Climate protection and nature conservation in peatland areas: How does this match with present day agricultural practice?

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SUMMARY

The northernmost German federal state of Schleswig-Holstein was selected as an example lowland area in central and western Europe with a high proportion of intensive agricultural use on peatlands that experience associated ecological and social functional problems. To get an overview of the current status of greenhouse gas (GHG) emissions and the nature conservation value of the vegetation, a state-wide calculation of GHG emissions from peatlands was carried out. For that purpose, a method was developed linking different data sources such as biotope surveys, land use categories and geographical units to allow the estimation of GHG emissions at the landscape scale. Potential rewetting scenarios were then extrapolated to reach the national reduction goals for 2030. The annual GHG emissions from peatlands in Schleswig-Holstein amount to about 2.9 Mt (CO_2-equivalent value). The highest emissions originate from intensively used agricultural areas. Abandoned and forested peatlands also have high GHG emissions, but their relative area is small. Vegetation types with conservation status (on fen peat) cover an area of only 650 ha, while bogs are present on 3,900 ha. To reach the reduction target, vast areas must be rewetted and agricultural use on peatlands has to be changed accordingly. We calculated that, in intensively used peatlands, such changes could lead to avoidance of GHG emissions (as CO_2-equivalent) up to 1.8 Mt yr^{-1}. This is more than twice the reduction target of the federal state.

KEY WORDS: biotope surveys, greenhouse gas emissions, land use, reduction potential, Schleswig-Holstein

INTRODUCTION

Under natural conditions, peatlands store and accumulate large amounts of carbon. After decades and centuries of land use intensification and drainage, they contribute considerably to global warming and thus belong to the largest human-induced sources of greenhouse gases (GHGs) worldwide (e.g. Joosten *et al.* 2016, Leitfeld *et al.* 2019). In Europe, Germany is one of the top CO_2-emitting countries. Although only about 5 % of Germany's land surface is covered by peatlands, the CO_2-equivalent (CO_2-eq) GHG emissions of these ecosystems are estimated at 53–55 Mt per year, corresponding to at least 6.7 % of total emissions nationwide (Tiemeyer *et al.* 2020, BMUV 2021). To reduce these high emissions, the German government has developed a national peatland protection plan which aspires to conserve, rewet and extend protected peatlands. The goal of the national peatland protection plan is to reduce annual GHG emissions from agricultural and forestry areas by at least 5 Mt (as CO_2-eq) by 2030 (BMUV 2021), and this peatland protection target fits into the nationwide strategy for reducing GHG emissions across the whole of Germany (Tanneberger *et al.* 2021a).

CO_2 emissions from peatlands can be calculated in different ways. Tanneberger *et al.* (2021a) followed Roßkopf *et al.* (2015) on area setting and Tiemeyer *et al.* (2020) on GHG emission factors to evaluate the effectiveness of stepwise sequential reduction scenarios in achieving the target of "net zero CO_2 by 2050" set by the Paris agreement of the United Nations Framework Convention on Climate Change (UNFCCC). The scenarios are based on changes in land use categories and the related mean annual water table levels. A different example of a large-scale reduction approach is based on the establishment of paludiculture on previously intensively used croplands and grasslands in Mecklenburg-Western Pomerania (Tanneberger *et al.* 2020b). Here, the so-called GEST method (Greenhouse Gas Emissions Site Types) of Couwenberg *et al*. (2008, 2011) and Joosten *et al.* (2013) is used to calculate the Global Warming Potential (GWP). This approach is based on a large database relating vegetation types with mean annual water level data (Koska *et al.* 2001). However, neither approach takes into account any detailed aspects of nature conservation, even though these are indispensable in avoiding conflicts between biodiversity and climate protection in the practical implementation of management measures. The present study tries to fill this gap by focusing on peatlands in the federal state of Schleswig-Holstein. This state is located in the very north of Germany and is an excellent example of a peatland-rich region with all of the ecological and socio-economic problems associated with intensive land use (e.g. Kimmel & Mander 2010, Zauft *et al.* 2010, Lamers *et al.* 2015, Poyda *et al.* 2016). To counteract negative human-induced effects on the ecosystem functions and services of peatlands, the state government introduced the so-called "state programme for biological climate protection" in 2021. Alongside a reduction in GHG emissions, the programme is aimed explicitly at nature conservation, which is compulsory for rewetting in restoration projects (BMUV 2021, MELUND 2021). To allow implementation of such programmes, comprehensive information about the current state of GHG emissions and the distribution of habitats relevant to nature conservation is needed. To obtain this we used a state-wide map of peatland areas (LLUR 2015) combined with results from a current biotope survey (LLUR 2019a) and additional areal vegetation information. The state-wide calculation of GHG emissions was based on the GEST approach (see above), whose area units represent different vegetation structures and thus allow alignment with biotope types to a certain extent.

This study pursues the following main targets:

- to develop a traceable method for linking calculations of GHG emissions with aspects of nature conservation on the landscape scale;
- to identify the peatland types with highest priority for reducing GHG emissions and those with highest nature conservation value;
- to disentangle potential conflicts between climate protection and nature conservation; and
- to compare different potential successional pathways for the reduction of GHG emissions.

