Leuphana University Lueneburg
Faculty of Sustainability

Bachelor Thesis

Peatlands as a Natural Climate Solution

– Potentials and Limitations under different Future Scenarios (The Case of Schleswig-Holstein) –

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Abstract

This thesis analysis the viability of peatlands as a Natural Climate Solution (NCS) under different climatic and economic future conditions, for the case of Schleswig-Holstein (northern Germany). Peatlands are a major terrestrial carbon store, however they emit vast amounts of greenhouse gases (GHGs) due to drainage (currently ca. 3% of all anthropogenic GHG-emissions). While the rewetting of drained peatlands can generally reduce GHG-emissions, the effect might be compromised by Climate Change, as it is depending particularly on wet and cool climatic conditions (in the northern hemisphere). The thesis explores the possible emission feedbacks of peatlands to Climate Change, in order to determine the effectiveness of rewetting (as a NCS) under a changing climate. As further GHG-emissions cause damages to society, which can be expressed in the *Social Cost of Carbon,* an economic evaluation of peatland-emissions was added, in order to assess if peatland rewetting can be economically sensible in the future.

Methodologically, a literature review was conducted, reviewing existing findings on climate and peatland relationships as well as carbon pricing. Subsequently, an explorative model was designed, that relates atmospheric temperature to peatland water table height, allowing for GHG-emission-estimates of different peatland management types (wet, rewetted, drained) under two climate scenarios (RCP2.6 & 8.5), between 2020-2100. Costs were calculated in accordance to a low and high carbon price pathway, applied to the calculated emissions.

The results indicate that climate warming will increase peatland emissions and costs, particularly for drained sites. Rewetting (and conserving wet sites) lowers costs and emissions significantly. A timely rewetting seems reasonable, as relative emissions rise exponentially with ongoing temperature increases. However, the scope for land-users to rewet agricultural drained peatlands seems stymied by existing policies, rather than by biophysical realities. The results seem to fit with other studies, despite simplified assumptions made.

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List of Abbreviations

a	Year
BT	Bachelor thesis
BfN	Bundesamt für Naturschutz (Federal Agancy for Nature Conservation)
BMUB	Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit (Federal Ministry for the Environment, Nature Conservation, Building and Nuclear Safety)
C	Carbon
CAP	Common Agricultural Policy (of the EU)
CO_2	Carbon dioxide
CO_2e	CO_2 equivalent emissions
CH_4	Methane
DGMTEV	Deutsche Gesellschaft für Moor- und Torfkunde e.V. (German Society for the Study of Peatlands)
DWD	Deutscher Wetterdienst (German Meteorological Service)
ESS	Ecosystem-Services
GHG	Greenhouse Gas(es)
Gt	Giga ton
GWP	Greenhouse-warming potential
H_20	Dihydrogen monoxide = Water
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
LLUR	Landesamt für Landwirtschaft, Umwelt und ländliche Räume Schleswig-Holstein (Federal Agency for Agriculture, Environment and Rural Areas, in SH)
LULUCF	Land use, land-use change, and forestry (as defined by the UNFCCC)
MELUND	Ministry of Energy Transition, Agriculture, Environment, Nature and Digitalisation (Ministerium für Energiewende, Landwirtschaft, Umwelt, Natur und Digitalisierung des Landes Schleswig-Holstein)
N_2O	Nitrous-oxide

a	Year
NCS	Natural Climate Solution
NPP	Net-primary-production
RCP	Representative Concentration Pathway
SCC	Social Cost of Carbon
SH	Schleswig-Holstein
SSP	Shared Socio-EconomicPathways
t	Ton
TEEB	The Economics of Ecosystems and Biodiversity
UBA	Umweltbundesamt (German Federal Environmental Agency)
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
yr	Year

1 Introduction

1.1 Situation and Problem

The global climate is changing and altering earth system processes as we know them. As all known life is confined to the earth systems' boundaries, earths' inherent processes determine life's quality. Due to anthropogenic influences these processes are being imperilled and put under pressure ("extremely likely", IPCC, 2014, p. 3), with potentially devastating outcomes for ecosystems, societal stability and well-being (see Lewis & Maslin, 2015; Steffen et al., 2018).

The good news is, anthropogenically induced changes are inherent to anthropogenic behaviour and choices, which can be changed and improved. With increasing scientific understanding of the climate system, solutions have been presented (e.g. to cut emissions and protect ecosystems) and are continuously being researched.

The following analysis aims to explore one of the proposed solutions: natural systems, i.e. ecosystems, can and do provide many valuable services to human societies, of which one is carbon storage, a crucial service with regard to the current CO_2-emissions reduction needs (see Griscom et al., 2017).

Peatlands are an important biome and carbon sink. As these potentially store (or emit) vast amounts of carbon, they are a potential, and in fact an acknowledged (Humpenöder et al., 2020), *Natural Climate Solution* (NCS) (Tanneberger et al., 2021, Wilson et al., 2016).

As further temperature increases are expected (IPCC, 2014) one might ask if peatlands will still be a viable NCS under changed climatic conditions, a question that this analysis will try to answer.

As peatlands function differently in different parts of the world, here the case for Schleswig-Holstein (SH), the northern most county in Germany, was considered, in order to analyse local future potentials and limitations of peatlands, which are specific to local dynamics. A potential decrease of peatland area has been estimated for the north sea region (Hölzel et al., 2016), which will be examined in more detail subsequently.

The lack of peatland inclusion in mitigation[1] policies (cf. Humpenöder et al., 2020, p. 2) might be due to insufficient research and an attention bias (Griscom et al., 2017) towards other land-based solutions (as outlined below). Peatlands are said to be vital for climate policy-making (Humpenöder et al., 2020), though further knowledge on peatland system

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[1] Mitigation describes anthropogenic interventions that reduce GHG-emissions in order to reduce pressures on natural and human systems from Climate Change (cf. Dinsa & Gemeda, 2019, p. 1298).

boundaries with regard to future feedbacks to a changing climate seems to be needed (Hölzel et al., 2016; Jensen et al., 2010).

As behaviour changes towards more sustainable actions are often constrained by economic and political reasons (see Günther et al., 2020), rather than natural scientific findings, this analysis will also look at how the costs for sustainable peatland management might make a difference in the future. The role that the social cost of carbon (SCC) might have on peatland management in the future (see von Oheimb et al., 2014) will be considered.

Carbon pricing and incentives for peatland carbon services seem to be sparsely included in mitigation plans (see von Oheimb et al., 2014), which seems to be problematic, as mitigation pathways are said to be ineffective in the long run without peatlands (cf. Humpenöder et al., 2020, p. 1). A better understanding of the reciprocal feedbacks between carbon prices and peatland emissions, respectively management kind, might prove useful.

1.2 Goals and Objectives

The goal of this analysis is, to find out if peatlands are or can be an ecologically and economically viable and effective *Natural Climate Solution* under changing future conditions (different climate and different carbon prices) in order to assess whether peatland protection and restoration should be scaled up and explored, or not. With that goal defined the following research questions will guide the prospective analysis:

RQ1: Will peatlands be a viable NCS (through rewetting and conservation) under future climatic conditions in SH?

RQ2: Will the social cost of carbon development impact peatland management in SH (conservation, rewetting or not rewetting)?

Further relevant questions that will be examined are: what uncertainties, with regard to peatland use as a NCS, lay within the biophysical response (emission feedbacks to a changing climate) or are owed to the economic sphere (carbon pricing developments)? Can adaptation to a changing climate be cost-effectively achieved through peatland protection and restoration?

The next section will describe the methodology of analysis to answer these questions.

1.3 Methods and Solution Pathway

As mentioned above, the case of peatlands potential feedbacks to local future climate estimates in SH has not been explicitly researched (to my best knowledge), though details on needed variables for such an analysis exist. For this analysis the valuation of "peatlands as a future NCS" was conducted and quantified once from a natural science perspective (carbon-emissions) with regard to total carbon stored or emitted, and was additionally quantified from an economic perspective, in monetary terms (the social cost of carbon).

Therefore, the following section (part 2) of this analysis is descriptive, compiling and outlining the existing and necessary scientific knowledge, needed for answering the proposed questions. This section was methodologically conducted as a literature review, analysing and condensing current knowledge.

Subsequently a modelling section (part 3) was generated, in order to synthesize the described information, guided by the research questions. An ecological model was compiled that calculates peatland emissions in relation to different climate conditions (temperature changes) and with regard to management cases, of either conserving existing peatlands, rewetting drained areas or leaving the drained areas unchanged.

An economical model was added that calculates the emission-dependent costs.

Research Design:

Observations → Climate is changing, peatlands can be a NCS and mitigation option
RQ → Will peatlands be a sensible NCS under changed climate & economic conditions?
Lit. review → Biophysical peatland processes, future climate, emission costs + synthesis
Exploratory Modelling → Climate Change and SCC effects on peatland emissions and costs (environmental & economic modelling)
Conclusion → Interpretation of model outputs & answering RQs

2 Literature Review

2.1 Climate and Peatlands

2.1.1 Climate Change – A Need for Action

Since pre-industrial times (ca. 1850) the atmosphere has warmed globally about 1°C, (Steffen et al., 2018) driven largely by anthropogenic greenhouse gasses (GHGs) and particularly CO_2-emissions (Handmer et al., 2012; Lewis & Maslin, 2015). The ongoing accumulation of GHGs in the atmosphere (Pfeifer et al., 2021), the resulting warming and the subsequent earth system changes are yet uncertain in their extent but can expected to be manifold and unfavourable to our species (see Handmer et al., 2012; Lewis & Maslin, 2015; Steffen et al., 2018).

Possible emission pathways (*Representative Concentration Pathways* = RCPs) and according climatic changes are extensively being researched and modelled, e.g. by the *IPCC* (see fig. 1), in order to inform policy-making and future actions (IPCC, 2014).

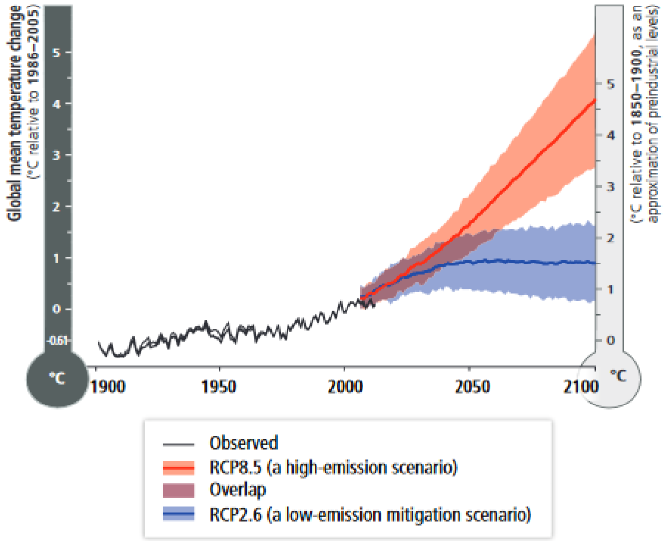

Figure 1: Two representative concentrations pathways (RCP2.6 & 8.5), as modelled by the IPCC and according temperature changes relative to pre-industrial levels. Each RCP consist of a set of scenarios (entire blue / red area) averaged with a mean trend line (blue / red line). Figure from: IPCC, 2014, p. 13.

The emissions pathways examined here are the RCP2.6 and 8.5, in which the former represents a future in which the *Paris Goals* (see below) are met and the latter a “worst-case scenario”, implying the unmitigated continuation of current global developments (see Friedrich et al., 2017), respectively a high emissions pathway. These RCPs consist of a set of *scenarios* which describe possible states of future atmospheric composition and their likely impact on radiative forcing (for 2100 relative to 1750), respectively 2.6 W / m^2 and 8.5 W / m^2 (cf. Yigini & Panagos, 2016, p. 840).

These future estimates informed e.g. the *Paris Agreement* (2015), in which over 200 countries pledged their intent to limit global warming well below 2°C, though effective ramifications are still sparse and inconsistent with the latest scientific advice (Burke et al., 2019).

Inaction seems increasingly dangerous (Burke et al., 2019), since medium and long term changes in climatic conditions have complex effects on earth system processes (Hölzel et al., 2016; Lewis & Maslin, 2015) and similarly on societies (see estimated socio-economic pathways, SSPs, in Popp et al., 2017). There is no guarantee for what might happen exactly, but as deductions can be drawn from e.g. the laws of physics and historic legacies, the currently changing climate can confidently be expected to be warmer and less stable (Steffen et al., 2018).

The need for mitigation has become urgent (Steffen et al., 2018) if we are to avoid predicted damages and worst-case scenarios (see RCP8.5 in fig.1, p. 4) (e.g. Handmer et al., 2012). Possible solutions are multifarious, of which one category is described, as follows.

2.1.2 Natural Climate Solutions

Ecosystems and biomes that can provide climate services like carbon storage are discussed as so-called *Natural Climate Solutions* (NCS) (see Griscom et al., 2017). The different "risks related to climate change can be reduced and managed through adaptation and mitigation" (IPCC, 2014), which is the aim of NCS.

NCS comprise climate-smart and sustainable land management practices, from wetland conservation, well-designed forestry and regenerative agriculture to peatland restoration, and can help reach the climate goals, if done properly (Wilson et al., 2016). Next to the importance of carbon storage, a variety of other ecosystem-services (ESS)[2] can potentially be derived from NCS, such as flood protection or water filtration (see Griscom et al., 2017; Amelung et al., 2020; Helbig et al., 2020; Joosten et al., 2016).

Some argue that a bias towards forests has outshone other NCS (see Fleischman et al., 2020; Temperton et al., 2019), like peatlands, in the past, resulting in scientific under-exploration, which makes it all the more important to research and communicate them further and include them into climate adaptation strategies today (Leifeld & Menichetti, 2018). This is particularly important because peatlands (and other non-forest solutions like grasslands) can be a net carbon sink in one geographic area, where forests would not be (and the other way round) (see Temperton et al., 2019). This means that place-specific, locally adapted land management makes a vital difference in NCS-effectiveness.

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[2] Ecosystem-services (ESS) describe various material and non-material, direct or indirect contributions to human well-being by nature and natural processes (cf. IPBES, 2018, p. 742; see TEEB DE, 2014).

Amongst the various possible NCS, peatlands are slowly receiving more attention, though often due to their degradation and the vast amounts of according GHG-emissions (Hölzel et al., 2016; Tanneberger et al., 2017), but also as a (potential) carbon sink and climate solution (Humpenöder et al., 2020; Joosten et al., 2016; Wilson et al., 2016).

Meanwhile peatlands are included in governmental CC policies, for example in Germany (BMUB, 2016) and Scotland (see Ferretto et al., 2019) and many specialist recommendations (e.g. Artz et al., 2013; Burke et al., 2019; The World Bank, 2008). Sustainable peatland management (see Dinsa & Gemeda, 2019) seems to be a necessity (Jensen et al., 2010) for reaching the *Paris Goals* (Humpenöder et al., 2020).

Better, scientifically well-informed peatland management and knowledge seems urgent (Humpenöder et al., 2020; Jensen et al., 2010), as Joosten et al. claim: “peatlands are the most space-effective carbon store of all terrestrial ecosystems” (2016, p. 14), but they are under threat (IPBES, 2018, p. 78).

While peatlands release or store (depending on their management and state) vast amounts of GHG (Dinsa & Gemeda, 2019; Wilson et al., 2016) they play a significant role on a global level. On the other hand, peatlands are usually locally managed, which brings enormous leverage to land-owners and managers (individually or collectively through legislation) (Tanneberger et al., 2021). With these perspectives in mind this analysis aims to explore the local potentials and limits of peatlands as a NCS in SH, in order to tackle the global commons problem of CC and the related GHG-emissions reduction needs (see 2.2).

2.1.3 Peatlands

Peatlands are defined as “a wetland landscape type that is characterized by permanently waterlogged conditions, resulting in accumulation of dead plant material as peat” (Müller & Joos, 2020), of at least 30 cm thickness (LLUR, 2013). Peatlands that are still peat-forming (sequestering carbon, see fig. 2, p. 8) are called mires (Tanneberger et al., 2017; Hölzel et al., 2016).

There are different kinds of peatlands (see Böckenhauer et al., 2016), that are defined by different factors of e.g. water inflow regime, latitude, or climatic zone: “Peatlands are globally distributed and can take multiple forms from minerotrophic fens [groundwater fed] to ombrotrophic bogs [precipitation fed] & forested tropical peat swamps“(Müller & Joos, 2020, p. 5285; for hydro-genetic peatland types in SH see Böckenhauer et al., 2016).

As mentioned peatlands play a significant role globally (von Oheimb et al., 2014), covering only 3% of global land mass, though holding “twice as much carbon as the entire

world's forest biomass" (Tanneberger et al., 2021, p. 5), which amounts to ca. 644 Gt of Carbon, 21% of the global total soil organic Carbon stock (Leifeld & Menichetti, 2018).
Ongoing destruction and drainage of peatlands (see *2.2.1* for SH) has an important climatic dimension, as the stored carbon is emitted through the degradation processes: "In 2015, annual GHG-emissions from degraded peatlands [...] amount to 1.50 Gt CO_2e yr of which 82% (1.24 Gt CO_2 yr) come from peat oxidation" (Humpenöder et al., 2020, p. 5), respectively carbon emissions[3]. In addition, the remaining 18% stem from other peatland gaseous emissions (CH_4 and N_2O, as described subsequently). The total emissions of degraded peatlands amount to roughly 5% of all anthropogenic GHG-emissions (cf. Günther et al., 2020, p. 2).

In order to restore these habitats, and make use of them as a NCS, peatlands can be conserved and rewetted (Leifeld & Menichetti, 2018). This process has been reported to effectively reduce and stop peatland GHG-emissions (Joosten et al., 2016), though depending on various factors (Wilson et al., 2016) like former land use type or specific restored water table height (Strack et al., 2004).

Rewetting is furthermore said to be a cost-effective NCS (e.g. Griscom et al., 2017; Günther et al., 2020; Leifeld & Menichetti, 2018). The costs to mitigate GHG-emissions through rewetting are thought to be low, with about €10-15 / t CO_2, and less when combined with wet land use, reported for the case of Germany (cf. Tanneberger et al., 2021, p. 3)[4].

2.1.4 Carbon Cycling and GHG Fluxes

"Peatlands are an essential part of the terrestrial carbon cycle and the climate system" (Müller & Joos, 2020, p. 5285). Peatland carbon and GHG cycling can be looked at e.g. with regard to:

- Carbon storage in peat soils (C accumulated in the past) and consequently avoided GHG-emissions (wet and rewetted peatlands)
- Carbon oxidation and decay and resulting GHG-emissions (degraded peatlands)
- as well as additional carbon sequestration from the atmosphere (mires).

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[3] For the most part of the subsequent analysis, the whole of peatlands' gaseous emissions are expressed and calculated in CO_2-equivalent units (CO_2e), meaning that the global-warming-potential (GWP) of gases like CH_4 and N_2O are converted into CO_2-equivalent amounts (e.g. 1 t of methane equals 28 t of CO_2 in terms of radiative forcing, over a hundred year time period) as commonly done (see Matthey & Bünger, 2020).

[4] An example of wet land cultivation (agriculture) on wet peatlands is *Paludiculture*. For more detail see Geurts et al., 2019; Schlattmann & Rode, 2019; Schröder et al., 2015.

GHG-emissions from drained peatlands account for the highest measured and predicted fluxes of peatland emissions (see Griscom et al., 2017, in: SI[5]), and wet and rewetted peatlands for the lowest. This analysis will therefore focus on peatland carbon storage and avoided emissions, hence peatland conservation and rewetting: the form in which they are useful as a NCS and thought to be useful for CC mitigation (Humpenöder et al., 2020; von Oheimb et al., 2014).

The role and functioning of carbon sequestration (mires) is therefore largely left out of this analysis (for details on mires see Amelung et al., 2020; Couwenberg et al., 2011; Leifeld & Menichetti, 2018).

As peatland vegetation (e.g. *sphagnum* species or reed) derives CO_2 from the atmosphere, atmospheric carbon is sequestered into plant organic matter. The dead organic matter decays partly at the surface and then accumulates and builds up in the form of peat (soil organic matter), as further decomposition is hampered due to the anoxic conditions through water-logged conditions (see fig. 2).

