 2023). Several reports suggest that there is a trend towards projects that include ecosystem services beyond cutting carbon emissions as part of their certification process (Scheid et al., 2023; Bloomberg, 2023, South Pole, 2022, ARC2020 2022). However, only a small fraction of the market covers agricultural land (Forest Trends' Ecosystem Marketplace, 2022). In the European Union, drained peatlands emit ~ 5 % of total GHG emissions (Tanneberger et al., 2020), and peatland rewetting and restoration is seen as a main category of carbon farming (McDonald et al., 2021a) with a high potential for GHG emission avoidance and potentially carbon removals (McDonald et al., 2021b).

To incentivise carbon removals, the European Commission (EC) published a *Proposal for a Regulation on an EU Certification for Carbon Removals* (COM, 2022). The Framework establishes rules to ensure high quality carbon removals within Europe and to trigger their upscaling, which could entail a significant market-based incentive for mitigation in the land sector. While focusing on carbon removals, the proposal deliberately includes emission reductions from biogenic carbon pools, placing organic soils in the heart of the Carbon Removal Certification Framework debate in Europe.

Another recent EC proposal relevant for peatland carbon markets is the Nature Restoration Law (NRL), which establishes targets to restore degraded land in the EU, including drained peatlands under agricultural use and peat extraction. In July 2023, the European Parliament voted for skipping the peatland targets. The outcome of the negotiations in the trilogue is still open.

We encourage scientists to apply our methodology as a model for assessing peatland ecosystem services and biodiversity in other geographical regions. Using vegetation mapping and indicator values derived from meta-analyses is a cost-efficient and robust approach to inform payment-for-ecosystem- services schemes and support conservation planning at regional to global scales.

CRediT authorship contribution statement

Franziska Tanneberger: Writing – review & editing, Writing – original draft, Funding acquisition, Formal analysis, Conceptualization. **Augustin Berghöfer:** Writing – review & editing, Funding acquisition, Conceptualization. **Kristina Brust:** Writing – review & editing, Formal analysis. **Jenny Hammerich:** Writing – review & editing, Formal analysis. **Bettina Holsten:** Writing – review & editing, Formal analysis. **Hans Joosten:** Writing – review & editing, Funding acquisition, Conceptualization. **Dierk Michaelis:** Writing – review & editing, Formal analysis. **Fiedje Moritz:** Writing – review & editing, Visualization, Formal analysis. **Felix Reichelt:** Writing – review & editing, Formal analysis. **Achim Schäfer:** Writing – review & editing, Funding acquisition, Conceptualization. **Aaron Scheid:** Writing – review & editing, Formal analysis. **Michael Trepel:** Writing – review & editing, Formal analysis. **Andreas Wahren:** Writing – review & editing, Formal analysis. **John Couwenberg:** Writing – review & editing, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

We have shared data that are not available in the cited references in the manuscript and in the Annexes.

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Appendix A. Supplementary data

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