METHODS

Study area

The current geomorphology of Schleswig-Holstein is the result of processes during two Ice Ages. The moraines of the older Saalian glaciation (300,000–130,000 BC) formed the western part, the so-called "Hohe Geest". The younger Weichselian (115,000–10,000 BC) glaciation formed the moraines of the "eastern hilly landscape" and its westward oriented meltwater deposits, called "Vorgeest" (LLUR 2015). The dominating soil type in the Hohe Geest area is brown earth with low nutrient availability, whereas the surface of the eastern hilly landscape consists of soil types developed from nutrient rich loamy soils. The prevailing soils of the Vorgeest are various podzols which originated from pure sand (LLUR 2019b). The climate in Schleswig-Holstein is suboceanic with mean annual precipitation 800–900 mm in the northwest and 550–700 mm in the southeast (LLUR 2020). These regionally different climate conditions and the heterogenous geomorphology of Schleswig-Holstein are main prerequisites for the development of diverse peatland types (LLUR 2015). The prevailing peatlands in the eastern hilly landscape area are terrestrialisation fens, which developed during the Holocene after melting of dead ice in kettle holes. Additionally, inundation mires along the courses of rivers are characteristic of this region (Schrautzer *et al.* 2016). The dominating mires of the adjacent Vorgeest are paludification mires (Trepel *et al.* 2017), which formed following sea level rise during the Holocene. In the Hohe Geest, inundation fens along brooks and small rivers are widespread. Furthermore, in both moraine areas, spring mires fed by base-poor or base-rich groundwater are typical peatland types. Due to locally increasing precipitation, extensive bogs occur in the transition zone between the marshland and Hohe Geest. A further series of bogs exists in the transition zone between the Vorgeest and the eastern hilly landscape (LLUR 2015).

Data acquisition

The distribution of peatlands in Schleswig-Holstein and the characterisation of their land use were derived from various data sources as described below.

State-wide distribution of peatlands

To determine the state-wide distribution of peatlands, the soil peatland database for Schleswig-Holstein was used (LLUR 2015). This database summarises information such as the geological overview map, the geomorphological map, the forestry site survey and the soil estimation of Schleswig-Holstein from approximately 430,000 cores. Only peatlands meeting the defined characteristics for Germany (Ad-hoc-Boden 2005), i.e. with a soil organic content above 30 % and a peat thickness greater than 30 cm, were considered. The databases of the Department for Soil Science of the State Agency for Agriculture, Environment and Rural Areas of the Federal State of Schleswig-Holstein were used to distinguish between fen peat and bog peat.

Land use and vegetation structure

In total, we obtained detailed information for 85 % of the peatlands in Schleswig-Holstein. Where detailed data about vegetation types were available, they were used preferentially for calculating GHG emissions and evaluating the nature conservation value of the systems. Otherwise, information from the database of the integrated Administration and Control System (IACS, "InVeKoS") was considered.

For vegetation characterisation, results of different surveys were collected. Firstly, the 2007–2012 Natura 2000 habitat survey (Flora-Fauna-Habitat (FFH) Directive; European Commission 2007), with an addition of data from repeat survey of a subset of the same areas to document changes in vegetation structure and distribution (LLUR 2019a). Secondly, all biotope types from a 2014–2019 survey in Schleswig-Holstein (LLUR 2019a). Although these data had not yet been fully released (status December 2019), more than 90 % (around 40,000 ha) of surveyed biotopes were available and could be used in the present study. Thirdly, a survey of raised bogs beyond the FFH Directive which was performed in 2009. This was done for areas which were not included in either the Natura 2000 habitat survey or the biotope mapping. Lastly, for characterising forests on peatlands, results for the distribution and ecological status of forest on peatlands in Schleswig-Holstein from a regional study (Schrautzer *et al.* 2021) were used, and GHG emission estimations and reduction opportunities of these ecosystems were calculated.

To complete the dataset, information from ATKIS (Topographic-Cartographic Information System – Digital Landscape Model) was used (AdV 2003). The ATKIS data were less detailed than the other sources but provided reliable information about agricultural use.

Data evaluation

All spatial information was handled with a Geographical Information System (Arc-GIS 10.7). To avoid data duplication and to obtain as much information as possible regarding the vegetation structure, a hierarchical approach was used. In the first step, the appropriate biotope types (see above) were assigned to phytosociologically defined alliances. These units were largely in accordance with the classified types of the European vegetation survey (Mucina *et al.* 2016), in which alliances represent the lowest scale and generally provide sufficiently accurate information with regard to site conditions. The list of vegetation types was completed by using regional classification units that correspond with site characteristics (for the peatland vegetation of Schleswig-Holstein see Dierssen *et al.* 1988, Schrautzer *et al.* 1992, Schrautzer & Wiebe 1993, Wiebe 1998, Schrautzer 2004). This transformation process allowed an assignment of biotope types to the GEST-units, which are also based on information about vegetation structure. Furthermore, according to the mapping guide, biotope types were evaluated for their nature conservation value by using the categories protected by § 30 of the Federal Act for the Protection of Nature and the endangered habitats of the FFH Directive. If the biotope survey data overlapped with the other applied surveys (IACS, ATKIS), they were removed to avoid duplication. As a last step, the ATKIS information was used. This database enabled the differentiation of grassland from cropland. In the case of grassland, a finer differentiation of land use intensity into "moderate" and "intensive" was possible for areas belonging to the "Foundation for Nature Conservation of Schleswig-Holstein". Following a land purchase by this organisation, all grasslands have been moderately managed as pasture or meadow without fertilisation.