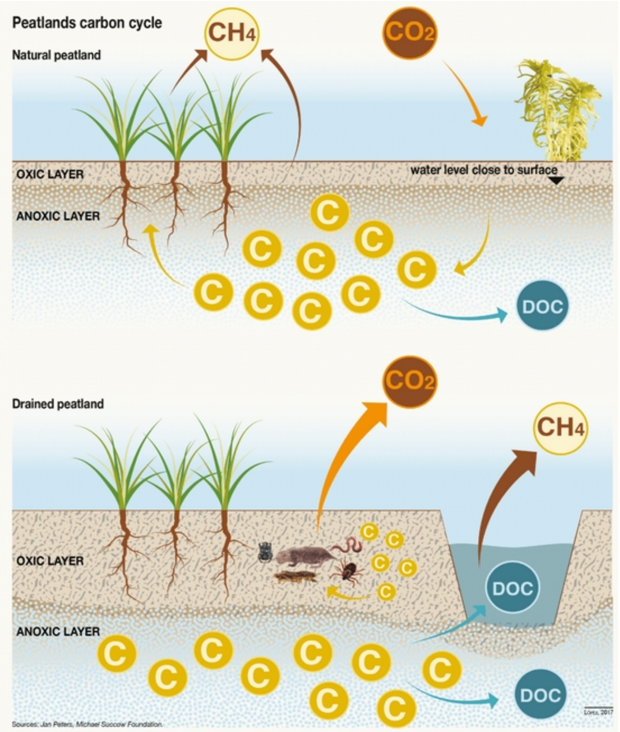

Figure 2: ***Simplified carbon cycle in wet (top) and drained peatlands.***

<u>Top</u>: Organic matter from dying plants, that accumulated atmospheric carbon (CO_2) over their lifetime, is partly decomposed in the oxic layer where some amounts of carbon emit as methane (CH_4) and further accumulate into peat (anoxic layer), storing carbon (C) potentially for thousands of years. Some carbon is dissolved and leached (DOC).

<u>Bottom</u>: In drained peatlands the oxic layer is much deeper, which leads to the further mineralization and decomposition of accumulated organic matter (C), releasing the carbon (CO_2) back into the atmosphere. DOC is leached and washed out partly into the drains, emitting further carbon (CH_4).

Methane emissions are usually higher in wet peatlands. Not shown here are nitrous-oxide (N_2O) emissions, which decrease with peatland re-wetting. It is important to note, that despite the higher methane emissions in wet peatlands, over a 100 years time-frame the net total GHG-emissions are lower compared to drained sites (cf. Tanneberger et al. 2021).

(Figure from N. L. Izquierdo (2017), Smoke on the water, Peatland Carbon Cycle. Available at https://www.grida.no/resources/12532 (last reviewed 05.02.2021).

This means reversely, that the drying of peatlands through drainage (also droughts), leads to the availability of oxygen in peat soils, which restarts the decomposition and mineralization processes, causing increased CO_2 and N_2O (nitrous-oxide) emissions (see App. 4).

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[5] SI = Supplementary Information to Griscom et al. 2017, as indicated in the literature list at the end.

Methane (CH_4) emissions on the other hand behave the other way round (Günther et al., 2020): In wet peatlands CH_4 emissions are higher compared to dry ones, as CH_4 is primarily formed in the presence of H_20, in anaerobic conditions (see Hölzel et al., 2016; Humpenöder et al., 2020; Strack et al., 2004).

Other factors determine the specific gaseous peatland cycling, for example: abiotic conditions like incoming solar radiation, evapotranspiration differences in connection to vegetation type (e.g. mosses or alder trees), erosion induced by extreme precipitation (Ferretto et al., 2019; Hölzel et al., 2016) or temperature (Ise et al., 2008; Jensen et al., 2010).

Peatland gaseous cycles are furthermore defined by biotic factors, which are said to be climate-sensitive, particularly with regard to precipitation and temperature changes: "[h]igher temperatures will generally increase microbial peat decomposition and carbon mobilisation" (Hölzel et al., 2016, p. 355) in soils, increasing DOC mobilisation and CH4 emissions (see fig. 2, p. 8).

Thus peatlands can act as a NCS through storing or additionally sequestering carbon (see Ferretto et al., 2019), which "depends upon the balance between carbon inputs and decomposition" (Yigini & Panagos, 2016, p. 849) constrained by the conditions mentioned above.

In the recent past and at the moment, the most severe driver of peatland degradation – and according increases of GHG-emissions – is drainage (e.g. for agricultural purposes, see Couwenberg et al., 2011; von Oheimb et al., 2014).

Drainage of peatland areas leads to the lowering of the water table, hence to oxic conditions with the described emission feedbacks (Humpenöder et al., 2020). The oxidation process leads ultimately to peat losses, depending in magnitude on the specific land use type and water table height after drainage (see Evans et al. 2021): Pasture use leads to ca. 1 cm of peat thickness lost per year, according to Hölzel et al. (2016), while arable land use costs 2 cm of peat layer per year, according to LLUR (2013) (see also App. 5 and 8).

These losses are happening rather quick compared to the previous accumulation which proceeded over thousands of years (Jensen et al., 2010; Müller & Joos, 2020), but can quite rapidly be stopped again through rewetting.

The rewetting of peatlands, technically simple to carry out through the backfilling of drains, is an established restoration and conservation practice, reversing the biochemical process towards lower emission, allowing peatlands to act as a NCS again (Griscom et al., 2017). Even with uncertainties with regards to increasing methane emissions (Günther et al., 2020) or timely transition periods after rewetting, in which GHG-emissions can still be high (Humpenöder et al., 2020), rewetted peatlands are mainly said to serve as a net carbon sink (Böckenhauer et al., 2016; Joosten et al., 2016; Tanneberger et al., 2021).

Next to rewetting the conservation of existing peatlands is paramount, because the preservation and conservation of existing peatlands is usually more effective, ecologically and economically, than their recovery and restoration (as goes for other ecosystems) (TEEB DE, 2014; von Oheimb et al., 2014).

Notably there are other physical and chemical peatland traits and functions, like local cooling effects through evapotranspiration (e.g. Helbig et al., 2020; Hölzel et al., 2016) which will not be part of this analysis due to scope guidelines (for further details see Jensen et al., 2010).

The usefulness of peatlands as a NCS seems given from a biochemical perspective, when kept wet, at least under currently known climatic conditions (Tanneberger et al., 2021).

2.1.5 Potential Climate Change Effects on Peatland Biochemistry

As outlined above, "[t]he main condition needed for a peatland to form is a water-logged surface and cool temperatures" (Ferretto et al., 2019, p. 2102). The stability of these factors is currently at risk (Yigini & Panagos, 2016).

The extent of anthropogenic disturbance and its implications, such as prospective GHG-emissions and the resulting extent of temperature regime changes in different parts of the world, can be expected to be extensive (Steffen et al., 2018), though manifested differently in different regions (for SH regional estimates see Friedrich et al., 2017; Hölzel et al., 2016). The mean global trend for warming is scientifically "virtually certain" (IPCC, 2014, p. 52), also because we are already committed to our past impacts and their continuing, unfolding feedbacks (see Steffen et al., 2018). Regional impacts can expected to be different but with regard to the focus area of SH, climatic changes towards warmer and drier regimes are likely (Friedrich et al., 2017; Hölzel et al., 2016) (see part *2.2.2*).

Even with uncertainties prevailing, peatlands and their biochemical functioning are thought to be under pressure by future climate changes (Hölzel et al., 2016; IPBES, 2018, p. 76). Temperature and precipitation changes are particularly vital to peatland biochemistry (e.g. MELUND, 2017; TEEB DE, 2014; Wilson et al., 2016), as they influence peatland anoxic conditions through changing inflow (precipitation) and outflow (evapotranspiration in relation to cloud cover, radiation balance and temperature) (Hölzel et al., 2016) of water, and consequently GHG cycling and soil atmosphere interactions (Couwenberg et al., 2011; Yigini & Panagos, 2016).

Ferretto et al. claim for instance, that prospective climate conditions might no longer "be able to support peatlands [in Scotland] in the near future"(2019, p. 2101), thus putting half of Scotland's peatlands at risk. Hölzel et al. (2016) underline this risk for the whole North Sea region, even if precipitation patterns stayed unchanged, as a temperature increase alone will suffice to change water flows and thus imperil peatlands (see Ise et al., 2008).
Additional factors like for instance vegetation changes through CO_2-fertilization or phenological changes (Helbig et al., 2020), leading to prolonged growing seasons (Jensen et al., 2010), might cause reciprocal feedbacks on peatland gaseous cycles (Steffen et al., 2018) which are complex and difficult to predict. Detailed estimates are possible and necessary to inform future actions, in order to be able to adapt and avoid undermining our own livelihood through vitiating moderate climate conditions (see Steffen et al., 2018, for different trajectories of the Earth System and tipping points).

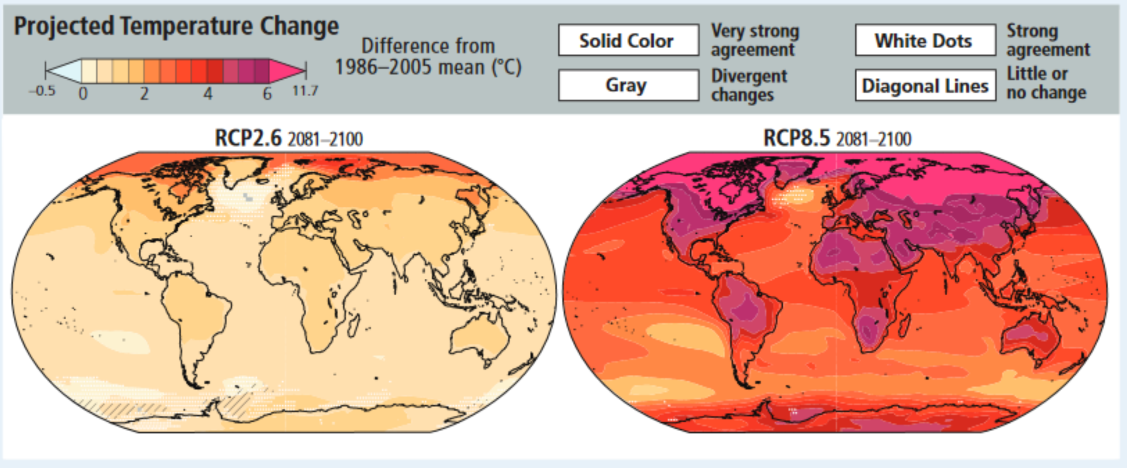

Figure 3: Projected mean surface temperature changes for RCP2.6 and 8.5, between 2081-2100 (compared to mean observations between 1986-2005). An overall global warming is expected, as visualized, with differences of several °C regionally and little probability for regional cooling. From: IPCC, 2014, p. 10.

For Europe the *IPCC* expects increasing risks from e.g. wildfires and heatwaves or additional threats from coastal flooding, which would imperil peatlands accordingly (Handmer et al. 2012). For a detailed look at Schleswig-Holstein the case will be made below (*2.2*).

With a look at the past a few hints give further directions: It has been found that peatlands responded strongly to climatic changes in the past. Peatlands appeared, vanished and shifted local distributions (e.g. from south to north), driven dominantly by temperature changes in the northern latitudes (reconstructed for the end of the last glacial maximum) (Müller & Joos, 2020; see App. 10, for other drivers of peatland changes).
"Most of to-day's peatlands [were] formed over the past 12 000 years as a result of deglacial climate change and ice sheet retreat" (Müller & Joos, 2020, p. 5285). This indicates

that there has been a relationship between climate and peatlands in the past but also implies that the relative climate stability of the last 12,000 years (see Lewis & Maslin, 2015) has allowed peatlands to grow and persist (unless humans interfered).

Changing climatic conditions today might alter that balance (Yigini & Panagos, 2016), as has been indicated: carbon losses are reported for all soil types, especially peat soils, in England and Wales (similar climatic zone to SH), with uncertain (though possible) attribution to CC and warmer temperatures (cf. Hölzel et al., 2016, p. 356).

The case for Schleswig-Holstein is yet to be assessed (see below).

2.2 The local context – Schleswig-Holstein

The following section will move from the macro-level of CC, as the overarching problem, with peatlands as a possible solution pathway, to the micro- and local-level of Schleswig-Holstein. This region and county of northern Germany provides an exemplary reference point and contextualization to the topic at hand, because it entails considerable amounts of (mainly degraded) peatlands (see Böckenhauer et al., 2016), which relates SH to the important issues and questions of peatland protection, conservation and restoration (see Humpenöder et al., 2020) plus the prevailing threat of peatland degradation (MELUND, 2017). In addition, there is suitable literature with regards to climate scenarios (e.g. Pfeifer et al., 2021), peatland history, development (e.g. LLUR, 2013) and policy (e.g. LLUR, 2012), and GHG-emissions related to SH peatlands (e.g. Jensen et al., 2010), which makes this circumscribed local subject suitable for an examination of the designated scope.

2.2.1 Peatlands in Schleswig-Holstein

Today's peatlands of northern Europe and SH have largely formed at the end of the last glacial period (Böckenhauer et al., 2016). By now, and for hundreds of years[6], about 95% of peatlands in Germany and SH have been or are being drained and degraded, and are therefore emitting vast amounts of GHGs (CO_2, CH_4 and NO_2) (e.g. Böckenhauer et al., 2016; Tanneberger et al., 2017)(as described above). These emissions amount to 10-30% of total GHG-emissions in SH, as reported by the federal environmental agency (LLUR, 2012). Jensen et al. from the *German Scientific Peatland Society* (*DGMTEV*) calculated 9.3% of total GHG-emissions from degraded peatlands (except LULUCF), corresponding to 2.4 Mt of CO_2e / a, while peatlands cover ca. 10% of land area in SH (Jensen et al., 2010).

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[6] Peatlands were being drained e.g. to convert them into nutrient-rich, arable land or pasture. Peat is also being used as heating fuel, bedding or as nutrient rich substrate in horticulture (see Böckenhauer et al., 2016; LLUR, 2013; von Oheimb et al., 2014).

From the remaining peatlands, about 12% are still considered near-natural ecosystems and carbon sinks, respectively peat-forming mires (Böckenhauer et al., 2016), leaving 88% fully to partly degraded (see App. 6, for a map of peatlands in SH). According to SH federal reporting, this current peatland area amounts to ca. 145,000 ha, of which 45,000 ha are wet, acting as carbon stores, of which 17,500 ha are mires, actively sequestering carbon (Jensen et al., 2010; LLUR, 2012).

Comparing these numbers to the whole of Germany, where degraded peatlands account for 30% of all LULUCF emissions and 3.7% of total GHG-emissions (8 Mt CO_2e / a) (BMUB, 2016; von Oheimb et al., 2014), SH and the other neighbouring northern counties provide for the largest shares of peatland area and according emissions (Böckenhauer et al., 2016; LLUR, 2012). Nationwide peatlands cover 3.58% (1,280,000 ha) of federal area, with 1.95% (25,000 ha) of these still forming peat (mires) (Tanneberger et al., 2017; see BMUB, 2016; Hölzel et al., 2016)[7](see App. 6 for other peatland types in SH)[8].

Peatlands in SH (as in many parts of the world, see IPBES, 2018) are considered to be under continuous and even increasing pressure from growing land use competition (e.g. Humpenöder et al., 2020). They are increasingly being acknowledged and included in climate mitigation and adaptation policies, as is the case in SH (see Friedrich et al., 2017, MELUND, 2021, for federal implementations).

There is still need for improvement it seems, as farmers for instance seem to have little incentives to use their land sustainably (e.g. through wet land-cultivation practices like paludiculture) (von Oheimb et al., 2014) despite knowing that land use is a vital factor for peatland functioning (Hölzel et al., 2016).

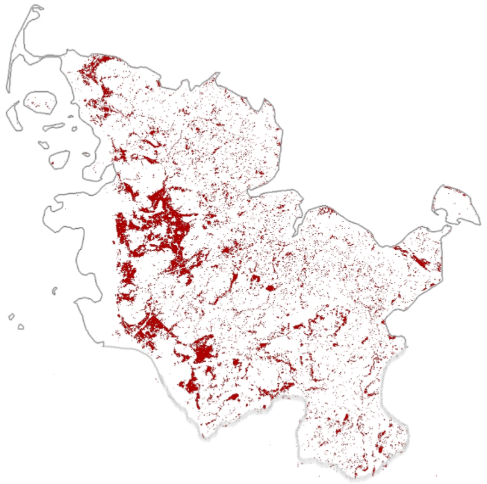

Figure 4: Cover of organic soils in SH. In up to 1 m depth, about half the terrestrial C-stock is found in organic soils, which amount to 10% of SH land area. As most peatlands have deeper peat soils, the actual amount is assumed to be much higher (cf. Jensen et al., 2010, p. 216). Figure adapted from: https://www.umweltdaten.landsh.de/atlas/script/index.php,(last reviewed 20.04.2021)

With this in mind many questions arise, e.g. how can peatland conserving land use practices be established through policy (see BMUB, 2016) or other incentives (see Joosten et al., 2016; Böckenhauer et al., 2016) and how can different needs

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[7] In the EU drained peat-lands emit ca. 220 Mt CO_2e / a (ca. 5% of total EU emissions) (cf. Tanneberger et al., 2021, p. 2).

[8] Note: Different areal numbers are reported, though within similar range, by e.g. Böckenhauer et al. (2016, pp. 7, 93) and LLUR (2013, p. 5). For the subsequent analysis and modelling the numbers mentioned above (according to Jensen et al., 2010, p. 215; and LLUR, 2012, p. 15) were used.

of e.g. food provisioning and climate protection be adequately balanced (e.g. Günther et al., 2020; Humpenöder et al., 2020; Schlattmann & Rode, 2019).

Assuming, based on the information provided so far, that peatland conservation and restoration are desirable goals with regard to CC mitigation (NCS), the questions in focus here are whether these goals will be viable and still sensible under future conditions of a changing climate (and changing economical factors, see *2.3*).

2.2.2 Climate in Schleswig-Holstein: Observations and Prognosis

The temperate zone climate in SH (see fig. 5), is strongly characterized and influenced by the surrounding water bodies of the North and Baltic Sea (see App. 6 for a map of SH) and its flatland topographical relief (Friedrich et al., 2017; Pfeifer et al., 2021).

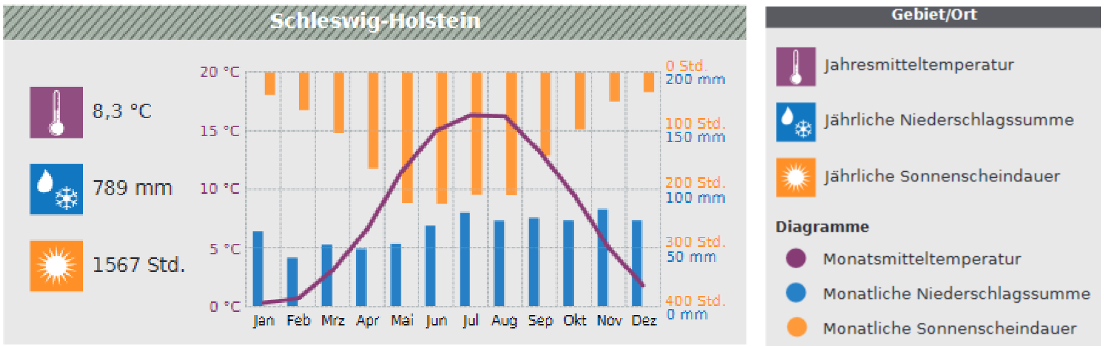

Figure 5: Current climatic conditions in SH (values between 1961–1990, measured by the DWD). From: Friedrich et al., 2017, p. 12.