In this study the vegetation and the derived mean annual water levels were used as proxies for the estimation of GHG emissions (e.g. Couwenberg *et al.* 2011, Couwenberg & Fritz 2012). Soil moisture is strongly correlated with GHG emissions (Berglund & Berglund 2011, Bartelheimer & Poschlod 2016) and is thus directly involved in GHG flux (Couwenberg & Fritz 2012, Gray *et al.* 2013, Karu *et al.* 2014, Dunn *et al.* 2016, Goud *et al.* 2017, Strack *et al.* 2017, Liu *et al.* 2020). Currently, the most practical vegetation proxy for GHG emissions is the GEST (GHG Emission Site Type) approach developed by Couwenberg *et al.* (2011) but which remains under development (Reichelt *et al.* 2015, Hirschelmann *et al.* 2020) with regard to the strong relationship between the GEST-units and the biotope and vegetation types. We used this approach in our study with the following exceptions. For the vegetation type "degraded bogs with birch", a CO_2-eq GWP of 18 t ha^{-1} yr^{-1} was used, which corresponds to the GEST-unit "Moist to very moist acidic *Molina* meadows". In Schleswig-Holstein, the water table depths for the vegetation types "degraded raised bogs with dominance of *Molina caerulea*" and "degraded raised bogs with birch" are similar, so the same GWP was used. Furthermore, the calculations of Schrautzer *et al.* (2021) were applied for forests on peatlands.

For approximately 4.3 ha no GEST-units were available (traffic facilities, settlements, hedgerows, etc.) and the IPCC value for deeply drained, nutrient rich grasslands in temperate regions (IPCC 2013) was used to get a full estimate of GHG emissions.

Potential successional pathways to reduce GHG emissions on peatlands

To derive management options for reducing GHG emissions, different potential successional scenarios were developed based on realistic vegetation dynamics after rewetting (Figure 1, Table 1). These scenarios are based on the ecological conditions of the landscape and, thus, could all potentially be implemented throughout Schleswig-Holstein. An essential prerequisite is that the proposed restoration measures will lead to an increase in the system's nature conservation value (NCV).

Pathway A represents a moderate rewetting of intensively drained areas under agricultural use. All areas of concern will be rewetted but maintain their usability. The final target vegetation type will be "Moist to very moist grasslands" (c.f. Schrautzer *et al.* 2012).

In **Pathway B**, agriculturally used peatlands will be rewetted to such an extent that their use as meadow or pasture will no longer be practicable. The water table will be near the soil surface and the vegetation will develop in the direction of "Wet reeds" or "Wet tall sedges" (Jensen & Schrautzer 1999, Schrautzer *et al.* 2006, Schrautzer *et al.* 2012, Mrotzek *et al.* 2020). Pathway B alternatively describes the rewetting of agriculturally used bogs. The final target ecosystems of this pathway are "Very moist *Sphagnum* lawns" and "*Sphagnum* hollows". To create optimal environmental conditions for these target types, the effects of external factors such as the hydrological regime should also be considered (Dierssen & Dierssen 2001).

Pathway C focuses on degraded bogs without any previous land use. Here, rewetting procedures and target systems are the same as for Pathway B bog peat (González *et al.* 2014, Lundin *et al.* 2017).

Pathway D concerns forests on degraded peatlands and their restoration due to rewetting. The target system is Swamp forests (Schrautzer *et al.* 2021).