To date, changes have already been observed similar to the global trend of warming of about 1°C, compared to pre-industrial levels. A SH federal climate report (joint report of *DWD* and *LLUR*) states a slightly stronger warming of 1.3°C for SH since 1881 (Friedrich

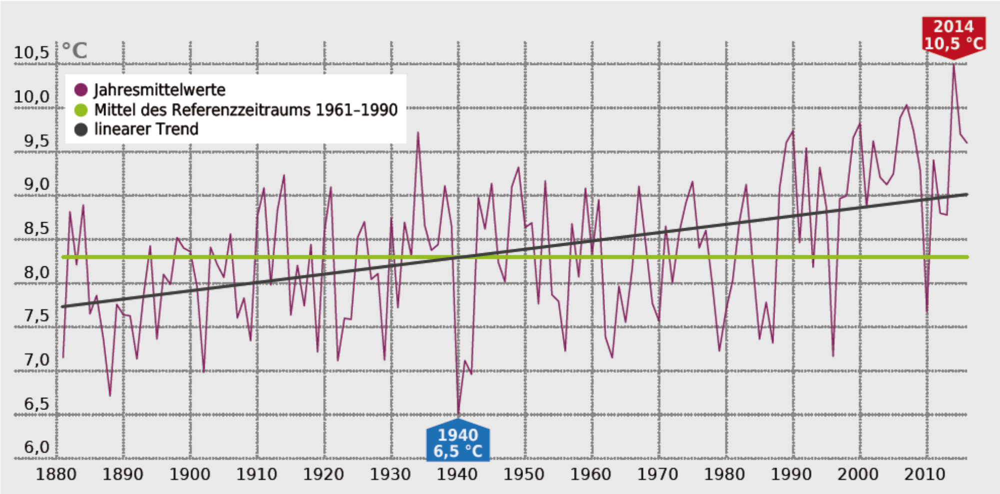

Figure 6: Observed annual mean temperature changes between 1880 and 2014 (compared to 1961-1990) in SH. The trend shows is a continuous warming, of ca. 1.3°C total over the whole depicted time-slice. From: Friedrich et al., 2017, p. 15.

et al., 2017), while Pfeifer et al. from the *Climate Service Center Germany* (*GERICS*) report 0.9°C warming, comparing the 30-year time slices of 1951-1980 versus 1986-2015. Overall warm days have increased (mainly in summer), while cold days have decreased (mainly in winter) (MELUND, 2017) (see fig. 6, p. 14 for annual observed changes).

With regard to precipitation, observed levels have slightly increased since 1881, most pronounced in autumn and winter, though less significantly and distinctly than temperature overall (Friedrich et al., 2017; MELUND, 2017).[9]

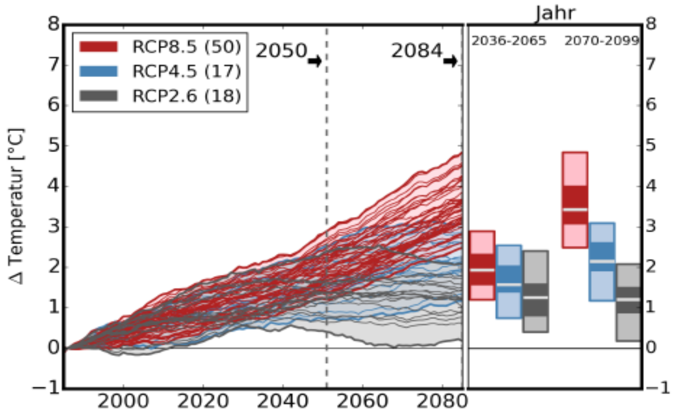

Figure 7: Relative temperature changes in different RCP scenarios for SH, based on modeling by GERICS. RCP2.6 leads to a temperature reversal around mid-century while RCP8.5 leads to a continued temperature increase. From: Pfeifer et al. 2021, p. 8.

The climatic changes so far have already resulted in a variety of consequences, for example phenological shifts (e.g. a prolonged growing period and species migration northwards), which can be expected to continue in the future (Hölzel et al., 2016).

The climatic trend for this century in SH, is a general warming, in line with the global developments (see fig. 1, p. 4, and fig. 3, p. 11, for the general RCP2.6 and 8.5 prognosis; for further global details see IPCC, 2019; for more SH detail see MELUND, 2017) as is visible in the *GERICS* scenario modelling (see fig. 7 for relative temperature changes; for absolute temperature changes see fig. 8).

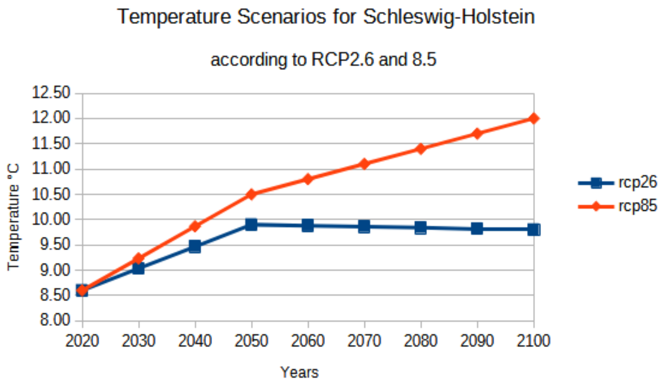

Figure 8: Temperature changes, per decade, according to the RCP pathways 2.6 and 8.5, based on extrapolated values (see 3.1.2 for details) from GERICS, for SH; starting with a mean temperature of 8.6°C today (see Pfeifer et al., 2021).

Summers are expected to be slightly drier and winters slightly wetter (see fig. 9, p. 16) though high uncertainties exist for precipitation forecasting, with the latter ranging between an 11.6% decrease to 33.2% increase, whereas the degree of certainty is highest for the RCP8.5 and therefore the warmest scenario (Pfeifer et al., 2021).

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[9] For a detailed descriptions of climate indicators (e.g. *summer days*, *ice days,* etc.) and observations see Pfeifer et al., 2021.

The modelled future climatic conditions for SH – especially the increasingly warmer, drier and longer summers (see Pfeifer et al., 2021) – cause a potential threat to peatlands in various ways (as introduced in *2.1.5*). For instance, increased evapotranspiration and changed precipitation patterns (wet winters, dry summers) or prolonged peatland vegetation growth (see Hölzel et al., 2016) are influencing peatlands functioning as carbon sinks or emitting sources (e.g. Friedrich et al., 2017; Griscom et al., 2017).

This problem has been acknowledged by the county of SH, in their *Climate Mitigation Report* (2017), recommending peatland conservation and restoration (rewetting)(see MELUND, 2017; Böckenhauer et al., 2016; Friedrich et al., 2017), though the impacts of different future climatic conditions and their possible damage cost (social value of carbon) have not been incorporated or assessed, as aimed for by this analysis.

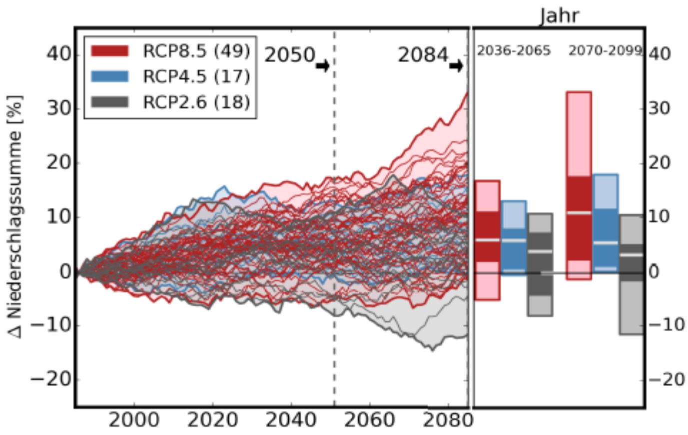

Figure 9: Precipitation scenarios, based on different RCP modellings from GERICS, for SH. From: Pfeifer et al. 2021, p. 13.

2.3 Peatland Valuation and Carbon Pricing

Peatlands and their ecosystem-services (ESS) – here carbon storage – can be quantified in different ways. As the *IPBES* states, *nature's contributions to people* can be valued in socio-cultural metrics (e.g. preference assessments) or in economic (e.g. monetary) terms (cf. IPBES, 2018, p. 147). This can be useful in order to compare different ESS and biomes, and to allow for accounting and quantifying utility and effectiveness of the same, which can ultimately strengthen policies and decision making, as concluded by the international *TEEB* process (TEEB DE, 2014; see Joosten et al., 2016).

The idea of ESS measurement is particularly useful to allow for integrating externalities[10] like GHG-emissions (Stern, 2009, p. 24), into land-use evaluation, which are usually not accounted for in conservative balancing (TEEB DE, 2014).

With regards to peatlands this means, that the monetary value of using peatland areas either as drained (e.g. pastures, see Böckenhauer et al., 2016) or wet land areas (e.g. palu-

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[10] Externalities describe "[a] positive or negative consequence (benefit or cost) of an action that affects someone other than the agent undertaking that action and for which the agent is neither compensated nor penalized through the markets" (IPBES, 2018, p. 810).

diculture, see Schröder et al., 2015; Tanneberger et al., 2021) is usually evaluated without incorporating the external costs of GHG-emissions according to the chosen land-use type (see App. 5). This analysis aims to explore both.

2.3.1 Social Cost of Carbon

For the matter at hand, the concept of carbon pricing, more specifically the 'social cost of carbon' (SCC), was used to measure the peatland service of carbon storage (respectively CO_2e-emissions) under different climatic conditions, in order to compare the cost-effectiveness of different peatland management practices under Climate Change and to find out if different future price pathways hamper or favour sustainable peatland management (in terms of degrading or rewetting the latter) (see Griscom et al., 2017).

Carbon pricing is a common tool (e.g. the EU *Green Deal* and other worldwide schemes, see World Bank, 2020) that is thought to be imperative to GHG emission reduction policies (High-Level Commission on Carbon Prices, 2017): "[p]ricing emissions ensures they are reduced as cheaply as possible, is easier to get right than regulation, and makes the polluter pay" (Burke et al., 2019, p. 4).

Carbon pricing means to put a monetary value on CO_2 (and equivalent) emissions, hence pricing indirectly the storage and mitigation of CO_2e (see Valatin, 2011). As theses emissions accumulate and stay in the atmosphere for a long time (see Matthey & Bünger, 2020), making it a societal problem of the commons, this damage can commonly be expressed as the social cost of carbon (SCC) (Stern, 2009, p. 25).

The SCC therefore quantifies the damage cost of an extra unit of CO_2e emitted into the atmosphere (The World Bank, 2020; Valatin, 2011), and will furthermore be used as a metric for this analysis (see Model 3.2).[11] Inherently this means pricing the value of (mitigated) future climatic conditions (externalities), hence the well-being of future generations, and internalizing this value into today's pricing schemes and markets (Kindermann et al., 2006; Stern, 2009, p. 23).

Discounting rates on future SCC developments reflect exactly that relationship. Low rates (e.g. 1%) value future generations benefits from emission limitations similarly to today's whereas high discounting rates (e.g. 5%) imply the opposite (see Matthey & Bünger, 2020). Discounting is used to describe future costs in present value terms (NPV) (Lowe, 2008).

In the model below, a medium discount rate of 2.5% was used, which is similar to *UK Green Book* (UK public spending guidelines) long-term discount rates (Lowe, 2008), al-

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[11] Another common pricing mechanism is the marginal abatement cost (MAC) (see Stern, 2009, p. 25).

lowing to express future prices in net present values (NPV). It should be noted however, that the concept of discounting is highly controversial e.g. due to its varying underlying assumptions (see Baumgärtner et al., 2015).

Estimates of the social value of carbon range from €0 to over €1000 / t of carbon (see World Bank, 2020), reflecting differing assumptions (e.g. the inclusion of social unrest damage costs) and uncertainties (emission developments) (cf. Valatin, 2011. p. v). The German government, for instance, quantifies the SCC as €195 (when favouring the present generation) and €680 (when valuing present and future generations equally), in 2020 values (Matthey & Bünger, 2020, p. 8; see DECC, 2011, for UK estimates; see Burke et al., 2019, for more up to date recommendations). Griscom et al. (2017) estimate a social cost of carbon for 2030 as €67-213[12] / t CO_2e, in order to meet the 1.5-2 °C climate target.

As mentioned above, there are other ways of quantifying and evaluating ESS (see IPBES, 2018, p. 146). In SH there are small-scale, local peatland valuation schemes that incentivise climate-friendly peatland management, e.g. through federal equalization payments schemes for land-users rewetting their lands (see Böckenhauer et al., 2016) or the voluntary *MoorFutures* scheme, trading emission offsets to finance rewetting (see Joosten et al., 2016).

Carbon pricing and its potential future effects on peatland management is particularly interesting, because "[g]reenhouse gas emissions in agriculture and land use are currently under-regulated" according to Burke et al. (2019, p. 8). As peatlands ESS, like carbon storage, are not usually traded in markets, this commonly leads to the unsustainable use and exploitation of these resources (cf. von Oheimb et al., 2014, p. 456). This shortcoming has been described as a key market failure (High-Level Commission on Carbon Prices, 2017; Stern, 2009, p. 24).

2.4 Interim Conclusion

In order to find out if Climate Change (reflected in the RCPs) and differing GHG-emission-costs (reflected in the SCCs) might have an impact on peatlands and their carbon services in the future, respectively their usefulness as a NCS, some concluding deductions can be drawn here, based on the descriptions above:

The global climate is changing which demands urgent mitigation action (e.g. Steffen et al., 2018). Peatlands offer mitigation potential (NCS), as they can act as a net carbon and

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[12] US$ values in Griscom et al. (2017) were converted into € according to the *European Central Bank* exchange rate of US$1 = €0,8189. https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html (last reviewed 20.05.2021).

GHG sink (e.g. Wilson et al., 2016) if managed properly. The relationship of soil-atmosphere interactions of peatlands and their meaning for CC is evident: “Peatlands are an essential part of the terrestrial carbon cycle and the climate system“ (Müller & Joos, 2020). This relationship is reciprocal and CC has been reported to negatively impact soil organic carbon on a global scale (see Yigini & Panagos, 2016; Ferretto et al. 2019) and has altered peatland abundance in the past (Müller & Joos, 2020).

As most peatlands are currently degraded, as is the case in SH, leading to vast GHG-emissions (e.g. Hölzel et al., 2016), rewetting seems like an affordable local solution and NCS strategy (e.g. Günther et al., 2020): The “[p]rotection of peat soils through conservation, rewetting and sustainable use is pivotal amongst the most effective measures to avoid significant GHG emissions” (Tanneberger et al., 2021, p. 3). With a changing climate given, the question is whether peatlands are still a viable NCS under future conditions.

Peatland abundance to climate variables has been studied in the laboratory and in the field (see Günther et al., 2020; Strack et al., 2004) as much as there is chemical and physical evidence for the relationships of temperature and peatland water saturation (see Hölzel et al., 2016; J. Clark et al., 2010; Jensen et al., 2010). Simultaneously temperatures in the study area of SH have risen and are estimated to rise further.

Although to differing extents, depending on the scenario, increasing future peatland imperilment can be assumed, as warmer conditions appear to be increasingly inadequate for peatland carbon retention (see Günther et al., 2020), “[w]hat appears not to be explicitly considered is that […] peatlands require certain climatic conditions that in the coming decades might no longer be satisfied […]” (Ferretto et al., 2019, p. 2102).

In addition to the biophysical insecurity of peatlands feedbacks to CC, an economical perspective was considered, examining how high or low SCCs affect peatland emissions and hence management and damage costs in the future. The subsequent synthesis and models therefore aim to give an ecological and an economical perspective with regards to peatlands as a NCS under future conditions.

3 Synthesis and Modelling

The following section aims at synthesizing the information examined thus far, in order to assess peatland processes under future conditions, through modelling.
A model is a simplified depiction of reality. Defined factors of inputs (here temperatures and carbon prices) and outputs (here emissions and costs) were set in a probabilistic relationship (as outlined below). This modelling can be useful in order to simulate future conditions of defined systems and their responses, to guide future actions or inform policy-making (here with regard to CC and peatland management).
Two models were designed: a biophysical model and an economical model. The biophysical model is conducive to estimate peatland gas fluxes and carbon- storage under different management (rewetting, not rewetting) and climatic conditions (RCP2.6 and RCP8.5), whilst the economic model aims to estimate the social value and cost-effectiveness of peatland carbon storage or emissions under these different management and climatic conditions, indicating the suitability of peatlands as a NCS in the future.
With regard to the scope of this work, assumptions and simplifications were inevitably made for the models, almost a necessity when predicting complex future events (Yigini & Panagos, 2016). The foci made here, the inclusion and exclusion of factors and the degree of adequate complexity, were therefore explained and made transparent, while complementary information was suggested (if not found above).

Other studies and models have conducted similar examinations but were not relevant to the specific RQs proposed here, when considering the scope and complexity desired for this thesis. As they were inspirational to the proposed model design below, they shall be referred to (if not found above):

- Ferretto et al. (2019) have modelled potential carbon losses from Scottish peatlands under CC.
- Humpenöder et al. (2020) designed a land-use model, projecting future peatland dynamics and according GHG-emissions, for a 2 °C mitigation pathway.
- Wilson et al. (2016) calculated GHG-emissions for rewetted peatlands.
- Clark et al. (2010) used an ensemble of statistical bioclimatic envelope models to estimate the vulnerability of blanket peat to CC.
- The *Potsdam Institute for Climate Impact Research* (*PiK*) has developed the *MagPie Model*, which can be used to assess and model land use competition and according GHG

emission consequences (see also (Humpenöder et al., 2020): https://rse.pik-potsdam.de/doc/magpie/4.1/ (20.05.2021).

- The University of Stanford has developed the *InVest Model*, which can be used to model land use changes and according GHG-emissions, ESS and costs: https://ecosystemsknowledge.net/invest (20.05.2021).
- The *Greifswald Mire Centre*, a unit of the University of Greifswald (a leading research institution in the field of peatland science) hosts an extensive online knowledge-base. The herein included *Klimaschutzrechner*, a digital tool to calculate peatland emissions, has provided valuable insights for the model design below: https://www.moorwissen.de/de/moore/tools/klimaschutzrechner.php (20.05.2021).

3.1 Biophysical Model

3.1.1 Objectives

The primary function of the biophysical model is to assess whether carbon stocks of a given peatland area (in SH) will subsist, increase or decline under future climate conditions. While looking at two common scenarios (RCP2.6 and RCP8.5) the possible time lag of peatland sensitivity to unfolding climatic changes (e.g. with regard to a future temperature threshold) shall be accounted for by generating results for the near future until the end of the century (which lies similarly within the common RCP time-scale, see IPCC, 2019). Additionally, a “no Climate Change” (noCC) case was calculated to allow for better comparison of present and future conditions.

These three climate conditions and their resulting CO_2e-emissions were calculated for three different peatland management conditions:

1. Wet peatlands in SH (conservation management) → assuming currently wet peatlands are to be left wet
2. Drained peatlands (drained management) → assuming currently drained peatlands are left drained (implying the continuation of the status quo in SH)
3. Rewetting of currently drained peatlands (rewetting management) → assuming an upscaling of wet peatlands, respectively the restoration degraded ones, for NCS purposes (intended GHG reduction)

3.1.2 Method and Data Processing

In order to find out if peatlands in SH can be a climate-effective natural solution (NCS), through rewetting (see fig. 10), under changing climatic conditions, the emissions of wet, degraded and rewetted peatlands were modelled for the RCP2.6 and 8.5 climate scenarios, within the time-frame 2020-2100 (decadal resolution).

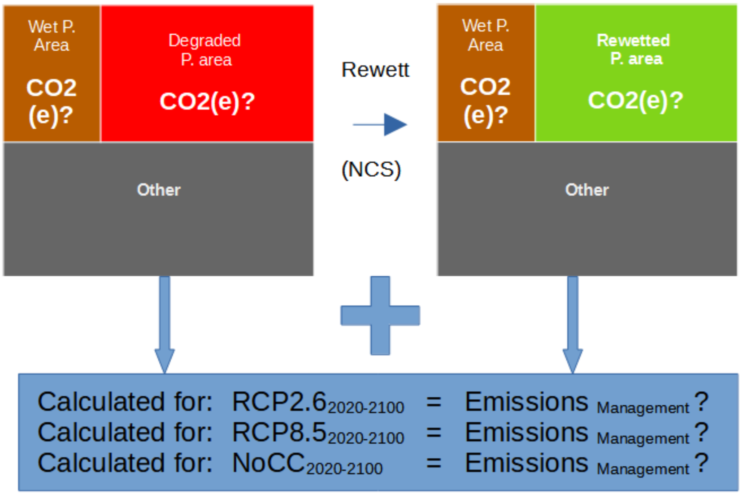

Figure 10: Of 1,579,965 ha total SH area (squares) 145.000 ha are peatlands (upper half of squares), of which 100,000 ha (red) are drained and 45,000 ha wet (brown). The figure illustrates the rewetting of degraded peatland area in SH (green) in order to scale up carbon storing wet peatland area as a NCS. According emissions are calculated for wet, degraded and rewetted peatlands, for the scenarios RCP2.6, RCP8.5 and noCC, all between 2020-2100. Note: Squares do not depict the accurate relative proportions.

In order to translate future climatic conditions of the two scenarios into peatland GHG-emissions, future temperatures were related to water table levels in peatlands (as done by Ise et al., 2008; Strack et al., 2004) because water saturation is closely related to peatland GHG-emissions and its most distinct and influential factor (e.g. Clark et al., 2010; Couwenberg et al., 2011; Jensen et al., 2010; TEEB DE, 2014; Wilson et al., 2016).