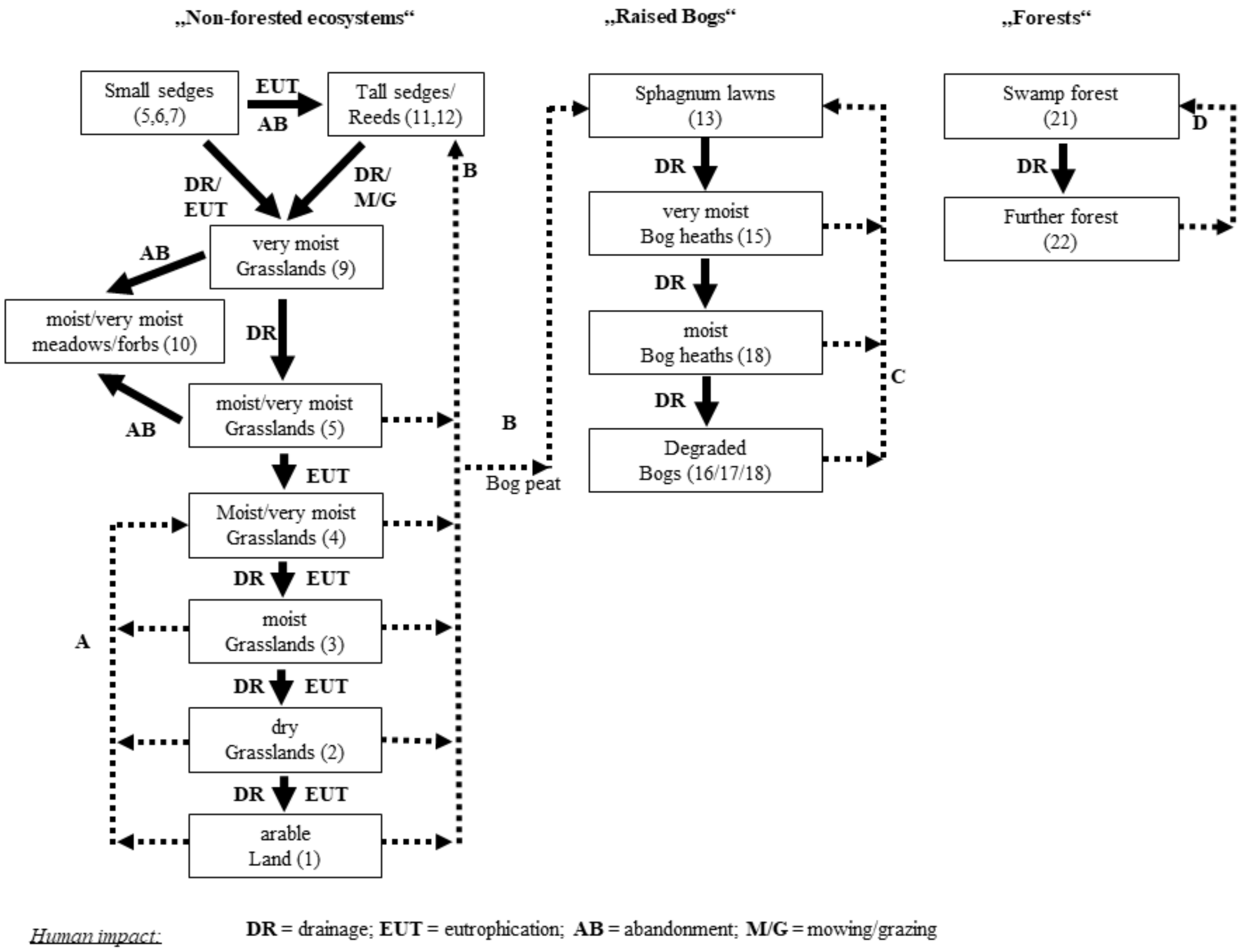

Figure 1. Successional pathways for rewetting measures of peatlands (A–D) in Schleswig-Holstein. Different vegetation types (1–22; see Appendix) and their corresponding Greenhouse Gas Emissions Site Types (GEST) are shown.

Table 1. Successional pathways of peatlands in Schleswig-Holstein that would be achievable through rewetting and land use change according to several sources; I: Schrautzer *et al*. 2012; II: Jensen & Schrautzer (1999), Schrautzer *et al*. (2012); III: González *et al*. 2013, Lundin *et al*. 2017; IV: Schrautzer *et al*. (2021). * GWP (as CO_2-eq) according to Hirschelmann *et al*. (2020); ** GWP according to Schrautzer *et al*. (2021).

Pathway	Initial types	Target types	Vegetational pathway	Target type GWP-Unit (t ha^{-1} yr^{-1})
A	Intensively used agricultural fields	Moist to very moist grasslands	I	14.5 *
B	Intensively and moderately used agricultural fields	Wet reeds or Wet tall sedges; Very moist *Sphagnum* lawn or *Sphagnum* hollows	II	6.5–7 * -3–4 *
C	Degraded bogs	*Sphagnum* lawn/ *Sphagnum* hollows	III	-3–4 *
D	Drained/degraded swamp forests	Swamp forests	IV	7.5 **

RESULTS

Land use and nature conservation value (NCV) of peatlands in Schleswig-Holstein

In Schleswig-Holstein, most peatlands are used for agricultural purposes (about 92,000 ha; Table 2 and Appendix). The intensively used “Dry to moderately moist” grassland” dominates, covering around 69,000 ha, while “Dry to moderately moist arable land” occurs on around 8,000 ha. In contrast, the pastures and meadows with moderate or low land use intensity cover only about 14,000 ha, with almost half of this protected by § 30 of the German Federal Act for Nature Protection. Peatlands without current land use (“Abandoned areas”; 6,600 ha overall) are also poorly represented in the dataset. This class comprises abandoned wet meadows (“Very moist meadows, forbs”), tall sedge reeds (“Wet tall sedges”) and reeds (“Wet reeds”). In many cases it is highly likely that tall sedge reeds and reeds have developed from previously managed wet grasslands after abandonment (Schrautzer *et al.* 2012). Owing to their near-natural character, these peatlands are also protected by § 30. However, the biotopes with highest priority for nature conservation are much less common than the above-mentioned types. These are communities of low-productivity species-rich small sedge reeds which grow predominantly on nutrient-poor sites (865 ha). Their high NCV is due to their status as a FFH Directive biotope. Within this group, base-rich sites occur much less frequently than base-poor sites. Very moist grasslands with a species composition characteristic of the wet meadow Calthion alliance are also extremely rare in Schleswig-Holstein, covering only 48 ha.

Forests on peatlands cover about 15,300 ha. Whereas about 6,000 ha (spring- and swamp forests) are characterised by near-natural hydrological conditions, most forests on peatland are affected by drainage (9,200 ha).

Active raised bogs no longer exist in their natural state in Schleswig-Holstein. Near-natural bog ecosystems such as the “Very moist *Sphagnum* lawn” (Rhynchosporion, FFH Directive type 7120) and “*Sphagnum* hollows” (Sphagnion magellanici, FFH Directive type 7120), as well as rewetted bogs, are found on about 3,900 ha. Degraded bog vegetation types (“Very moist bog heath”, “Degraded bogs with birch”, “Moist to very moist acidic *Molinia*-meadows”, “Moist bog heath”) occur on about 4,400 ha. Because of the generally high importance of bog ecosystems in Europe they are all listed as endangered habitats in the FFH Directive.