As atmospheric near-surface temperature determines evapotranspiration of peatland water levels and as temperature increases have been reported to lower water table levels in the past (Hölzel et al., 2016; Ise et al., 2008; Müller & Joos, 2020) discrete temperature values were related to discrete peatland water table levels, based on Strack et al. (2004) (see tab. 1).

***Table 1:** Strack et al. (2004) report a 14 cm peatland water level decline in accordance with a 3°C temperature increase (in northern Canadian peatlands). This correlation is here assumed to be linear and translated into 0.1°C temperature steps (used subsequently in the model).*

Temperature (°C)	Water table level (cm)	Conversion (factor)
3	-14	
1	-4.67	/ 3
0.1	-0.47	/ 10

Subsequently the different RCP temperature values for SH (according to Pfeifer et al., 2021) were first extrapolated for all decades (linear regression) and then calculated into discrete water table levels (see tab. 2, p. 24), based on the relation found by Strack et al. (2004).

Table 2: *Calculations of RCP temperature projections for SH, according to Pfeifer et al. (2021). The reported mean temperature increases for SH (G) were extrapolated into decadal steps (E) and their relative temperature differences. The water table was calculated as described above: - 0.1°C equalling -0.47 cm.*

RCP2.6	**Mean temp. increase (°C)**				**Water table (m)**		In cm *x100*
	G	*E*	*Difference*		*Relative*	*Absolute*	
2020	0	8.60	-	=	-	-	-
2030		9.03	0.43	=	0.0204	0.0204	2.04
2040		9.47	0.43	=	0.0204	0.0407	4.07
2050	1.3	9.90	0.43	=	0.0204	0.0611	6.11
2060		9.88	-0.02	=	0.0009	0.0602	6.02
2070		9.86	-0.02	=	0.0009	0.0592	5.92
2080		9.84	-0.02	=	0.0009	0.0583	5.83
2090		9.82	-0.02	=	0.0009	0.0573	5.73
2100	1.2	9.80	-0.02	=	0.0009	0.0564	5.64
					Total	**0.0564**	**5.64**

RCP8.5	**Mean temp. increase (°C)**				**Water table (m)**		In cm *x100*
	G	*E*	*Difference*		*Relative*	*Absolute*	
2020	0	8.60	-	=	-	-	-
2030		9.23	0.63	=	0.0298	0.0298	2.98
2040		9.87	0.63	=	0.0298	0.0595	5.95
2050	1.9	10.50	0.63	=	0.0298	0.0893	8.93
2060		10.80	0.30	=	0.0141	0.1034	10.34
2070		11.10	0.30	=	0.0141	0.1175	11.75
2080		11.40	0.30	=	0.0141	0.1316	13.16
2090		11.70	0.30	=	0.0141	0.1457	14.57
2100	3.4	12.00	0.30	=	0.0141	0.1598	15.98
					Total	**0.1598**	**15.98**

G = Values from the Climate Service Center Germany for SH, reported for 2020, 2050 and 2100 (Pfeifer et al., 2021).
E = Extrapolated values for the other decades.

As climatic conditions expressed in temperature were now translated into discrete water table levels (see tab. 2) GHG-emissions could be calculated, similarly to Jensen et al., 2010:

$$CO_2e\ (A) = \sum_{t=2020}^{2100} (A * E_t) \quad \text{where} \quad E_t = x_t * \frac{0.5\ t}{10\ cm} * CO_2e / ha / a$$

x_t = cm of water table height (from tab. 2)

That means the model calculates the summed GHG-emissions (in CO_2e) of the given area (A) during a given time-frame (t) between 2020 and 2100, with a specific emission factor according to peatland type and drainage degree (E) (for details on peatland types, and Emissions in SH see see App. 8). The emissions factor was chosen based on Couwenberg et al. (2011) and Greifswald Mire Centre (2021), reporting 5 t / CO_2e / ha / a, per 10 cm drainage on agriculturally used fens, which is the predominant case in SH (LLUR, 2012).

The model calculates total CO_2e emissions in tons, per single hectare, per decade (summing the annual values of temperature changes, water table level changes and emissions within one decade together), for ease of representation. The decadal emissions per total area (100,000 ha and 45,000 ha) were calculated additionally (see also App.1).

Hereinafter the independent variable is the *water table level according to temperature* and the dependent variable the *GHG-emissions*.

For the wet peatland conservation management case (45,000 ha in SH), in 2020, emissions were assumed to be zero (similarly to Wilson et al., 2016) for the current status quo and the noCC scenario, to allow for better comparison of wet, drained and rewetted peatlands under the proposed different circumstances.

For the drained peatland sites (100,000 ha in SH), in 2020, a water table of -50 cm was assumed and set, similarly to Couwenberg et al. (2011) who set this depth as a threshold for deep drainage. According to the numbers above -50 cm equal 250 t of CO_2e / ha / decade (= E). Noting that most of the drained peatlands in SH are used as pasture land and acreage (LLUR, 2013), this number is within the same range as Jensen et al. report, with 24 t CO_2e / ha / a (Jensen et al., 2010).

For the left drained management case (as opposed to rewetting formerly drained sites, see below) these emissions were assumed and modelled to continue (simplified assumption) for the whole time-frame (based on Leifeld & Menichetti, 2018) assuming furthermore that the available carbon stock and bulk density is sufficiently abundant (which can be expected, according to Jensen et al., 2010). Possible CC-induced water table level changes over the century and according GHG-emissions were modelled in building on these figures (see below).

The left drained management case seemed useful as there are factors for its probability, like e.g. increased land demand as a risk to peatland degradation (Humpenöder et al., 2020).

For the rewetting management case it was assumed that rewetting is implemented in year 2030, resulting in a restored water table level near surface (here set at 0 cm; see Jensen et al., 2010) for the entire 100,000 ha of formerly drained peatland area (similarly to Wilson et al., 2016). This means that for the first modelled decade, peatlands in the rewetting case are still accounted for as drained sites (-50 cm equalling 250 t of CO_2e / ha / decade). After rewetting GHG-emissions are modelled to continue with 36,5 t CO_2e / ha / decade for 20 years (based on Griscom et al. 2017, in: SI) after which they stop entirely. This entire emission stop is a simplified assumption excluding factors like vegetation and former land use (e.g. Couwenberg et al., 2011; Ferretto et al., 2019; von Oheimb et al., 2014) but was similarly done by Wilson et al. (2016) who levelled out increased methane emission (see Günther et al., 2020) with decreased CO_2e emissions (= 0 t).

The rewetting management case was modelled because from an ecological perspective it is the way to restore these ecosystems (Couwenberg et al., 2011; Joosten et al., 2016) and from a NCS perspective this is the state in which they make sense, as they store carbon (Griscom et al., 2017; Jensen et al., 2010; Joosten et al., 2016): emissions are negligible at low water levels (>-20cm) (cf. Wilson et al. p.72, see Evans et al. 2021).

3.1.3 Model Boundaries

Assumptions on water table levels are made here neglecting precipitation for different reasons: Firstly, "[e]ven unchanged precipitation patterns mean less water availability because rising temperature imply water evapotranspiration" (Hölzel et al 2016: 343).

Secondly, precipitation forecasts have higher uncertainties for long-term trends (higher complexity) compared to temperature developments (see Friedrich et al., 2017; Pfeifer et al., 2021).

A long-term lowering of peatland water tables is expected for the North Sea region, induced by atmospheric warming. Possibly increased rainfall in winter doesn't seem to counteract this trend but would rather increase erosion and lateral washing out of DOC (Hölzel et al., 2016), which is notably another possible form of carbon loss but not part of this analysis. The seasonal distribution of precipitation is therefore of importance, rather than just an annual total.

Thirdly, precipitation is thought to be less important than temperature when it comes to peatland influences in temperate regions, as has been deduced from historic findings (Clark et al., 2010; Müller & Joos, 2020) (see App. 7 for the relationship of precipitation and temperature in relation to peatland area).

Hence temperature was chosen as the key indicator of peatland water saturation and according emissions.

Other factors that were excluded here include: possible feedbacks of e.g. fertilization due to increasing atmospheric CO_2 abundance or changed photosynthesis patterns due to differing radiation regimes in future climates (Hölzel et al., 2016), possible phenological changes (see Ise et al., 2008) resulting in e.g. more growing degree days of vegetation, increasing subsequently net evapotranspiration, which is consequently influencing the neglected factor of regional atmospheric cooling effects from peatlands (see Helbig et al., 2020; Joosten et al., 2016; von Oheimb et al., 2014).

The model is therefore valid for the proposed factors and assumptions and depicts a simplified reality (see J. Clark et al., 2010). Despite the challenges of simplified and neglected factors, environmental modelling can still give useful indications and deliver advancements towards better environmental systems understanding. As a recent modelling study (2019) exploring peatland feedbacks to a changing climate in Scotland states:

> “One of the main limitations of such models is that they are static, which means that they do not consider eventual feed-backs and, also, they do not take into account the possibility of adaptation of peatland vegetation to the new climatic condition. Keeping in mind these limitations, and considering the uncertainties which stem from this, at a national scale, they can still give a first estimate of how climate change can affect habitat extent. They also represent a useful tool to inform policies, indicating where best to focus restoration efforts“ (Ferretto et al., 2019, p. 2102).

3.2 Economic model

The subsequent economic model is largely extending the ecological model and is therefore determined by the emissions calculations and their intrinsic assumptions and limitations, as described above.

3.2.1 Objectives

The primary function of the economic model is to assess what societal damage, measured in the social cost of carbon (SCC), peatland GHG-emissions will have under different climatic scenarios and different management practices. Two different pricing pathways (a low cost and high cost pathway) were looked at, for similar points in time as in the ecological model to account for a possible time lag or threshold for carbon pricing changes.

Thereafter it was possible to evaluate the societal value of emission damages, or their avoidance, resulting from different peatland management practices (here conserving, rewetting or not rewetting) and their respective GHG-emissions under respective future climate scenarios (similar to the ecological model).

Focussing on rewetting seemed interesting also because it is thought to be a cost-effective climate mitigation strategy (e.g. Burke et al., 2019; Günther et al., 2020; Leifeld & Menichetti, 2018), at least under current climatic conditions (ca. 10-15 Euro / t CO_2 according to Tanneberger et al., 2021). This cost-effectiveness can hereby be evaluated for changing future conditions.

3.2.2 Method and Data processing

In order to find out if peatlands in SH can be a price-effective natural climate solution (NCS) through rewetting, under changing climatic conditions, the emissions of wet, degraded and rewetted peatlands (modelled above in the ecological model) were evaluated according to two discounted pricing pathways (see fig. 11). The price pathways processed here are fictive, with the idea of a low and a high price pathway in order to compare possible differences. Ranges are informed and within a similar span as other projections and assumptions (see Burke et al., 2019; DECC, 2011; High-Level Commission on Carbon Prices, 2017; Matthey & Bünger, 2020).

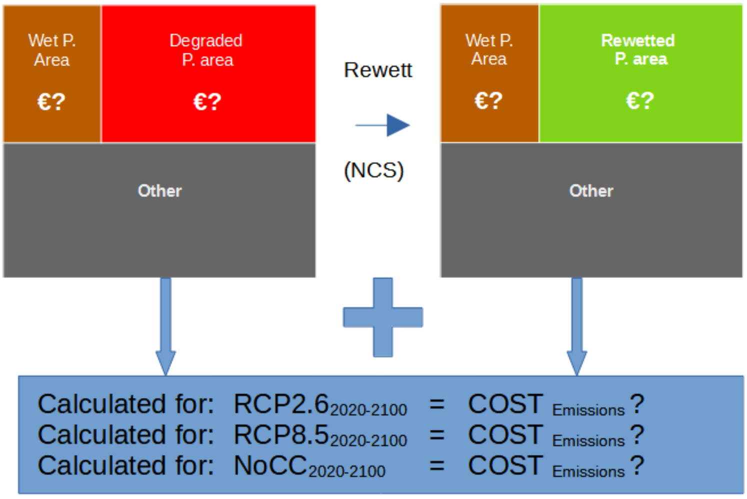

Figure 11: Of 1,579,965 ha SH area, 145,000 ha are peatland area, of which 100,000 (red) are degraded and 45,000 wet (brown). The figure illustrates the rewetting of degraded peatland area (green) if carbon storing wet peatland area were to be scaled up, as a natural climate solution. The model aims to calculate the costs accordingly. Note: Squares do not depict the accurate relative proportions.

The SCC price pathways were calculated for the low price pathway with a €3 increase per year and for the high price pathway with €10 per year, which are simplified assumptions as prices are usually dependent on e.g. emission developments in the future (the more CO_2e emissions there are in the atmosphere, the higher the SCC and the other way around; Matthey & Bünger, 2020, Stern, 2009).

These prices were used to calculate the costs of the resulting emissions, from the ecological model, for the three cases of existing wet peatlands, drained peatlands and rewetting of the drained peatlands, each for the climatic scenarios of noCC, RCP2.6 and RCP8.5 (as above). Costs for society (SCC) processed in this analysis can be regionally different and are processed here for the SH region (i.e. Western Europe) (for equity-weighting see Matthey & Bünger, 2020).

Discounting was used (as described in *2.3.1*), as commonly done, to allow for a net present value NPV expression of future prices and to be able to compare the different calculated cases in today's terms. The used discount rate of 2.5% can be described as a “medium rate”, valuing present generations’ benefits slightly higher than future generations’.

The emission costs were calculated by multiplying the emission results from the ecological model with the two mentioned price pathways (decadal resolution, 2020-2100):

$$\text{Emission cost}_{\text{Year}} = \left(\text{SCC}_{\text{Pathway(high, low)}} \times \text{Emissions}_{\text{Scenario (wet, drained, rewetted)}}\right)_{\text{Year}}$$

The NPV was being calculated for decadal steps, based on the years passed since 2020:

$$\text{NPV Emission cost}_{\text{Decade}} = \text{Emission cost}_{\text{Decade}} \,/\, (1 + 0{,}025)^{\text{(Years passed since 2020)}}$$

The decadal resolution is a simplification but seemed sufficient to account for differences between the scenarios (see App. 3 for discrete values). The independent variables are therefore the *decadal carbon prices (SCCs) per emissions*, as calculated in the ecological model. The dependent variables are the *emissions costs* (in accordance to climate scenarios and peatland management) calculated as NPVs, reported in € / t CO_2e / ha / decade.

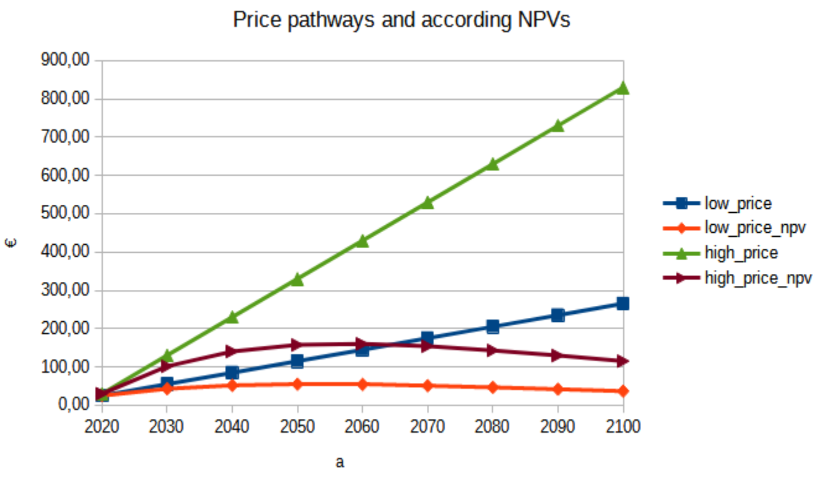

Figure 12: The model calculates emissions costs according to two given fictive (but literature informed) price pathways and their respective NPV values.

3.2.3 Model Boundaries

As mentioned above, the social cost of carbon varies widely depending on how it is measured and what assumptions and prerequisites are being made, and was used here within a similar range as e.g. the German and UK government expect them (see BMUB, 2016; High-Level Commission on Carbon Prices, 2017; Kindermann et al., 2006).

Discounting is similarly controversially debated and ideologically biased (see Baumgärtner et al., 2015), which ties the model outputs somewhat to the given prerequisites (valid for a 2.5% discounting case).

All other factors concerning the climatic scenarios and management cases underlay the same prerequisites and limitations as the ecological model, described above.

4 Results

The most striking findings and results, with regard to the research questions, are outlined subsequently as key messages. Based on the relationship of temperature and peatland water table level (see fig. 13), as described in *3.1.2* above, the following emissions were calculated. The emission costs were similarly modelled as described in *3.2.2*, according to price pathways and NPV values (see also fig. 12, p. 28).
For a full list of calculations and results see Appendix 1.

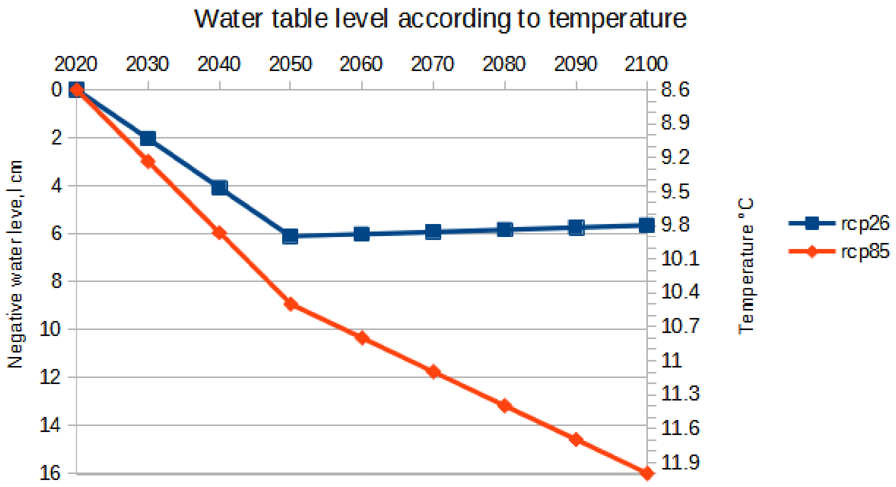

Figure 13: Water table levels according to temperatures, for the climate scenarios RCP2.6 and 8.5.(Calculated as outlined in 3.1.2)

The results are displayed here per single hectare, per decade, as it was more sensible to compare those values as opposed to total area values, which are different for wet and drained sites in SH, therefore tempering direct comparison. The total area values were compared when it seemed useful and can otherwise be thought of with the factor 45,000 for wet peatland area and 100,000 for drained / rewetted areas in SH, as outlined above in *3.1.2*. These values can also be found in the list of full results (see App. 1).

4.1 Key Messages

1. Peatland Emissions are Sensitive to Climate Change

The model reports that a warming, due to Climate Change, drives peatland emissions up (see fig. 14), regardless of the management case and most strongly for the worst-case scenario (RCP8.5). Notably, degraded peatlands have by far the highest emissions generally, increasing with climate warming and wet peatlands the lowest. Rewetted peatlands decrease emissions compared to drained sites, even in a warmer climate.

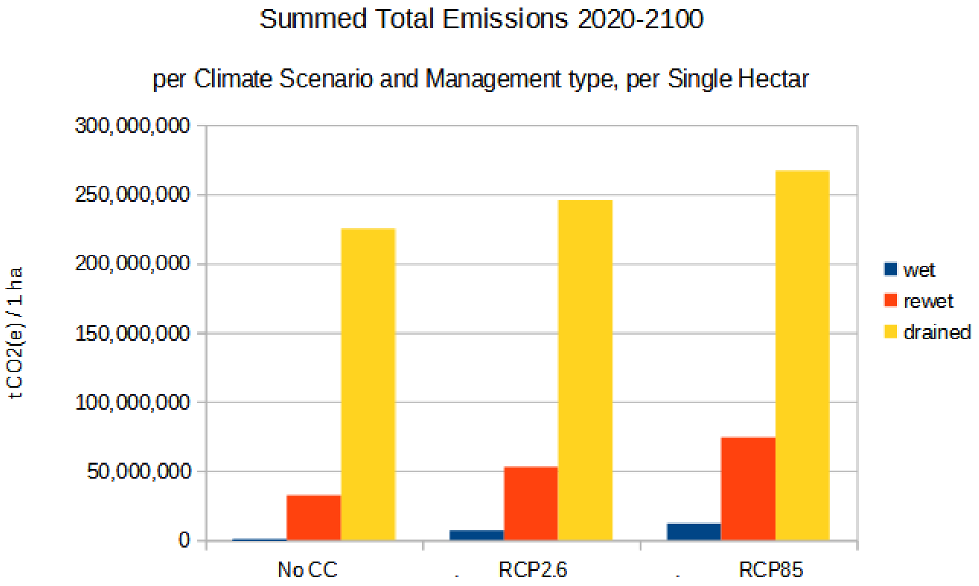

Figure 14: Total CO_2e emissions in SH, according to the extent of Climate Change (warming) and management type (summed up for the 80 year time period)

2. Costs of Peatland Emissions are Sensitive to Climate Change

The emission costs under all management cases and all price pathways rise with increasing CC. The warmer the temperature, the higher the costs (as are the emissions).