Greenhouse gas emissions calculated by GEST

Overall, the potential GHG emission rate (as CO_2-eq) from 123,798 ha of peatlands in Schleswig Holstein is around 2.9 Mt yr^{-1} (Appendix). The relevance of different GEST-types for the GHG balance of the state can also be seen in the Appendix. The most prominent emission source is “Dry to moderately moist grassland”, whose CO_2-eq contribution is 1,736,000 t yr^{-1}, or 61 % of the total emissions from peatlands in Schleswig-Holstein. Another strong

Table 2. Summary of the distribution of vegetation/management types on peatlands in Schleswig-Holstein. The dispersion on fen peat and bog peat is shown, along with the CO_2-eq GWP of each unit and its GWP-Unit. * GWP corresponding to Hirschelmann *et al.* (2020); ** GWP corresponding to Schrautzer *et al.* (2021).

Land use type	Total area (ha)	Fen area (ha)	Bog area (ha)	GWP-Unit (t ha^{-1} yr^{-1})	GWP (t yr^{-1})
Arable land	8,251	7,994	257	37.5 *	309,413
Intensively used grassland	69,440	58,405	11,035	25 *	1,736,000
Moderately used grassland	13,629	9,593	4,036	14.5–19.5 *	238,565
Extensively used grassland	865	401	464	3–5 *	2,691
Abandoned	6,610	4,959	1,751	6.5–15.5 *	64,297
Bog, *Sphagnum* rich	3,917	437	3,480	-3–4 *	7,856
Bog, degraded	4,410	847	3,554	4–18 *	75,358
Forest	15,312	-	-	5–30.5 **	326,909
Ditches/ Lake holes	1,476	1,047	429	51 *	75,276
Other	4,215	2,902	1,313	22	92,730
Totals	**128,116**	**86,585**	**26,319**		**2,929,095**

agricultural driver is the “Dry to moderately moist arable land” (309,413 t yr^{-1}). Besides agriculture, the forestry on peatlands is a strong source of GHG emissions. Deeply drained forests on peatlands (“Drained forests”) are widely distributed in Schleswig-Holstein and the rate of GHG emissions from their soils (as CO_2eq) is 282,064 t yr^{-1}, whereas spring and swamp forest types are characterised by high water tables and, consequently, lower total GHG emissions. The highest GHG emissions from abandoned areas originate from degraded bog types, with 24,840 t yr^{-1} from “Degraded bogs with birch” and 44,874 t yr^{-1} from “Moist to very moist acidic *Molinia* meadows”. In contrast, “Very moist *Sphagnum* lawn” potentially acts as a CO_2 sink resulting in -3,348 t yr^{-1}.

Potential successional pathways to reduce GHG emissions from peatlands

The highest potential for reduction of (CO_2eq) GHG emissions is offered by **Pathway B on fen ecosystems**. The emission of approximately 1.4 Mt yr^{-1} can be prevented by this scenario (Table 3). Furthermore, **Pathway B on bog ecosystems** can prevent about 450,000 t yr^{-1}, resulting in a total reduction potential of about 1.8 Mt yr^{-1}. **Pathway A** also shows high reduction potential of about 960,000 t yr^{-1}. The reduction potential for rewetting measures in forested peatlands (**Pathway D**) is about 210,000 t yr^{-1}, whereas a smaller reduction of 90,000 yr^{-1} could potentially be realised if all degraded bogs were rewetted using **Pathway C**.

DISCUSSION

Database and methodology

Previous calculations of GHG emissions on large spatial scales are based upon emission factors differentiated by classifications of climate, nutrient status and drainage (IPCC 2014) or peat type and land use (Tubiello *et al*. 2016), among other attributes. A new approach for measurement, reporting and verification (MRV) of human induced GHG emissions from drained organic soils at the national scale of Germany was developed by Tiemeyer *et al.* (2020), whereby calculations of GHG emissions were based on high resolution maps of land use, organic soil types and mean annual water tables (WT). However, the applicability of the GEST approach, which was used in that study, is often questioned due to lack of accuracy and completeness. Even though the GEST approach is based on the relationship between groundwater dynamics and

Table 3. CO_2-eq emission reduction potentials of the rewetting pathways A–D. The current and target vegetation types are shown. The calculations of GWP reduction potentials follow * Hirschelmann *et al*. (2020) and ** Schrautzer *et al*. (2021).

Scenario	Current vegetation type	Target vegetation type	Reduction potential ($t\ yr^{-1}$)
Pathway A *	Dry and moist agriculturally used land	Moist to very moist grassland	959,838
Pathway B * *Fen ecosystems*	All agriculturally used land on fen peat	Wet tall sedges	1,395,505
Pathway B * *Bog ecosystems*	All agriculturally used land on bog peat	Very moist *Sphagnum* lawn	466,704
Pathway C *	Degraded bogs	Very moist *Sphagnum* lawn	88,489
Pathway D **	Drained forests	Swamp forests	212,704

vegetation structure over several years, and thus represents medium hydrological conditions (Scholle & Schrautzer 1993, Koska *et al.* 2001, Liu *et al*. 2020), there is uncertainty in relation to the relative resilience of vegetation structure after hydrological changes. The reliability of the GEST approach and, consequently, the transferability of the method is dependent on the availability of similar datasets in regions other than those used in this study. In general, we assumed that the listed biotope types broadly reflect the peatland vegetation of lowlands in Central Europe. All of the data sources employed in this study - both the information about land used (ATKIS, IACS) and biotope mappings which allow the differentiation of nature conservation values - are available for the whole of Germany. A comparison of the biotope classification for the German states with high proportions of peatlands (Schleswig-Holstein, Lower Saxony, Mecklenburg-Western Pomerania, Brandenburg and Bavaria) showed that the differentiation of biotope types followed the same method. Consequently, the process of transformation into GEST-units presented here is applicable in other federal states. Furthermore, this method can be transferred to other peatland-rich lowlands in central Europe for which appropriate data are available.