Wet peatlands are the least costly sites, even less costly under high CC conditions (RCP8.5) than drained sites under low CC conditions (see App. 1 for the full list of results).

Table 3 (p. 31) depicts exemplary the cost developments in accordance to temperature (and emission changes), for the case of drained sites in a RCP2.6 scenario: increasing temperatures lead to higher costs, though if the temperature increase gets reversed, as is the case in the RCP2.6 scenario (see temperature maximum in 2050, in tab. 3, p. 31), than costs decrease accordingly, similarly for the low and high price pathways but with different magnitudes.

Table 3: *Relationships of temperature, water table, emissions and prices (low, high, NPVs), per decade and single hectare in a RCP2.6 scenario under drained management.*

Drained	**Temp**	**Water table**	**Emissions**	**High Price**	**Low Price**	**NPV high**	**NPV low**
RCP2.6	*°C*	*cm*	*tCO_2e / ha / dec*	*€ / t CO_2*	*€ / t CO_2*	*€ / dec / ha*	*€ / dec / ha*
2020	8.60	-50	250.00	30	25	7,500	6,250
2030	9.03	-52.04	260.20	130	55	25,389	11,180
2040	9.47	-54.07	270.35	230	85	35,091	14,024
2050	**9.90**	**-56.10**	**280.50**	**330**	**115**	**39,331**	**15,379**
2060	9.88	-56.02	280.10	430	145	40,036	15,126
2070	9.86	-55.92	279.60	530	175	38,550	14,236
2080	9.84	-55.83	279.15	630	205	35,797	13,006
2090	9.82	-55.73	278.65	730	235	32,404	11,627
2100	9.80	-55.64	278.20	830	265	28,781	10,226
Total	**-**	**-55.64**	**1,899.90**	**-**	-	**111,053**	**312,088**

The chosen discount rate of 2.5% leads to the tapering off of cost developments over the course of the century, as seen in fig. 15, for the low cost pathway depiction (the graphs for the high cost pathway look similar though with higher magnitude, see App. 3).

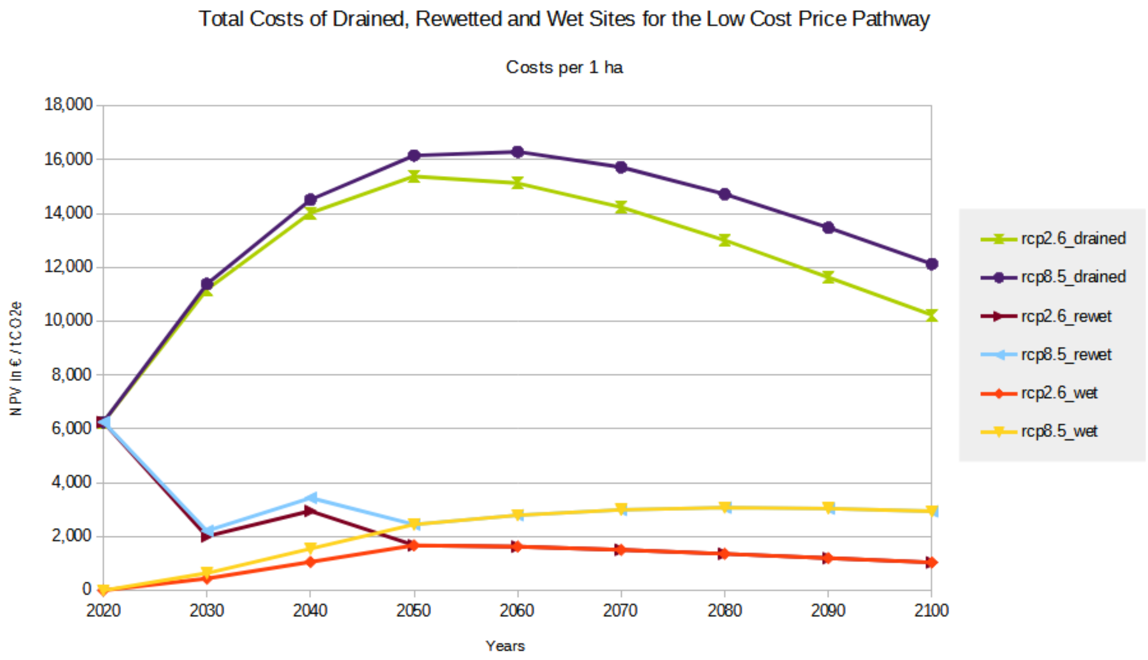

Figure 15: Depiction of decadal NPV developments for all management cases: drained (= status quo) and rewetted sites (NCS solution) in addition to price changes of wet sites (affected similarly by climate change), each per RCP2.6 and 8.5. Costs are displayed per single hectare.

If, similar to the status quo, drained sites and wet sites exist simultaneously costs of both could be added together according to the factors of their actual areal distribution. But as future distributions are unclear single hectare values of each possible management case (wet, drained, rewetted) are displayed here.

3. Emissions and Costs Differ Strongly with Regard to Management

As already visible above (e.g. fig. 14, p. 30) peatland management choices make a considerable difference to emissions and costs (for all of the climatic and pricing combinations). Draining leads to ongoing emissions and high costs, in any of the CC scenarios. Rewetting, on the other hand, always reduces emissions (see fig. 16) and costs compared to drained peatland use, while conserving wet conditions leads to the lowest overall damage costs (see fig. 15, p. 31).

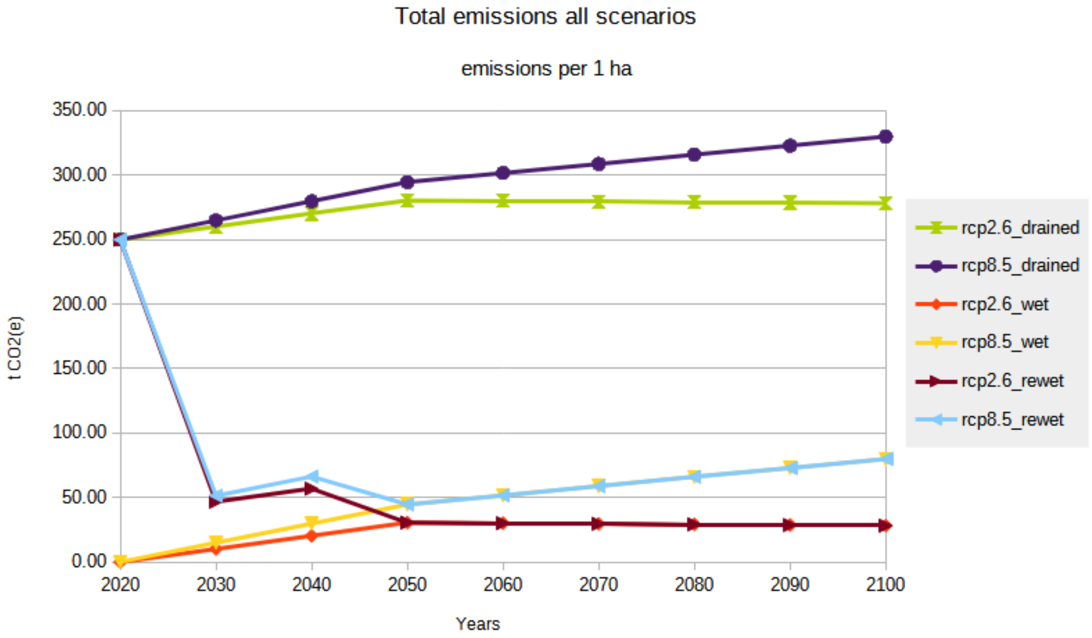

Figure 16: Total CO_2e-emissions for all climate scenarios and management cases per hectare.

4. Peatlands' Future Viability as a NCS Depends on the Extent of Climate Change

Whether peatlands will be a viable NCS – meaning the conservation of existing peatlands and the rewetting of drained sites – as initially asked, depends on the extent of CC within this model.

In the RCP2.6 scenario peatlands are a viable NCS: In a RCP2.6 future, were temperatures (accordingly emissions and costs) initially rise but taper off around mid-century (see tab. 4, p. 33) peatland rewetting lowers emissions and costs in all examined climate scenarios (see App. 1 for more details), compared to drained land use management. The initially increasing emissions and costs due to Climate Change, under all peatland management cases, can be stopped and reversed in a RCP2.6 scenario by rewetting, however not brought back to zero within the current century (see fig. 17, p. 33).

Table 4: *Emissions and NPV costs, per decade and single hectare, according to temperature and water table.*

Rewet	**Temp**	**Water table**	**Emissions**
RCP 2.6	*°C*	*cm*	*tCO_2e / ha / dec*
2020	8.60	-50	250.00
2030	9.03	-2.04	46.70
2040	9.47	-4.07	56.85
2050	**9.90**	**-6.10**	**30.50**
2060	9.88	-6.02	30.10
2070	9.86	-5.92	29.60
2080	9.84	-5.83	29.15
2090	9.82	-5.73	28.65
2100	9.80	-5.64	28.20
Total	**-**	**-5.64**	**472.90**

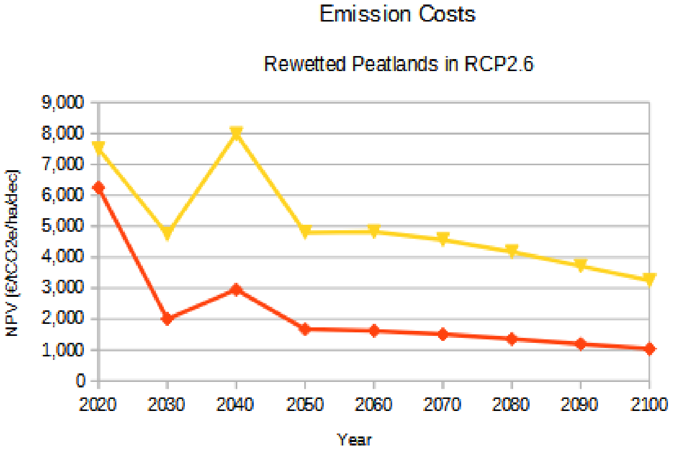

Figure 17: Emission costs of rewetted peatlands in a RCP2.6 scenario (see part 3.1.2 the rewetting conditions and timing), for the high (yellow) and low (red) SCC pathways.

In RCP8.5 scenario peatlands are a limited NCS: Under a RCP8.5 future emissions keep rising (as do temperatures) under all management cases (see fig. 18). Emissions keep increasing, even after rewetting, in a RCP8.5 scenario, whilst in a RCP2.6 scenario they are tapering off after rewetting (see fig. 16, p. 32).

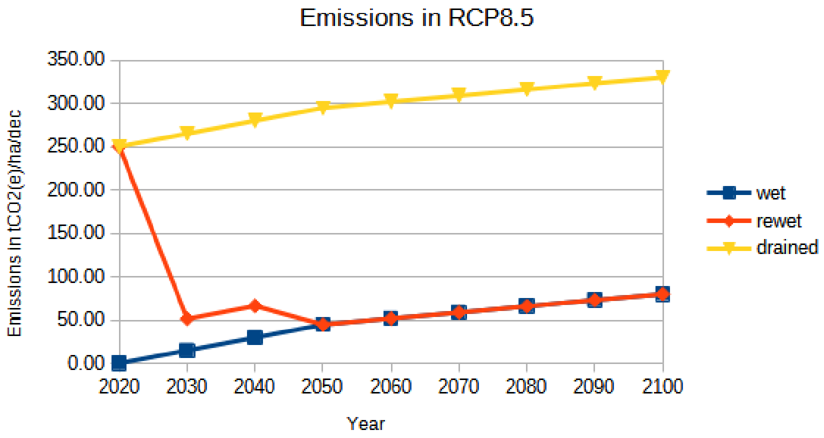

Figure 18: Differing emissions with regard to management type under the same climate regime (RCP8.5).

Accordingly, in RCP8.5, costs increase 20 years after rewetting still (as do emissions), though through discounting with a 2.5% rate this trend is reversed to a decrease by 2090, as seen in fig. 19, p. 34 (undiscounted costs still increase as seen in App. 1). This means rewetting in a high CC future does still reduce emissions and costs compared to drained sites, though less effectively, with higher emissions and costs compared to a low CC scenario (RCP2.6).

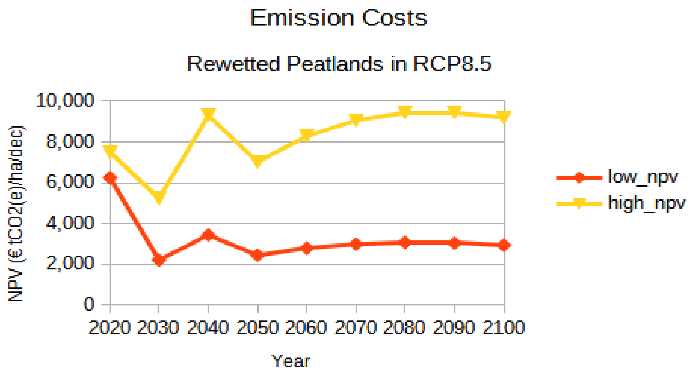

Figure 19: Emission costs of rewetted peatland in a RCP8.5 scenario, expressed in decadal NPVs. Notably costs increase even after rewetting (implemented in 2030) until 2090.

5. Emission- and Cost-Sensitivity to Management Type Rise with a Warming Climate
As described above, emissions and costs in relation to management type increase from wet to rewetted to drained. CC amplifies this in an exponential relationship, within the examined RCP scenarios. Additionally, not just the absolute values increase with increasing CC but also the relative differences between the emissions, meaning that the warmer the

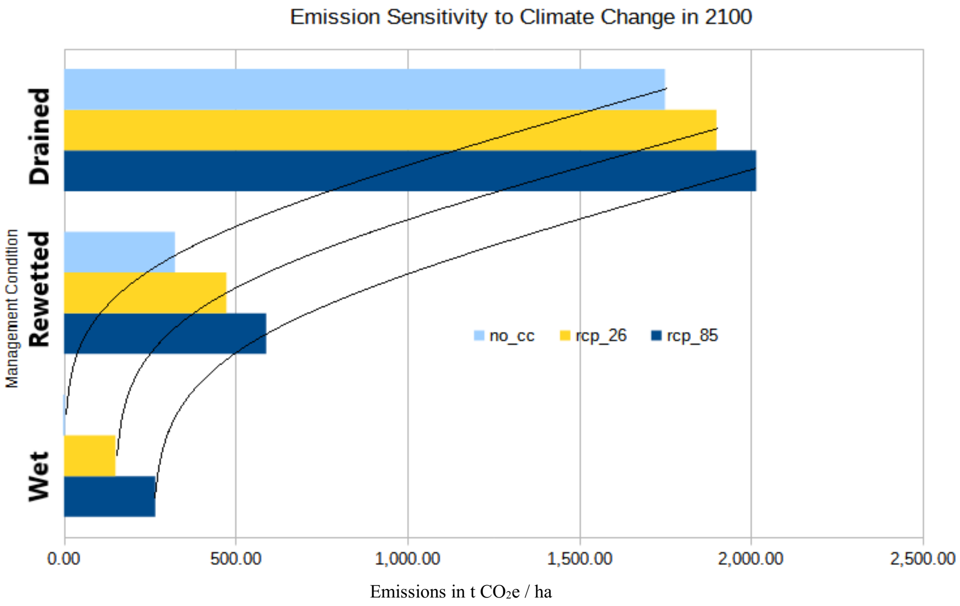

Figure 20: Total emissions (summed values from 2020-2100) according to climate scenario and management type. Emission differences between management types increase exponentially with increasing warming, meaning the relative costs of peatland emissions rise exponentially with increasing temperatures.

temperature the stronger the relative emission increases, indicating an exponential growth relationship (see fig. 20). The same would be valid for costs, which have a linear relationship to emissions in this model.

Total area correction

As mentioned above, emissions and prices were shown per single hectare. If corrected by actual area in SH small differences are visible, in line with the areal multiplication factor.

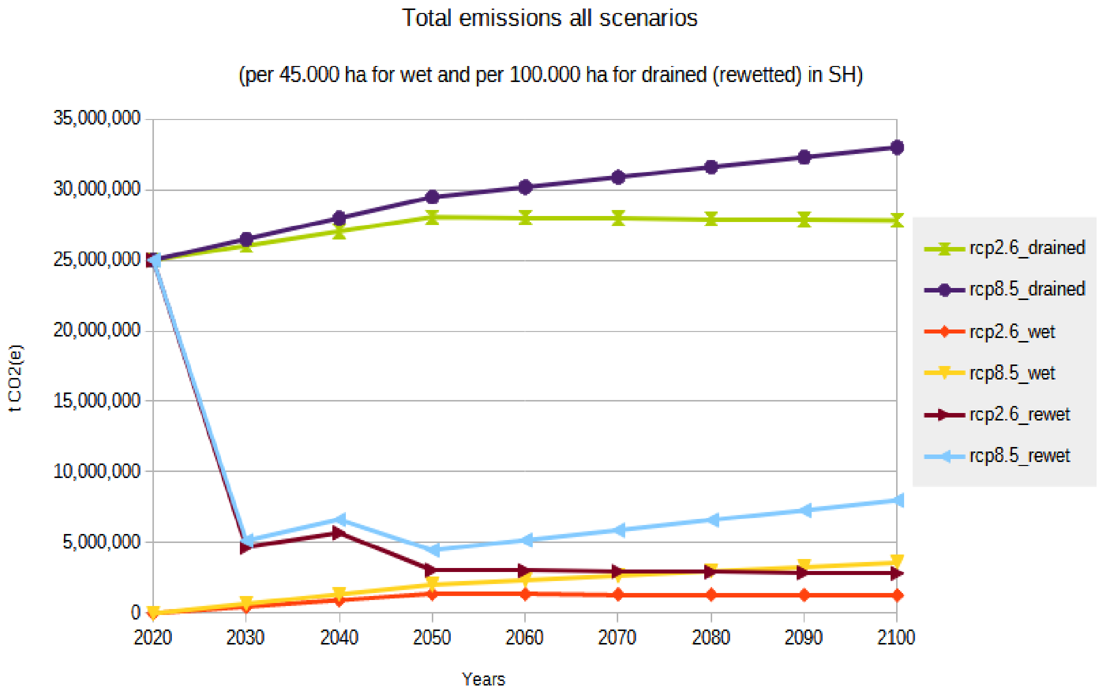

Figure 21: Total emissions (all climates, all management types) to scale (per actual SH area).

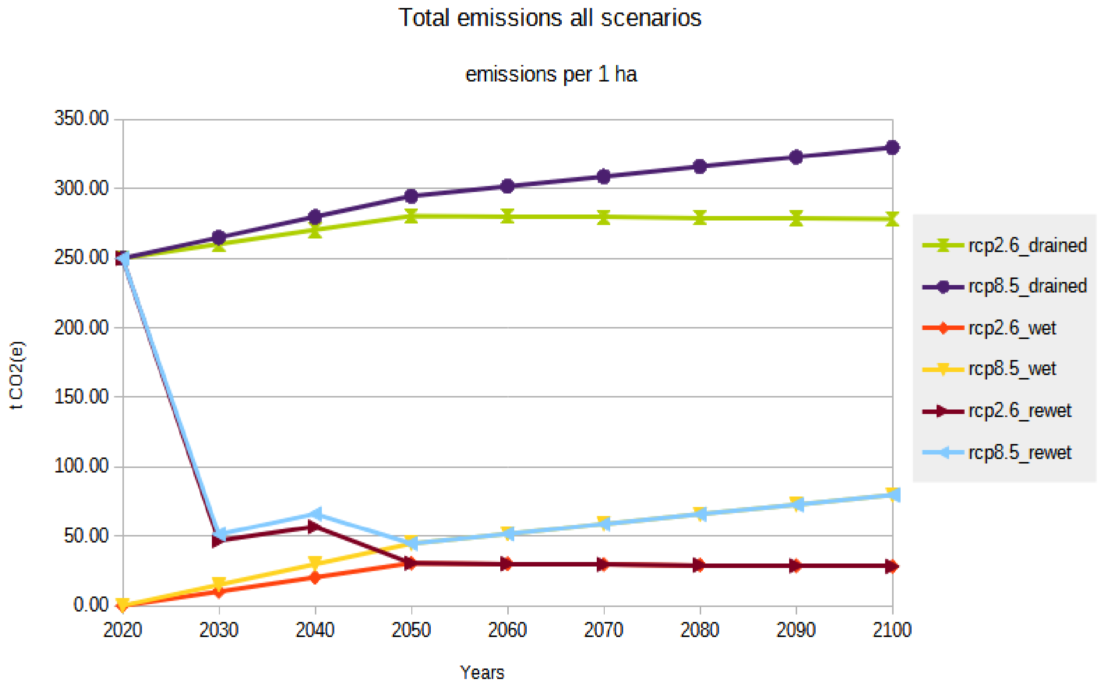

Figure 22: Total emissions (all climates, all management types) per single hectare.