Land use and GHG emissions

In Schleswig-Holstein, about 72 % of the peatland area is used for agricultural purposes. This is almost exactly the same result (73 %) presented by Tiemeyer *et al.* (2020) for organic soils in Germany (GER). The dominant land use category on peatlands in Schleswig-Holstein is grassland, which covers about 65 % (GER 53 %), whereas the proportion of cropland (about 6 %) is considerably less than at national scale (20 %). The relative area of forests on peatlands is about 12 % in Schleswig-Holstein, which is again similar to the German national value.

In Schleswig-Holstein, GHG emissions from all sectors amount to about 24,990,000 $t\ yr^{-1}$ as CO_2eq. The agricultural sector (without emissions from peat soils) emits 5,050,000 $t\ yr^{-1}$ (MELUND 2019). Peatlands emit about 2,900,000 $t\ yr^{-1}$, which means they are responsible for approximately 10 % of all emissions. Grassland ecosystems are the dominant source of GHG emissions from peatlands in Schleswig-Holstein, being responsible for about 70 % of total peatland emissions which is clearly higher than for the whole of Germany (51 %; Tiemeyer *et al.* 2020). On the other hand, the contribution of forest ecosystems on peatlands in Schleswig-Holstein (14 % of total GHG emissions) is comparable with the nation-wide figure (13 %).

In Schleswig-Holstein, intensively used grasslands constitute the most widespread land use type and are responsible for the highest GHG emissions. Grasslands with moderate land use contribute less to the total GHG emissions, but nonetheless offer a significant reduction potential because they are still drained.

Long-term changes in land use and GHG emissions from peatlands in Schleswig-Holstein can be crudely assessed by comparing the results of Jensen *et al.* (2010) - who used data from a 1978–1997 survey - with the results of the current study.

One of the major differences between these two studies is the area of peatland upon which the calculations of GWP are based; about 145,000 ha in the Jensen study versus 128,000 ha in the current study. Despite the large difference in peatland area considered, the estimates of CO_2-eq GHG emissions are very similar, at 2.4 Mt yr^{-1} in the Jensen study and 2.9 M t yr^{-1} in the current study. Thus, we assume that the GHG emissions per hectare have increased considerably during the last three decades. This could be due to an increase in land use intensity in grasslands since the proportion of intensively managed grasslands increased from 29 % to 54 %, corresponding to an increase in mean CO_2-eq GWP from 18.8 to 23.3 t ha^{-1} yr^{-1} for all grasslands (range of intensities).

In contrast, restoration measures for bog ecosystems without any history of agricultural management led to a reduction of GHG emissions. This was due to a significant reduction in the area of degraded states containing purple moor-grass (*Molinia caerulea*) and birch (*Betula pubescens*) in favour of very moist *Sphagnum* lawns and hollows, and resulted in a reduction of the mean CO_2-eq GWP from 15.2 t ha^{-1} yr^{-1} during the period 1978–1997 to 9.6 t ha^{-1} yr^{-1} during our study. In total, the reduction in GHG emissions from restored bogs to date varies between 50,000 and 70,000 t yr^{-1}.

In previous studies, forested peatlands were not regarded as high sources of GHG emissions. However, based on the current biotope survey, their soils contribute considerably (almost 300,000 t yr^{-1} or 11.5 %) to the state-wide GHG emissions of peatlands, which highlights the importance of these ecosystems in the context of climate protection strategies (Schrautzer *et al.* 2021).

GHG reduction pathways and nature conservation

The main prerequisite for achieving the objectives of the Paris Agreement is a strong reduction of human-induced CO_2 emissions (UNFCCC 2015). In the IPCC (2019) Special Report on climate change, restoration of peatlands is mentioned as a potentially effective mitigation measure in natural ecosystems. Due to the predominant importance of the water regime for GHG emissions, rewetting of drained peatlands in agriculturally managed areas and woodlands is considered to be an indispensable measure for this purpose (Trepel *et al.* 2017). The German Climate Protection Plan (BMU 2016) also refers to the conservation and restoration of peatlands as measures to avoid GHG emissions and preserve net carbon sinks. The plan aims to make Germany carbon-neutral by 2050, with an intermediate reduction of 55 % by 2030 compared to the situation in 1990. The reduction target of 5 Mt yr^{-1} (as CO_2-eq) listed in the peatland protection strategy of the German government (BMUV 2021) corresponds to a 10–12 % reduction of total emissions depending on the calculation used.

In contrast, the government of Schleswig-Holstein is pursuing a reduction of 25 % by 2030, which converts to 0.7 Mt yr^{-1} (MELUND 2020). The first nationwide emission reduction pathways, in light of the "net zero" target in 2050, were provided by Tanneberger *et al.* (2020a). The authors compared projections for four different hydrological scenarios, referring primarily to CO_2 emissions and considering the radiative forcing of greenhouse gases (Günther *et al.* 2020). Moreover, they proposed pathways of concrete changes in land use and rewetting along timelines from 2020 to 2030 and 2040 until 2050.

In Schleswig-Holstein, the highest reduction potential is offered by **Pathway B**, which would potentially yield more than twice the regional reduction targets. According to this pathway, traditional agricultural use will no longer be possible because water tables will be permanently high. An interesting alternative for farmers would be paludiculture. Although paludiculture is considered to be the most effective land use type for climate protection, several conditions have to be fulfilled and conflicts must be overcome before substantial implementation can be achieved (Tanneberger *et al.* 2020b). The conversion of high-intensity land use to paludiculture would also enhance the nature conservation value of peatlands, although in the long run a succession to unmanaged reed ecosystems would probably be more effective in terms of plant diversity (Timmermann *et al.* 2006, Rosenthal *et al*. 2012, Schrautzer *et al.* 2016) and the habitat requirements of some bird species (Görn *et al.* 2015).

Pathway A, which involves moderate rewetting of utilised peatlands, would also contribute to the climate goals of Schleswig-Holstein. In this scenario the usability of grassland would be maintained although water tables would be closer to the soil surface. As shown by the results of Poyda *et al.* (2016), even intensively managed grassland (high input of cattle slurry and mineral fertiliser, several mowings per year), with high herbage yield and good fodder quality, would have a significantly reduced GWP after rewetting. Thus, at one site with mean water table level 21 cm below ground surface, the CO_2-eq GWP amounted to only 11.7 t ha^{-1} yr^{-1} (GWP for the corresponding GEST-type "moist to very moist grassland" is 14.5 t ha^{-1} yr^{-1}) and, at another site with mean water level 33 cm below ground surface, a GWP of 17.7 t ha^{-1} yr^{-1} was measured (GWP for the corresponding GEST-type "moist grassland" being

19 t ha^{-1} yr^{-1}). However, grassland management that involves mowing several times per year does not meet the habitat requirements of typical meadow birds (Lamers *et al.* 2002) and the potential for improving plant diversity is low (Klimkowska *et al.* 2010). Consequently, if the aspiration is to pursue nature conservation goals in combination with reducing GHG emissions, the intensity of land use has to be reduced.

In **Pathway C**, long-term abandoned degraded bogs are rewetted, and since all of these areas are reserved for nature conservation, the implementation of rewetting is easily possible. Thus, there is generally a high potential for bog restoration. According to the estimations from this study, the transformation of degraded bogs (GEST-types "very moist bog heath", "degraded bogs with birch") by rewetting into *Sphagnum*-dominated stages (GEST-types "very moist *Sphagnum* lawn", "*Sphagnum* hollows") will significantly reduce GHG emissions.

Pathway D focuses on forested peatlands. In Schleswig-Holstein, most of these are highly affected by more or less deep drainage and peat subsidence. The estimations in this study show that rewetting of all drained forests on peatlands could potentially achieve almost one third of the regional reduction target. However, this result does not reflect the total potential of these ecosystems because there is a lack of reliable GHG measurements that include the functions of trees (Huth *et al.* 2018). Nevertheless, the potential for implementation of rewetting measures is high because many forested peatlands are owned by the state and rewetting is easily possible from a technical point of view. Furthermore, these measures would significantly improve the NCV of the forests (Wiebe 1998, Maanavilija *et al.* 2014, Woziwoda & Kopec 2014).

Due to the small area of highly endangered species-rich fen meadows in Schleswig-Holstein, the highest priority should be given to maintenance of appropriate management measures for the restoration of peatlands, especially fens (e.g. Seer & Schrautzer 2014, Lamers *et al.* 2015). Ecosystems such as mesotrophic small sedge reedbeds or species-rich eutrophic wet meadows do not essentially contribute to the GHG emissions of peatlands due to their relatively small area in Schleswig-Holstein as well as their low GWP per ha. Furthermore, they host the majority of characteristic fen species on their restricted area in central Europe. Due to widespread high airborne nutrient inputs and low water quality of rivers that could potentially be used for rewetting in many areas, a further rise in the water table would increase the competitiveness of tall-growing species and the displacement of endangered light-demanding species (Grootjans *et al.* 2002, Bobbink *et al.* 2003, Seer & Schrautzer 2014).

CONCLUSIONS

The federal state of Schleswig-Holstein can act as an example for the kinds of problems associated with intensive use of peatlands in central and western Europe. The methodological approach of this study enabled us to document both GHG emissions and aspects of nature conservation on large scales, showing that it is well-suited for implementing concepts for management of peatlands.

In Schleswig-Holstein, the percentage of GHG emissions from peatlands is higher than the German average. The main reason for this is the widespread intensive use of grasslands for fodder production; approximately 60 % of all GHG emissions come from intensively used grasslands. However, unused areas and forests on peatlands also show high GHG emission rates because water tables remain low.