5 Discussion

To point 1: The model outputs clearly show that peatland GHG-emissions are sensitive to Climate Change. With CC set to proceed to at least some extend in the near future, as today's emissions will feedback for centuries (NASA, 2021), peatland emissions can be expected to rise accordingly.

What seems unambiguous is that, in any of the modelled climates, wet peatlands have the lowest current and future emissions compared to drained sites, with rewetting being an emission-effective NCS compared to leaving peatlands drained. This result is furthermore similar to what Jensen et al. (2010) found for SH.

Under a RCP8.5 scenario emissions keep increasing over the course of the century (as do temperatures), but if temperature developments can be reversed, as in RCP2.6, peatland emission feedbacks can be too and peatland rewetting and conservation therefore offer long-term mitigation benefits, as also found in the literature (e.g. TEEB DE, 2014). In order to achieve this, it is vital to stick to at least the *Paris Goals* (The World Bank, 2020).

Ferretto et al. (2019)(see fig. 23) report a peatland area decline for Scotland under CC, which is similar to the model outputs presented here.

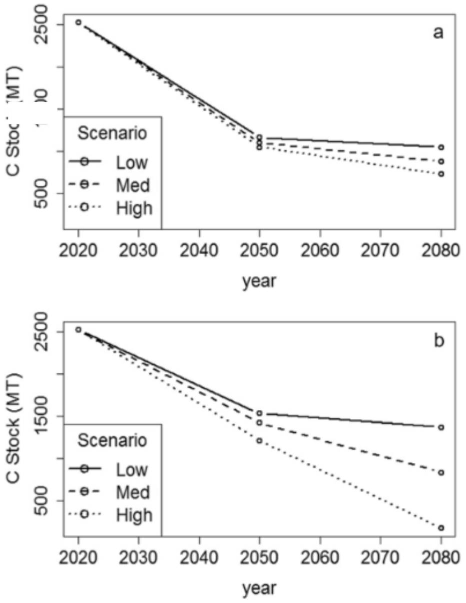

Fig. 6 Trend of carbon stock stored in Scottish blanket bogs according to BBOG TREE (**a**) and LM models (**b**)

Figure 23: Peatland carbon stocks under different climate warming scenarios (low, medium, high) for the case of Scotland. From: Ferretto et al., 2019, p. 2109.

→ *This means there is an insecurity with regards to peatland emissions depending on the extent of CC.*

Emissions of drained peatlands were calculated here with 5 t / CO_2e / ha / a / per 10 cm of peat loss, for a drainage depth of 50 cm (as outlined above), leading to 25 t of CO_2e / ha / a. However, Geurts et al. (2019) report even higher numbers of 40 to 60 t CO_2e / ha / a for rewetted former grasslands (a common case in SH), which is to say, if the model was based on these much higher values, the subsequent emission figures would be even higher. Hence the results calculated in the model might need correcting upwards.

To point 2: The model indicates that peatland costs are sensitive to CC and will be increased by temperature increases, even if all other factors (management case, price pathway, discount rate) remain constant. This calls for action regarding better peatland management, if costs are to be reduced. For society this means peatlands will become more costly in the future in line with rising temperatures.

While costs of rewetting peatlands are low (and can be expected to stay low), the cost-effectiveness of rewetting decreases with increasing temperatures and emissions, as the ratio between rewetting costs and emission costs rise exponentially. Hence there is a mathematical logic and reason implying prompt rewetting, as it would be most effective, rather than delaying action, defining a need to act now. Wet and rewetted sites produce significantly lower costs compared to drained sites, in all CC scenarios.

→ *In a CC future peatlands become less price-effective.*

Obviously, these calculated costs depend on the SCC rates and pathways (usually inherent to emissions developments) and used discount rates. A high SCC would likely incentivise emission saving peatland management (wet and rewetted land use, e.g. through paludiculture) as would lower discount rates, and the other way around. Looking for example at emissions costs of drained peatlands – used conventionally as pasture land in SH – the model predicts costs of ca. NPV €1,538 / ha / a, in 2050, for the low price pathway and NPV €4,413 / ha / a, for the high price pathway. Comparing these figures to an average revenue from dairy farming (as expected from to pasture land use) of €588 / ha / a [13] (mean net profit value for EU agriculture, in 2017, see IPBES 2018, p. 147) rewetting seems economically sensible, especially if revenues through e.g. paludiculture can be added to the emissions savings (see Geurts et al. 2019 for wet land use options; see App. 5; see App. 11 for more EU agricultural revenue values).

For farmers this might mean that under Climate Change and a SCC of at least the amounts processed in the model, the costs of drained peatlands will rise considerably, making rewetting more economically sensible. However this is only effective if this price is accounted into farmers' land use balancing, which it is usually not. Therefore, there seems to be a current lack of motivation for sustainable peatland use (von Oheimb et al., 2014). Incentives and payment schemes for sustainable land management (see Kindermann et al., 2006), like e.g. the *MoorFutures* incentive scheme (see Joosten et al., 2016), are of limited extent, for the scaling up of other rewetting policies could correct this market failure and trigger sustainable land use (Böckenhauer et al., 2016; Kindermann et al., 2006).

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[13] The US$ value in IPBES (2018, p. 147) was converted into € as above (see p. 18)..

Burke et al. (2019) suggest a carbon price of at least €46[14] / t CO_2, by 2020, would incentivise most mitigation actions and the World Bank reports a price of at least €33-66 / t CO_2, by 2020, and €41-82[15] / t CO_2, by 2030, “to cost-effectively reduce emissions in line with the temperature goals of the Paris Agreement“ (The World Bank, 2020, p. 7). The model calculations support these claims, as for instance a carbon price of €55 / t CO_2e produced significant SCC damage costs of ca. 112 million € for all drained peatlands in SH in a single year (2030) under the RCP2.6 scenario, compared to ca. €20 million when rewetted (and ca. €1.9 million for wet areas) (see full list of results, App. 1).

→ *There is an uncertainty with regards to the future viability of peatlands as a NCS that lies with the pricing and SCC mechanisms, as much as the discounting rate (see Matthey & Bünger, 2020).*

To point 3: Future peatland emissions and costs differ, strongly depending on the chosen management type within this model (similarly to the status quo under current conditions), which has also been reported by Günther et al. (2020) (see fig. 24). Hölzel et al. (2016) underline this: “Whether increased peat decomposition and carbon mobilisation due to higher temperatures leads [...] to higher net carbon emissions, will depend on the land use of peatlands“ (p. 356), with rewetting management avoiding emissions and costs compared to drained sites (see also App. 9).

Wet peatlands provide the lowest costs under all CC scenarios, and are still less costly under high temperature increases (RCP8.5) than drained sites under no temperature change at all (roughly factor 10 for the low price and factor 5 for the high price pathway). This means even if temperatures increase, it seems most cost effective to conserve wet peatlands followed by the rewetting of degraded ones, in comparison to leaving sites drained (or even draining more). Günther et al. support these findings, as seen in fig. 24.

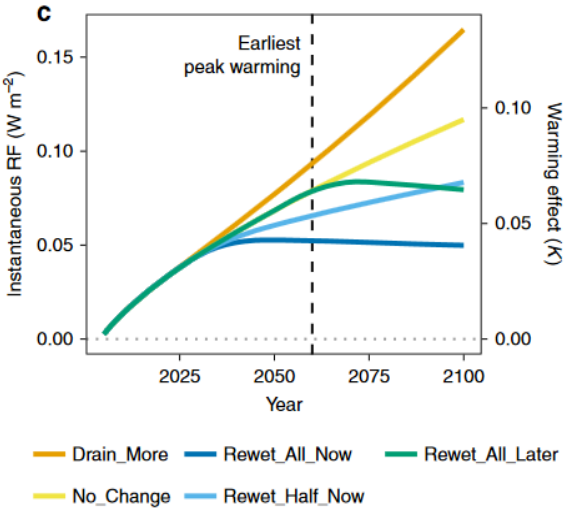

Figure 24: Global warming potential (radiative forcing in Watt / m² and resulting instant warming effect in °K) in relation to global peatland management (see trendlines). From: Günther et al., 2020, p. 2.

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[14] The £ values in Burke et al. (2019) were converted into € according to the *European Central Bank* exchange rate of £1 = €1.1583. https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-gbp.en.html (last reviewed 20.05.2021).

[15] The US$ values in World Bank (2020) were converted into € as above.

For farmers this might mean again a change to wet land cultivation, e.g. through paludiculture (e.g. Schlattmann & Rode, 2019; Tanneberger et al., 2021), could be an effective option as emissions and costs can be reduced (see App. 8 for GHG-emissions in relation to land use type), while still being able to provide goods and income options.

One of the current barriers for such transitions is for instance the current EU *common agricultural policy* (CAP), which subsidizes conventional peatland use (for pastures or croplands) but not paludiculture (see Tanneberger et al., 2021). Incentives for wet land-cultivation are therefore lacking.

For SH it has been estimated that under a moderate rewetting management, GHG-emissions could be reduced by 800,000 t / CO_2e / a, and under a paludiculture management emissions could be reduced by 1,300,000 t / CO_2e / a, according to Jensen et al. (2010). As these values are not time-constrained and can therefore be expected for current climatic conditions, the future might look different. The model predicts a value of 2,500,000 t / CO_2e / a, of potential emission reductions 30 years after rewetting compared to left drained, within a similar NoCC scenario, though notably with a restored water table at 0 cm (which might have been different in the study of Jensen et al., 2010). In the subsequent modelled RCP scenarios, these mitigation potentials, for rewetting versus draining, stay similar in their relative values, though absolute costs rise compared to noCC, as outlined above.

→ *This means, future costs and emissions are largely up to peatland management choices.*

As rewetting is not much more expensive than protecting wet peatlands (Tanneberger et al., 2021; TEEB DE, 2014) it seems like a very effective NCS measure economically, with long-term ecological benefits (TEEB DE, 2014). Clearly it is more expensive and emission-intense to leave peatlands drained, in any of the modelled cases, as has been described before (e.g. Günther et al., 2020; Wilson et al., 2016); without rewetting emissions continue for decades and longer (Leifeld & Menichetti, 2018).

Even when considering the uncertainties of neglected factors like methane feedbacks or emission delays after rewetting (Wilson et al., 2016), the main trend in the literature too is that restoration (rewetting) leads to an overall reduction of GHG-emissions, avoiding further losses (e.g. Artz et al., 2013; Tanneberger et al., 2021).

Apart from rewetting, the conservation of existing peatlands and the protection of current NCS, seems vital (see Wilson et al., 2016; Tanneberger et al., 2021; Jensen et al., 2010), as it is less costly and more efficient to protect existing ecosystems rather restoring them (see

Böckenhauer et al., 2016; TEEB DE, 2014; von Oheimb et al., 2014), as also shown by the model.

To point 4: Peatlands future viability as a NCS depends on the extent of CC. Under RCP8.5 peatlands still increase their emissions over the course of the century, even when rewetted. Indeed, rewetting lowers the emission-developments over the century considerably, compared to drained sites. Even so: emissions keep increasing after rewetting, uniquely in RCP8.5, in this model (in line with temperatures).

This indicates that in a high CC future peatlands might make less and less sense as a NCS, as they increasingly emit GHGs rather than storing them. This might mean that if the temperature increases pass a certain threshold (here within a temperature range somewhere between 2.3°C and 2.9°C warming, see full temperature and emissions results for RCP2.6 and 8.5 in App. 1), peatlands start to be of limited NCS use. This does not mean that conservation and rewetting should not be aimed for, as both still have considerably lower emissions than drained sites. But an entirely different peatland management regime might become more sensible. It would be interesting to assess whether transitioning peatlands into e.g. alder forest (with a lower but not entirely drained water table) could bring down emissions under RCP8.5 (see App. 8 for emissions of forests on former peatland areas). Even draining peatlands sooner rather than later, to establish more climate resilient ecosystems would be worth consideration, though needing further investigation.

Müller & Joos (2020) support these findings, stating that: “global warming will likely diminish the net carbon sink of remaining global peat-lands” (p. 5286). An entirely different type of land use might become more sensible.

→ *This means peatlands might stop to be an effective NCS in the future, if temperatures increase past a threshold of ca. 2.3°C.*

Similarly the damage costs of drained peatlands increase until the end of the century, in the worst-case scenario, (as seen in fig. 15, p. 31), though that is not visible at first glance due to the discounted NPV values (see App. 1 and 2). This is to say, when dealing with the NPVs, one should keep in mind the underlying assumptions and values of discounting (to what extent are present generations’ benefits valued over future generations’ damages), which influence (and possibly limit) the results accordingly (see Baumgärtner et al., 2015). With restoration costs being low – €8-82[16] / t CO_2, according to Burke et al. (2019), and €10-15 / t CO_2, according to Tanneberger et al. (2021) – the technical transition to wet

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[16] US$ values in Burke et al. (2019) were converted as above (see p. 18).

peatland management is feasible (though notably other factors like machinery might need to add to adaptation costs too).

Even just raising the water table height to half of the drainage depth of agricultural drained sites, without compromising their current "productive use", could be enough to lower emissions considerably (ca. 1% of anthropogenic GHGs) (cf. Evans et al. 2021, p. 548).

To Point 5: The increasing emission sensitivity to further warming shows an exponential growth relationship of peatland emissions over time, within the model. This makes it even more important to mitigate CC and use peatlands as a NCS sooner rather than later, as also found by Tanneberger et al. (2021): "Prompt action is [...] needed as climate warming may make peatland restoration more difficult in the coming decades" (p. 3).

→ *Emission sensitivity of peatlands to management type rises with a warming climate.*

Similar results have been reported by Günther et al. (2020), who argue for prompt rewetting of peatlands as a mitigation measure (NCS), since delayed action would increases damages over time, considering additional factors like methane:

> "Essentially, management must choose between CO_2 emissions from drained, or CH_4 emissions from rewetted, peatland. This choice must consider radiative effects and atmospheric lifetimes of both gases, with CO_2 being a weak but persistent, and CH_4 a strong but short-lived, greenhouse gas. The resulting climatic effects are, thus, strongly time-dependent. […] Our results show that CH_4 radiative forcing does not undermine the climate change mitigation potential of peatland rewetting. Instead, postponing rewetting increases the long-term warming effect through continued CO_2 emissions" (Günther et al., 2020, p. 1).

→ *The insecurities are ultimately dependent on human decisions and actions.*

Not yet mentioned, but clearly a relevant point could be future feedbacks from phenological changes, leading to longer growth periods and therefore higher annual net primary production (NPP) of plant tissue and organic matter, which might increase peat accumulation consequently (Tanneberger et al., 2021); in fact this has already been observed according to Friedrich et al. (2017).

Furthermore, precipitation has largely been neglected, as reasoned above. In order to provide some more context and a brief thought, it can be added that the likelihood for droughts is anticipated to increase, as was furthermore being observed in the recent past (see Marx, 2021). With that said, it is worth noting that the case of wet peatlands implies that there is a balance between water outflow (e.g. evapotranspiration) and water inflow (e.g. rain). Any climatic changes, especially temperature variations and major precipitation shifts, are likely to have an impact on this balance. Avoiding these impacts, with uncertain outcomes and possible non-linear feedbacks (see Steffen et al., 2018), seems sensible, even if concrete predictions are difficult to make. Land use type and choices are seemingly a major factor affecting this balance.

If the results were corrected for the simplified assumptions, of e.g. precipitation negligence, necessary measures to halt these emissions could be designed with more accuracy (e.g. technical solutions to water level compensation or assisted vegetation adaptation).

5.1 Answering the Research Questions

In order to refine the results, the initial research questions are briefly answered below:

With regard to the ecological perspective and **RQ1**, "Will peatlands be a viable NCS (through rewetting and conservation) under future climatic conditions in SH?", the modelled outputs and answer seems to depend on the extent of the climatic changes. The calculations imply that warmer temperatures will lead to increasing peatland emissions for all examined management cases, meaning the more temperatures increase, the less viable are peatlands as a NCS (though compared to drained sites they are still more cost- and emissions-effective). The efficiency of peatlands as a NCS might considerably sink with continued CC.

With regard to the economic perspective and **RQ2**, "Will the SCC development impact peatland management in SH (conservation, rewetting or not rewetting)?", the answer within the proposed model and its assumptions depends on who the costs are attributed to, the rate of the SCC, the discount rate and the climate scenario. Low discount rates and high SCCs seem to make emissions costly and therefore rewetting and conservation more attractive economically and vice versa. The stronger the climate warming, the higher (and costlier) the emissions from all peatlands, especially from drained ones, making the latter less attractive. If costs are assigned to land-managers high SCCs might therefore incentivise rewetting and conservation (however depending on the revenues from drained management and other factors not examined here). If emission costs are not assigned to anyone in particular (as is currently the case with peatland emissions), the damage costs go to society, whether the SCC is high or low, making carbon pricing redundant.

Conserving wet and rewetting peatlands lower costs significantly, compared to drained sites, in all climate scenarios examined. In the worst-case (RCP8.5) costs might still continue to rise, even after rewetting.

5.2 Outlook

As mentioned throughout, for good policy-making it is important to keep in mind the stakeholders affected, most notably current land users, like farmers. Their economic decision-making is largely constraint by systemic economic considerations rather than ESS thinking: “To achieve a net-zero outcome, a price on positive emissions will have to be combined with an incentive scheme [...] that specifically rewards carbon sinks” (Burke et al., 2019, p. 10).

As the emissions trading scheme introduced with the EU Green Deal currently omits land use emissions, it could be extended for peatland GHG reduction services (see von Oheimb et al., 2014) and higher prices, countering the current underpricing of many high-carbon sectors (cf. Burke et al., 2019, p. 5). It seems that carbon pricing is needed to make peatland rewetting competitive.

Additionally, there are other international schemes like e.g. the *Global Soil Strategy* (see Amelung et al., 2020), that can make peatland conservation economically viable. Assessment tools like the *GEST*-model (providing a GHG-emission directory for different peatland management cases, see Jensen et al., 2010) could be used and developed, in order to easily assess peatland sites and expected near-future conditions, providing at the same time scientifically and economically sound alternatives, like e.g. paludiculture practices and funding options (as is increasingly being explored, e.g. Greifswald Mire Centre, 2020; Schlattmann & Rode, 2019; Tanneberger et al., 2021). Another example here is the *WISE-tool* providing restoration guidance for Scottish peatlands (see Artz et al., 2013).

Indeed, peatland conservation and rewetting being climate effective strategies has been widely acknowledged, even when considering possible trade-offs (e.g. Humpenöder et al., 2020, Evans et al. 2021), and is being upscaled and supported in SH (LLUR, 2012), recently by increased efforts of the environmental agency (see MELUND, 2021). While the German climate protection law has recently been rejected (May 2021) by the *German Constitutional Court* (Bundesverfassungsgericht), as being unconstitutional in the sense that the protection of future generations is inadequately designed, the policies will need to be refined: peatlands and other NCS mitigation options might be missing pieces here.

Policies exist, though more explicit and increased efforts would be needed in order to achieve the CC mitigation goals (Günther et al., 2020; TEEB DE, 2014) that most of the world has committed to in 2015 (*Paris Goals*).[17]

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[17] As noted by Ferretto et al. (2019): Scotland for instance includes peatlands explicitly in their national climate mitigation policy, see https://www.gov.scot/publications/climate-ready-scotland-second-scottish-climate-change-adaptation-programme-2019-2024/pages/6/, last reviewed 08.05.21.

As he latest IPCC evidence shows: in order to reach the 1.5°C goal, global GHG-emissions will have to fall to ‘net-zero’ levels by 2050 (cf. Burke et al., 2019, p. 10).

From the herein assessed scenarios, the RCP2.6, until 2040, is the most likely path to describe the peatland feedbacks, that would result from a successful *Paris Agreement* realization (note, in RCP2.6 between 2030 and 2040 the 1.5° limit is exceeded and between 2040 and 2050 the 2° limit). According to the model, peatlands would hereby increase emissions initially, though rewetting and conservation – as a NCS – would be effective mitigation measures. Leaving peatlands drained and unprotected, leaving rewetting and conservation out of the policies, could seriously threaten this goal or make it impossible to reach, as similarly found by Günther et al. (2020), Humpenöder et al. (2020) and Tanneberger et al. (2021): “in order to reach climate-neutrality in 2050 [...] it is insufficient to focus rewetting efforts on selected peatlands only: to reach the Paris goal, CO_2 emissions from (almost) all drained peatlands have to be stopped by rewetting” (Günther et al., 2020).

Another thought worth exploring might be, whether peatland water saturation imbalance due to CC could be corrected by additional water inflow from alternative sources (not precipitation or ground water). A renewable source, for instance, could be sea water. If sea water, from the nearby North or Baltic Sea, in which water levels are rising, could be emission-neutrally desalinated and transported (e.g. driven by wind or solar power), peatlands could possibly be kept wet despite rising temperatures. Whether this can be a viable solution must, however be part of a different analysis.

Even if carbon mitigation services decrease to be provided by peatlands, or decrease to be cost-effective under increasing CC, accounting for other ESS (see Tanneberger et al., 2021) might still make peatland conservation and rewetting a viable strategy overall (see Joosten et al., 2016). There are many other benefits of peatlands which could add to the monetary value (cf. von Oheimb et al., 2014, p. 456), like local cooling effects (Hölzel et al., 2016; Joosten et al., 2016), water retention, or species habitat and biodiversity protection (see TEEB DE, 2014), which might be an economic game-changer if they were accounted for as externalities, when making land use decisions: “[r]ewetting can have several objectives such as nature conservation, GHG emission reductions and the promotion of leisure activities or paludiculture on saturated organic soils“ (Wilson et al., 2016, p. 2).

Implementing these perspectives could strengthen the argument for peatland protection and NCS implementation even more (see TEEB DE, 2014): “most natural pathways can increase resilience to climate impacts” (Griscom et al., 2017, p. 11649).

5.3 Conclusion

The initial questions could be answered and the answers seem likely within the assumptions made, and resemble largely the results of other studies. It seems peatland conservation and restoration are key for CC mitigation, though a limited viability of peatlands under a high CC future leads to further questions of what could be alternative land uses, with lower emissions and at what price?

An ongoing, more sophisticated exploration of the matter, including more detail on climatic variations and indices, like e.g frost days, tropical nights, etc. (see Pfeifer et al., 2021), additional scenarios (e.g. RCP6.5), vegetation feedbacks, addition SCC developments and different discount rates, might lead to more detailled results. With all the unknowns and uncertainties regarding the earth's systems and societal feedbacks to CC, it might be best to try to mitigate it as much as possible, as underlined by this analysis. As Griscom et al. (2017) estimate, if we manage to limit warming below 2C° it is less likely that the terrestrial carbon stocks turn into net emitters (cf., p. 11649).

Actions on CC mitigation and carbon pricing seem to be impacted by the current Covid-19 pandemic, so the reasonings of the post-Covid world are yet to be determined (The World Bank, 2020) but might bear new challenges for peatland conservation (as much as new windows of opportunity might open). It seems that as long as farmers don't get paid for carbon services or don't get similar financial support for wet peatland cultivation to that for drained practices (as mentioned above), change is difficult for land users and farmers (e.g. Schlattmann & Rode, 2019; Tanneberger et al., 2021; von Oheimb et al., 2014), implying ecological peatland solution pathways are politically constrained.

As noted above, peatlands and other non-forest climate solutions and their protection have been under-represented in the public (and scientific) discourse, which calls for a correction of this attention imbalance. Conserving the global variety and richness in ecosystems and biomes seems like a good idea, also with regard to NCS thinking:

> "Preventing ecosystem destruction is the most cost-effective natural climate solution. Because ecosystems are crucial to carbon sequestration, avoiding deforestation, improving forest management, and protecting grasslands, peatlands, and shrublands from land-use conversion should be the priority" (Fleischman et al., 2020, p. 1).

6 Personal Reflection

This bachelor thesis project turned out to be a rather exciting challenge, leading to many new insights as well as ongoing questions. Thus far I seem to know more of what I don't know, though with a higher degree of certainty. In other words: I believe I gained a better understanding of methodological work processes in sciences, have a better conspectus of peatlands as a natural climate solutions and possible climatic feedbacks as much as I have come to find many subsequent questions and insights I was not aware of beforehand.

Looking back at my starting point, which consisted of piles of notes and ideas on what to explore and write about, the topic examined in the end proved to be interesting enough to keep me going over the course of time.

My original questions and concepts of a possible thesis shifted around the more I red and with feedback given. Hence narrowing a topic down, finding the right scope, as much as making decisions, were some of the main challenges I encountered. A fair amount of reading and exploring new perspectives were essential steps here, even if leading to the discarding of many initial ideas (from e.g. attempted GIS-modelling to examined NASA simulations that exceeded the possible scope).

During the first thesis discussion the incorporation of the economics of Climate Change and environmental modelling were suggested, which were largely unknown subject matters to me. Which is why there were challenging as much as they were interesting, leading to entirely new findings (particularly in carbon pricing and discounting mechanisms). At the same time, it was difficult to tie the economical and ecological spheres together, as mentioned I was lacking expertise, especially regarding the former. Reviewing relevant literature and additional guidance led to what has been written above.

Similarly interesting was the modelling part, as I was lacking prior knowledge here too, though the references mentioned above (e.g. *InVest* or *MagPie*) gave helpful directions. As complexity was limited by scope and (my) expertise, the synthesis of initial questions and the unknown variables (future emissions and costs), of the known variables found in literature in addition to necessary simplifications, while at the same time generating somewhat meaningful model outputs, was as much a difficulty as it was interesting.

Towards the later part of the process it was challenging to find an appropriate way of expressing and discussing the model results. The suggestion of sticking to a few key messages was helpful in that regard. Still, at the end of the process the generated content needed some narrowing down. Getting to the point, leaving *nice to know* but not *neces-*

sary information out of the analysis, as much as keeping the overview, were troublesome though hopefully somewhat fruitful in conclusion.

With the challenges given, feedback, critique and support throughout the process were very helpful, which is to say: thanks to my examiners, for being generous with your time and expertise. The same goes for my supporting friends: thank you so much!

All in all, the thesis-project was a fun task, merging the insights I gained throughout my studies into a final project. With that said, this work has been a personal success, if nothing else. I certainly feel like I have learned a fair amount and am motivated to continue learning from here onwards, which is a nice way of finishing these bachelor studies.

7 Appendices

Appendix 1: Full List of Model Results

Wet Peatlands, Conservation Management: Emissions

Temp °C	**Wet noCC**	**Water table** *cm*	**Emissions** *tCO$_2$e/ha/dec*	**Emissions** *per total ha*
8.6	2020	0	0	0
8.6	2030	0	0	0
8.6	2040	0	0	0
8.6	2050	0	0	0
8.6	2060	0	0	0
8.6	2070	0	0	0
8.6	2080	0	0	0
8.6	2090	0	0	0
8.6	2100	0	0	0
	total	0	0	0

Temp °C	***Wet RCP2.6***	**Water table**	**Emissions** *tCO$_2$e/ha/dec*	**Emissions** *per total ha*
8.60	2020	0	0	0
9.03	2030	-2.04	10.20	459,000
9.47	2040	-4.07	20.35	915,750
9.90	2050	-6.10	30.50	1,372,500
9.88	2060	-6.02	30.10	1,354,500
9.86	2070	-5.92	29.60	1,332,000
9.84	2080	-5.83	29.15	1,311,750
9.82	2090	-5.73	28.65	1,289,250
9.80	2100	-5.64	28.20	1,269,000
	total	-5.64	149.90	6,745,500

Temp °C	***Wet RCP8.5***	**Water table** *cm*	**Emissions** *tCO$_2$e/ha/dec*	**Emissions** *per total area*
8.60	2020	0	0	0
9.23	2030	-2.98	14.90	670,500
9.78	2040	-5.95	29.75	1,338,750
10.50	2050	-8.93	44.65	2,009,250
10.80	2060	-10.34	51.70	2,326,500
11.10	2070	-11.75	58.75	2,643,750
11.40	2080	-13.20	66.00	2,970,000
11.70	2090	-14.57	72.85	3,278,250
12.00	2100	-15.98	79.90	3,595,500
	total	-15.98	265.75	11,958,750

Wet Peatlands, Conservation Management: Costs (Low Price)

Temp °C	**Wet** **noCC**	**Low price** *€ / t* CO_2	**Cost to emit** *€ / decade / ha*	**Cost to emit** *per total area*	**NPV** *€ / dec / ha*	**NPV** *per total area*
8.6	2020	25	0	0	0	0
8.6	2030	55	0	0	0	0
8.6	2040	85	0	0	0	0
8.6	2050	115	0	0	0	0
8.6	2060	145	0	0	0	0
8.6	2070	175	0	0	0	0
8.6	2080	205	0	0	0	0
8.6	2090	235	0	0	0	0
8.6	2100	265	0	0	0	0
	total		0	*0*	0	0

Temp °C	***Wet*** ***RCP2.6***	**Low price** *€ / t* CO_2	**Cost to emit** *€ / decade / ha*	**Cost to emit** *per total area*	**NPV** *€ / dec / ha*	**NPV** *per total area*
8.60	2020	25	0	0	0	0
9.03	2030	55	561	25,245,000	438	19,721,354
9.47	2040	85	1,730	77,838,750	1,056	47,502,727
9.90	2050	115	3,508	157,837,500	1,672	75,247,874
9.88	2060	145	4,365	196,402,500	1,625	73,146,306
9.86	2070	175	5,180	233,100,000	1,507	67,818,629
9.84	2080	205	5,976	268,908,750	1,358	61,118,546
9.82	2090	235	6,733	302,973,750	1,195	53,794,073
9.80	2100	265	7,473	336,285,000	1,037	46,644,266
	total		*35,524*	*1,598,591,250*	9,889	444,993,773

Temp °C	**Wet** ***RCP8.5***	**Low price** *€ / t* CO_2	**Cost to emit** *€ / decade / ha*	**Cost to emit** *per total area*	**NPV** *€ / dec / ha*	**NPV** *per total area*
8.60	2020	25	0	0	0	0
9.23	2030	55	820	36,877,500	640	28,808,644
9.78	2040	85	2,529	113,793,750	1,543	69,445,019
10.50	2050	115	5,135	231,063,750	2,448	110,157,953
10.80	2060	145	7,497	337,342,500	2,792	125,636,678
11.10	2070	175	10,281	462,656,250	2,991	134,606,231
11.40	2080	205	13,530	608,850,000	3,075	138,381,612
11.70	2090	235	17,120	770,388,750	3,040	136,785,277
12.00	2100	265	21,174	952,807,500	2,937	132,158,754
	total		*78,084*	*3,513,780,000*	19,466	875,980,168

Wet Peatlands, Conservation Management: Costs (High Price)

Temp	**Wet**	**High price**	**Cost to emit**	**Cost to emit**	**NPV**	**NPV**
°C	***noCC***	*€ / t CO_2*	*€ / decade / ha*	*per total area*	*€ / dec / ha*	*per total area*
8.6	2020	30	0	0	0	0
8.6	2030	130	0	0	0	0
8.6	2040	230	0	0	0	0
8.6	2050	330	0	0	0	0
8.6	2060	430	0	0	0	0
8.6	2070	530	0	0	0	0
8.6	2080	630	0	0	0	0
8.6	2090	730	0	0	0	0
8.6	2100	830	0	0	0	0
	total		0	0	0	0

Temp	***Wet***	**High price**	**Cost to emit**	**Cost to emit**	**NPV**	**NPV**
°C	***RCP2.6***	*€ / t*	*€ / decade / ha*	*per total area*	*€ / dec / ha*	*per total area*
8.60	2020	30	0	0	0	0
9.03	2030	130	1,326	59,670,000	1,036	46,614,109
9.47	2040	230	4,681	210,622,500	2,856	128,536,792
9.90	2050	330	10,065	452,925,000	4,798	215,928,681
9.88	2060	430	12,943	582,435,000	4,820	216,916,630
9.86	2070	530	15,688	705,960,000	4,564	205,393,561
9.84	2080	630	18,365	826,402,500	4,174	187,827,725
9.82	2090	730	20,915	941,152,500	3,713	167,104,992
9.80	2100	830	23,406	1,053,270,000	3,247	146,093,362
	total		107,388	4,832,437,500	29,209	1.314.415.851

Temp	**Wet**	**High price**	**Cost to emit**	**Cost to emit**	**NPV**	**NPV**
°C	***RCP8.5***	*€ / t CO_2*	*€ / decade*	*per total area*	*€ / dec*	*per total area*
8.60	2020	30	0	0	0	0
9.23	2030	130	1,937	87,165,000	1,513	68,093,159
9.78	2040	230	6,843	307,912,500	4,176	187,910,052
10.50	2050	330	14,735	663,052,500	7,025	316,105,429
10.80	2060	430	22,231	1,000,395,000	8,280	372,577,734
11.10	2070	530	31,138	1,401,187,500	9,059	407,664,585
11.40	2080	630	41,580	1,871,100,000	9,450	425,270,321
11.70	2090	730	53,181	2,393,122,500	9,442	424,907,457
12.00	2100	830	66,317	2,984,265,000	9,198	413,931,192
	total		237,960	10,708,200,000	58,144	2,616,459,928

Drained Peatlands, Rewetting Management: Emissions

Temp °C	**Rewet** ***noCC***	**Water table** *cm*	**Emissions** *tCO_2e / ha / dec*	**Emissions** *per total area*
8.60	2020	-50	250	25,000,000
8.60	2030	0	36.5	3,650,000
8.60	2040	0	36.5	3,650,000
8.60	2050	0	0	0
8.60	2060	0	0	0
8.60	2070	0	0	0
8.60	2080	0	0	0
8.60	2090	0	0	0
8.60	2100	0	0	0
	total	0	323	32,300,000

Temp °C	**Rewet** ***RCP2.6***	**Water table** *cm*	**Emissions** *tCO_2e / ha / dec*	**Emissions** *per total area*
8.60	2020	-50	250.00	25,000,000
9.03	2030	-2.04	46.70	4,670,000
9.47	2040	-4.07	56.85	5,685,000
9.90	2050	-6.10	30.50	3,050,000
9.88	2060	-6.02	30.10	3,010,000
9.86	2070	-5.92	29.60	2,960,000
9.84	2080	-5.83	29.15	2,915,000
9.82	2090	-5.73	28.65	2,865,000
9.80	2100	-5.64	28.20	2,820,000
	total	-5.64	472.90	52,975,000

Temp °C	**Rewet** ***RCP8.5***	**Water table** *cm*	**Emissions** *tCO_2e / ha / dec*	**Emissions** *per total area*
8.60	2020	-50	250.00	25,000,000
9.23	2030	-2.98	51.40	5,140,000
9.78	2040	-5.95	66.25	6,625,000
10.50	2050	-8.93	44.65	4,465,000
10.80	2060	-10.34	51.70	5,170,000
11.10	2070	-11.75	58.75	5,875,000
11.40	2080	-13.20	66.00	6,600,000
11.70	2090	-14.57	72.85	7,285,000
12.00	2100	-15.98	79.90	7,990,000
	total	-15.98	588.75	74,150,000

Drained Peatlands, Rewetting Management: Costs (Low Price)

Temp	**Drained**	**Low price**	**Cost to emit**	**Cost to emit**	**NPV**	**NPV**
°C	***noCC***	*€ / t CO_2*	*€ / decade / ha*	*per total area*	*€ / dec / ha*	*per total area*
8.60	2020	25	6,250	625,000,000	6,250	625,000,000
8.60	2030	55	2,008	200,750,000	1,568	156,825,579
8.60	2040	85	3,103	310,250,000	1,893	189,336,560
8.60	2050	115	0	0	0	0
8.60	2060	145	0	0	0	0
8.60	2070	175	0	0	0	0
8.60	2080	205	0	0	0	0
8.60	2090	235	0	0	0	0
8.60	2100	265	0	0	0	0
	total		11,360	*1,136,000,000*	9,712	971,162,139

Temp	**Drained**	**Low price**	**Cost to emit**	**Cost to emit**	**NPV**	**NPV**
°C	***RCP2.6***	*€ / t CO_2*	*€ / decade / ha*	*per total area*	*€ / dec / ha*	*per total area*
8.60	2020	25	6,250	625,000,000	6,250	625,000,000
9.03	2030	55	2,569	256,850,000	2,007	200,650,809
9.47	2040	85	4,832	483,225,000	2,949	294,898,176
9.90	2050	115	3,508	350,750,000	1,672	167,217,497
9.88	2060	145	4,365	436,450,000	1,625	162,547,346
9.86	2070	175	5,180	518,000,000	1,507	150,708,064
9.84	2080	205	5,976	597,575,000	1,358	135,818,990
9.82	2090	235	6,733	673,275,000	1,195	119,542,384
9.80	2100	265	7,473	747,300,000	1,037	103,653,925
	total		*46,884*	*4,688,425,000*	*19,600*	*1,960,037,191*

Temp	**Drained**	**Low price**	**Cost to emit**	**Cost to emit**	**NPV**	**NPV**
°C	***RCP8.5***	*€ / t CO_2*	*€ / decade / ha*	*per total area*	*€ / dec / ha*	*per total area*
8.60	2020	25	6,250	625,000,000	6,250	625,000,000
9.23	2030	55	2,827	282,700,000	2,208	220,844,788
9.78	2040	85	5,631	563,125,000	3,437	343,658,825
10.50	2050	115	5,135	513,475,000	2,448	244,795,450
10.80	2060	145	7,497	749,650,000	2,792	279,192,617
11.10	2070	175	10,281	1,028,125,000	2,991	299,124,958
11.40	2080	205	13,530	1,353,000,000	3,075	307,514,694
11.70	2090	235	17,120	1,711,975,000	3,040	303,967,283
12.00	2100	265	21,174	2,117,350,000	2,937	293,686,120
	total		89,444	8,944,400,000	29,178	2,917,784,735

Drained Peatlands, Rewetting Management: Costs (High Price)

Temp	**Drained**	**High price**	**Cost to emit**	**Cost to emit**	**NPV**	**NPV**
°C	***noCC***	*€ / t CO_2*	*€ / decade / ha*	*per total area*	*€ / dec / ha*	*per total area*
8.60	2020	30	7,500	750,000,000	7,500	750,000,000
8.60	2030	130	4,745	474,500,000	3,707	370,678,642
8.60	2040	230	8,395	839,500,000	5,123	512,322,457
8.60	2050	330	0	0	0	0
8.60	2060	430	0	0	0	0
8.60	2070	530	0	0	0	0
8.60	2080	630	0	0	0	0
8.60	2090	730	0	0	0	0
8.60	2100	830	0	0	0	0
	total		20,640	2,064,000,000	16,330	1,633,001,098

Temp	**Drained**	**High price**	**Cost to emit**	**Cost to emit**	**NPV**	**NPV**
°C	***RCP2.6***	*€ / t CO_2*	*€ / decade / ha*	*per total area*	*€ / dec / ha*	*per total area*
8.60	2020	30	7,500	750,000,000	7,500	750,000,000
9.03	2030	130	6,071	607,100,000	4,743	474,265,550
9.47	2040	230	13,076	1,307,550,000	7,980	797,959,771
9.90	2050	330	10,065	1,006,500,000	4,798	479,841,513
9.88	2060	430	12,943	1,294,300,000	4,820	482,036,956
9.86	2070	530	15,688	1,568,800,000	4,564	456,430,136
9.84	2080	630	18,365	1,836,450,000	4,174	417,394,945
9.82	2090	730	20,915	2,091,450,000	3,713	371,344,426
9.80	2100	830	23,406	2,340,600,000	3,247	324,651,915
	total		*128,028*	*12,802,750,000*	*45,539*	*4,553,925,212*