Major changes in the agricultural use of peatlands will be necessary to reach state government and nationwide GHG emission reduction goals by 2030. In general, water tables in agriculturally used peatlands, and especially in intensively used grasslands, have to be raised in many areas and this should be accepted by land users. The potential pathways derived from this study identify opportunities for meeting and exceeding these goals. Paludicultures could be a sensible alternative in future, in terms of both ecological and economical demands on peatland management. Furthermore, the results of the state-wide analysis show that potential conflicts between rewetting and the requirements of nature conservation can be recognised in advance of planning. To achieve the goals of the Paris agreement (zero emissions from agriculturally used peatlands), even stronger efforts will be necessary.

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AUTHOR CONTRIBUTIONS

TM and JS compiled the data and developed the categories for peatland distribution in Schleswig-Holstein. TM analysed the data and wrote the manuscript. JS contributed central ideas for data evaluation and the discussion. MT critically reviewed the manuscript and contributed ideas for evaluating the data. All authors contributed to the final version of the manuscript.

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Appendix

The distribution of vegetation types on peat soils in Schleswig-Holstein. The occurrences of vegetation types are classified according to the GEST model, showing the corresponding water classes and GHG emissions (Couwenberg *et al*. 2011, Reichelt 2015, Hirschelmann *et al*. 2020). In addition, the vegetation alliances are shown for the GEST types, according to Mucina *et al*. (2016). For all vegetation types, the total extent is given (in ha) as well as the division between fen and bog peat. Abbreviations: NCV = Nature Conservation Value; GWP = Global Warming Potential. For GWP and emission rates, the data shown are CO_2-equivalent (CO_2-eq) values. *Type 5 Calthion palustris is separated from Type 9 following Schrautzer (2004). **The GEST model does not include a direct equivalent for Type 16 (Degraded bogs with birch) which was, for this reason, assigned to Type 17.

Land use class	GEST (2021)			From Mucina *et al*. (2016)		NCV	GWP (t ha^{-1} yr^{-1})	Area (ha)			Emission rate (t yr^{-1})
	Ecosystem type	Type No	Water class	Vegetation alliances	Code			Total	Bogs	Fen, Gyttja	
Intensively managed	Dry to moderately moist arable land	1	2+, 2-	-	-	-	37.5	8,251	257	7,994	309,413
	Dry to moderately moist grassland	2	2+, 2-	Cynosurion cristati	MOL-01C	-	25.0	69,440	11,035	58,405	1,736,000
Moderately managed	Moist grassland	3	3+, 2+	Potentillion anserinae	MOL-10A	-	19.5	8,189	2,499	5,690	159,686
	Moist to very moist grassland	4	4+, 3+	Potentillion anserinae	MOL-10A	+	14.5	359	124	235	5,206
	Moist to very moist grassland	5	4+, 3+	Calthion palustris*	MOL-05B	++	14.5	5,081	1,413	3,668	73,675
Low land use intensity	Wet small sedges (base-rich)	6	4+, 5+	Caricion davallianae	SCH-01A	+++	3.0	104	40	64	312
	Wet small sedges (base-poor)	7	4+, 5+	Caricion fuscae / Molinion caerulae	SCH-03B/ MOL-05A	+++	3.0	218	129	89	654
	Wet small sedges (base-poor)	8	4+, 5+	Sphagno warnstorfii-Tomentypnion nitentis/ Magrnocaricion elatae	SCH-02D/ PHR-04A	+++	3.0	495	295	200	1,485
	Very moist grasslands	9	4+	Calthion palustris	MOL-05B	+++	5.0	48	0	48	240

Land use class	GEST (2021)			From Mucina *et al*. (2016)		NCV	GWP ($t\ ha^{-1}\ yr^{-1}$)	Area (ha)			Emission rate ($t\ yr^{-1}$)
	Ecosystem type	Type No	Water class	Vegetation alliances	Code			Total	Bogs	Fen, Gyttja	
Abandoned areas	Very moist meadows, forbs	10	4+, 3+	Archangelicion litoralis	EPI-05B	++	15.5	2,259	453	1,806	35,015
	Wet tall sedges	11	5+	Magnocaricion elatae	PHR-04A	++	7.0	2,001	915	1,086	14,007
	Wet reeds	12	5+	Phragmition communis	PHR-01A	++	6.5	2,350	383	1,967	15,275
Bogs	Very moist *Sphagnum* lawn	13	5+, 4+	Scheuchzerion palustris	SCH-04A	+++	-3.0	1,116	1,007	109	-3,348
	Sphagnum hollows	14	5+, 4+	Sphagnion medii	OXY-02B	+++	4.0	2,801	2,473	328	11,204
	Very moist bog heath	15	4+	Ericion tetralicis	OXY-01A	+++	4.0	110	107	3	440
	Degraded bogs with birch	16	4+, 3+*			+	18.0	1,380	1,228	152	24,840
	Moist to very moist acidic *Molinia* meadows	17	4~			+	18.0	2,493	1,887	606	44,874
	Moist bog heath	18	3+			++	12.5	412	330	82	5,150
	Moist bare peat	19					9.0	6	2	4	54
Forests	Spring forest	20	5+, 4+	Alnion- glutinosae	ALN-01A	+++	5.0	254			1,270
	Swamp forest	21	5+, 4+	Alnion- glutinosae	ALN-01A	+++	7.5	5,810			43,575
	Drained forests	22	3~	Alnion incanae	POP-02A	-	30.5	9,248			282,064
"Further"	Ditches, lakeshores	23				-	51.0	1,476	429	1,047	75,276
	Others	24				-	22.0	4,215	1,313	2,902	92,730
							Totals	**128,116**			**2,929,095**