Temp	**Drained**	**High price**	**Cost to emit**	**Cost to emit**	**NPV**	**NPV**
°C	***RCP8.5***	*€ / t CO_2*	*€ / decade / ha*	*per total area*	*€ / dec / ha*	*per total area*
8.60	2020	30	7,500	750,000,000	7,500	750,000,000
9.23	2030	130	6,682	668,200,000	5,220	521,996,772
9.78	2040	230	15,238	1,523,750,000	9,299	929,900,349
10.50	2050	330	14,735	1,473,450,000	7,025	702,456,509
10.80	2060	430	22,231	2,223,100,000	8,280	827,950,520
11.10	2070	530	31,138	3,113,750,000	9,059	905,921,300
11.40	2080	630	41,580	4,158,000,000	9,450	945,045,158
11.70	2090	730	53,181	5,318,050,000	9,442	944,238,793
12.00	2100	830	66,317	6,631,700,000	9,198	919,847,093
	total		258,600	25,860,000,000	74,474	7,447,356,495

Drained Peatlands, Leave Drained Management: Emissions

Temp *°C*	**Leave d.** ***noCC***	**Water table** *cm*	**Emissions** *tCO₂e / ha / dec*	**Emissions** *per total area*
8.60	2020	-50	250	25,000,000
8.60	2030	-50	250	25,000,000
8.60	2040	-50	250	25,000,000
8.60	2050	-50	250	25,000,000
8.60	2060	-50	250	25,000,000
8.60	2070	-50	250	25,000,000
8.60	2080	-50	250	25,000,000
8.60	2090	-50	250	25,000,000
8.60	2100	-50	250	25,000,000
	total	-50	1,750	225,000,000

Temp *°C*	**Leave d.** ***RCP2.6***	**Water table** *cm*	**Emissions** *tCO₂e / ha / dec*	**Emissions** *per total area*
8.60	2020	-50	250.00	25,000,000
9.03	2030	-52.04	260.20	26,020,000
9.47	2040	-54.07	270.35	27,035,000
9.90	2050	-56.10	280.50	28,050,000
9.88	2060	-56.02	280.10	28,010,000
9.86	2070	-55.92	279.60	27,960,000
9.84	2080	-55.83	279.15	27,915,000
9.82	2090	-55.73	278.65	27,865,000
9.80	2100	-55.64	278.20	27,820,000
	total	-55.64	1,899.90	245,675,000

Temp *°C*	**Leave d.** ***RCP8.5***	**Water table** *cm*	**Emissions** *tCO₂e / ha / dec*	**Emissions** *per total area*
8.60	2020	-50	250.00	25,000,000
9.23	2030	-52.98	264.90	26,490,000
9.78	2040	-55.95	279.75	27,975,000
10.50	2050	-58.93	294.65	29,465,000
10.80	2060	-60.34	301.70	30,170,000
11.10	2070	-61.75	308.75	30,875,000
11.40	2080	-63.20	316.00	31,600,000
11.70	2090	-64.57	322.85	32,285,000
12.00	2100	-65.98	329.90	32,990,000
	total	-65.98	2,015.75	266,850,000

Drained Peatlands, Leave Drained Management: Costs (Low Price)

Temp	**Leave d.**	**Low Price**	**Cost to emit**	**Cost to emit**	**NPV**	**NPV**
°C	***noCC***	*€ / t CO_2*	*€ / decade / ha*	*per total area*	*€ / dec / ha*	*per total area*
8.60	2020	25	6,250	625,000,000	6,250	625,000,000
8.60	2030	55	13,750	1,375,000,000	10,741	1,074,147,802
8.60	2040	85	21,250	2,125,000,000	12,968	1,296,825,754
8.60	2050	115	28,750	2,875,000,000	13,706	1,370,635,220
8.60	2060	145	36,250	3,625,000,000	13,501	1,350,061,011
8.60	2070	175	43,750	4,375,000,000	12,729	1,272,872,160
8.60	2080	205	51,250	5,125,000,000	11,648	1,164,828,388
8.60	2090	235	58,750	5,875,000,000	10,431	1,043,127,257
8.60	2100	265	66,250	6,625,000,000	9,189	918,917,773
	total		326,250	32,625,000,000	101,164	10,116,415,364

Temp	**Leave d.**	**Low Price**	**Cost to emit**	**Cost to emit**	**NPV**	**NPV**
°C	***RCP2.6***	*€ / t CO_2*	*€ / decade / ha*	*per total area*	*€ / dec / ha*	*per total area*
8.60	2020	25	6,250	625,000,000	6,250	625,000,000
9.03	2030	55	14,311	1,431,100,000	11,180	1,117,973,033
9.47	2040	85	22,980	2,297,975,000	14,024	1,402,387,370
9.90	2050	115	32,258	3,225,750,000	15,379	1,537,852,717
9.88	2060	145	40,615	4,061,450,000	15,126	1,512,608,357
9.86	2070	175	48,930	4,893,000,000	14,236	1,423,580,224
9.84	2080	205	57,226	5,722,575,000	13,006	1,300,647,378
9.82	2090	235	65,483	6,548,275,000	11,627	1,162,669,640
9.80	2100	265	73,723	7,372,300,000	10,226	1,022,571,697
	total		361,774	36,177,425,000	111,053	11,105,290,415

Temp	**Leave d.**	**Low Price**	**Cost to emit**	**Cost to emit**	**NPV**	**NPV**
°C	***RCP8.5***	*€ / t CO_2*	*€ / decade / ha*	*per total area*	*€ / dec / ha*	*per total area*
8.60	2020	25	6,250	625,000,000	6,250	625,000,000
9.23	2030	55	14,570	1,456,950,000	11,382	1,138,167,011
9.78	2040	85	23,779	2,377,875,000	14,511	1,451,148,018
10.50	2050	115	33,885	3,388,475,000	16,154	1,615,430,670
10.80	2060	145	43,747	4,374,650,000	16,293	1,629,253,628
11.10	2070	175	54,031	5,403,125,000	15,720	1,571,997,118
11.40	2080	205	64,780	6,478,000,000	14,723	1,472,343,082
11.70	2090	235	75,870	7,586,975,000	13,471	1,347,094,539
12.00	2100	265	87,424	8,742,350,000	12,126	1,212,603,893
	total		404,334	40,433,400,000	120,630	12,063,037,960

Drained Peatlands, Leave Drained Management: Costs (High Price)

Temp	**Leave d.**	**High Price**	**Cost to emit**	**Cost to emit**	**NPV**	**NPV**
°C	***noCC***	*€ / t CO_2*	*€ / decade / ha*	*per total area*	*€ / dec / ha*	*per total area*
8.60	2020	30	7,500	750,000,000	7,500	750,000,000
8.60	2030	130	32,500	3,250,000,000	25,389	2,538,894,806
8.60	2040	230	57,500	5,750,000,000	35,091	3,509,057,921
8.60	2050	330	82,500	8,250,000,000	39,331	3,933,127,153
8.60	2060	430	107,500	10,750,000,000	40,036	4,003,629,205
8.60	2070	530	132,500	13,250,000,000	38,550	3,854,984,256
8.60	2080	630	157,500	15,750,000,000	35,797	3,579,716,509
8.60	2090	730	182,500	18,250,000,000	32,404	3,240,352,754
8.60	2100	830	207,500	20,750,000,000	28,781	2,878,119,816
	total		967,500	96,750,000,000	282,879	28,287,882,420

Temp	**Leave d.**	**High Price**	**Cost to emit**	**Cost to emit**	**NPV**	**NPV**
°C	***RCP2.6***	*€ / t*	*€ / decade / ha*	*per total area*	*€ / dec / ha*	*per total area*
8.60	2020	30	7,500	750,000,000	7,500	750,000,000
9.03	2030	130	33,826	3,382,600,000	26,425	2,642,481,714
9.47	2040	230	62,181	6,218,050,000	37,947	3,794,695,236
9.90	2050	330	92,565	9,256,500,000	44,130	4,412,968,665
9.88	2060	430	120,443	12,044,300,000	44,857	4,485,666,161
9.86	2070	530	148,188	14,818,800,000	43,114	4,311,414,392
9.84	2080	630	175,865	17,586,450,000	39,971	3,997,111,454
9.82	2090	730	203,415	20,341,450,000	36,117	3,611,697,180
9.80	2100	830	230,906	23,090,600,000	32,028	3,202,771,732
	total		1,074,888	107,488,750,000	312,088	31,208,806,534

Temp	**Leave d.**	**High Price**	**Cost to emit**	**Cost to emit**	**NPV**	**NPV**
°C	***RCP8.5***	*€ / t CO_2*	*€ / decade / ha*	*per total area*	*€ / dec / ha*	*per total area*
8.60	2020	30	7,500	750,000,000	7,500	750,000,000
9.23	2030	130	34,437	3,443,700,000	26,902	2,690,212,936
9.78	2040	230	64,343	6,434,250,000	39,266	3,926,635,814
10.50	2050	330	97,235	9,723,450,000	46,356	4,635,583,662
10.80	2060	430	129,731	12,973,100,000	48,316	4,831,579,724
11.10	2070	530	163,638	16,363,750,000	47,609	4,760,905,556
11.40	2080	630	199,080	19,908,000,000	45,248	4,524,761,667
11.70	2090	730	235,681	23,568,050,000	41,846	4,184,591,547
12.00	2100	830	273,817	27,381,700,000	37,980	3,797,966,910
	total		1,205,460	120,546,000,000	341,022	34,102,237,817

Appendix 2: SCC Pricing Calculations and Pathways

Year	**Low price *(€)***	***NPV (€)***	**High price *(€)***	***NPV (€)***
2020	25.00	25.00	30.00	30.00
2030	55.00	42.97	130.00	101.56
2040	85.00	51.87	230.00	140.36
2050	115.00	54.83	330.00	157.33
2060	145.00	54.00	430.00	160.15
2070	175.00	50.91	530.00	154.20
2080	205.00	46.59	630.00	143.19
2090	235.00	41.73	730.00	129.61
2100	265.00	36.76	830.00	115.12

Discounted with 2.5 %

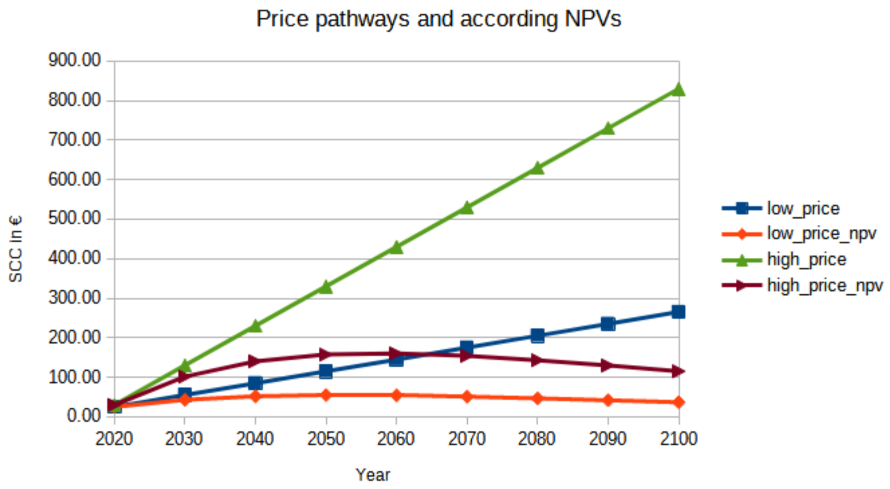
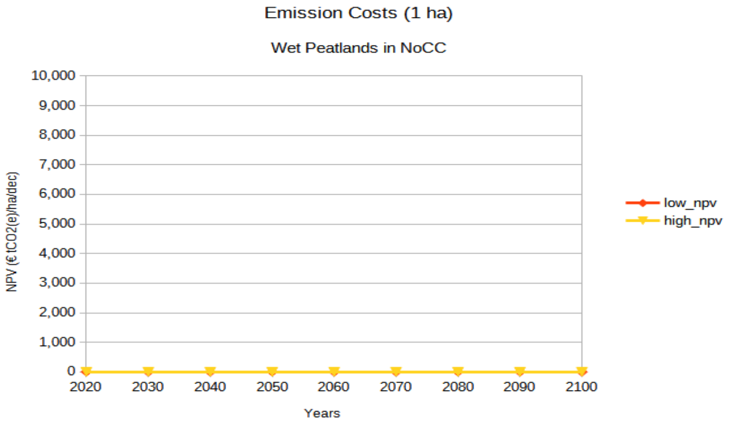
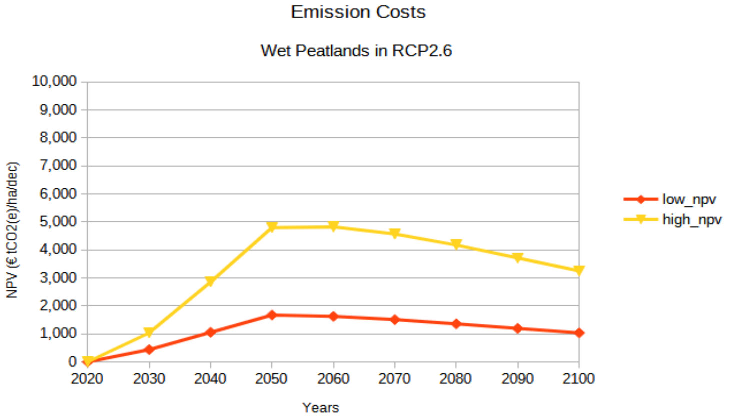


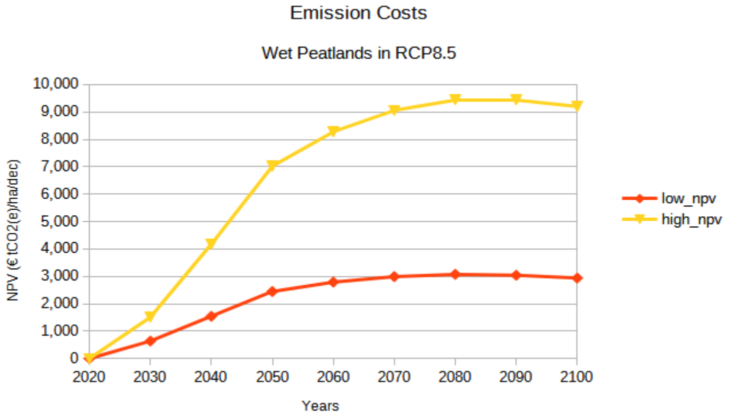
Figure 25: Price pathways and according NPVs in € (for each decade) calculations, that fed the model.

Appendix 3: Illustrated Peatland Costs in Net Present Values

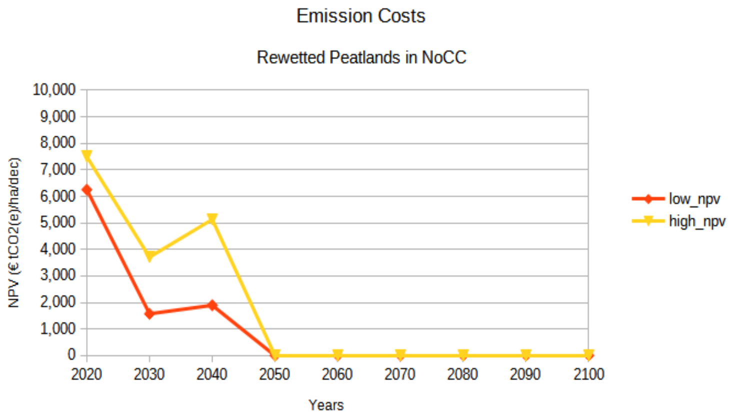
Wet peatland costs per management type and climate scenario (per 1 ha)

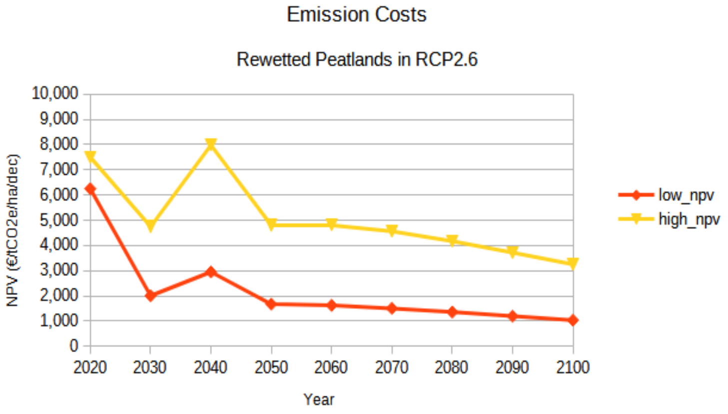


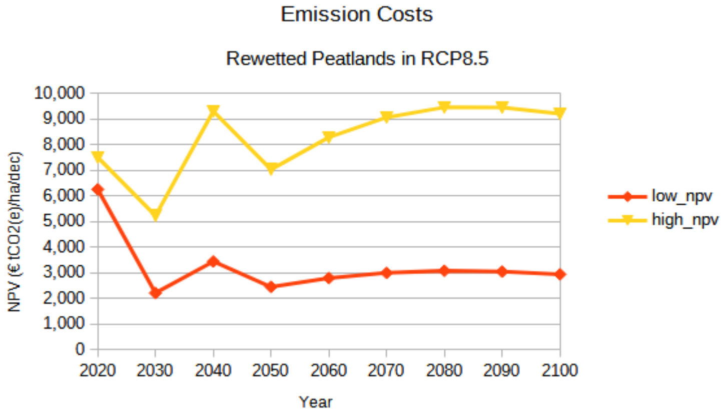




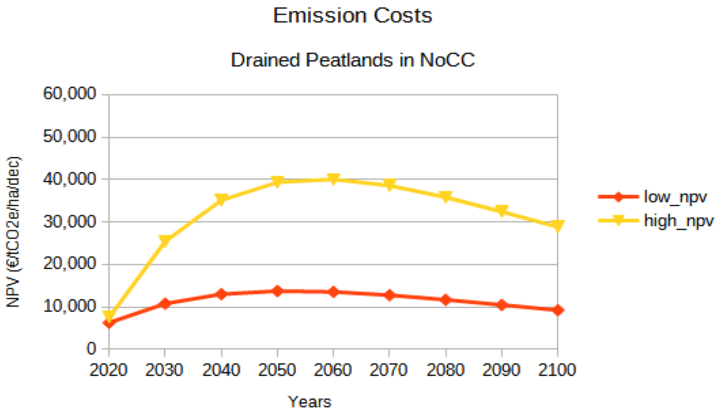
Rewetted peatland costs per management type and climate scenario (per 1 ha)

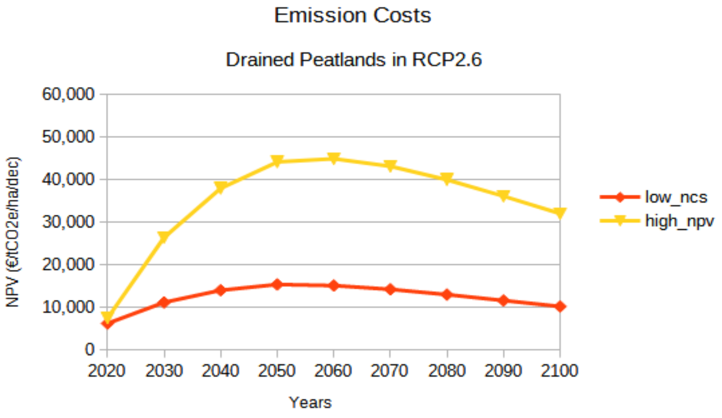


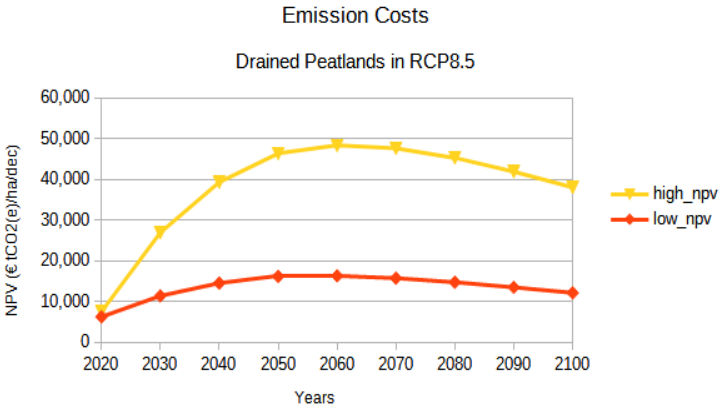




Drained peatland costs per management type and climate scenario (per 1 ha)







Appendix 4: Peatland GHG-Emissions in Relation to Water Saturation

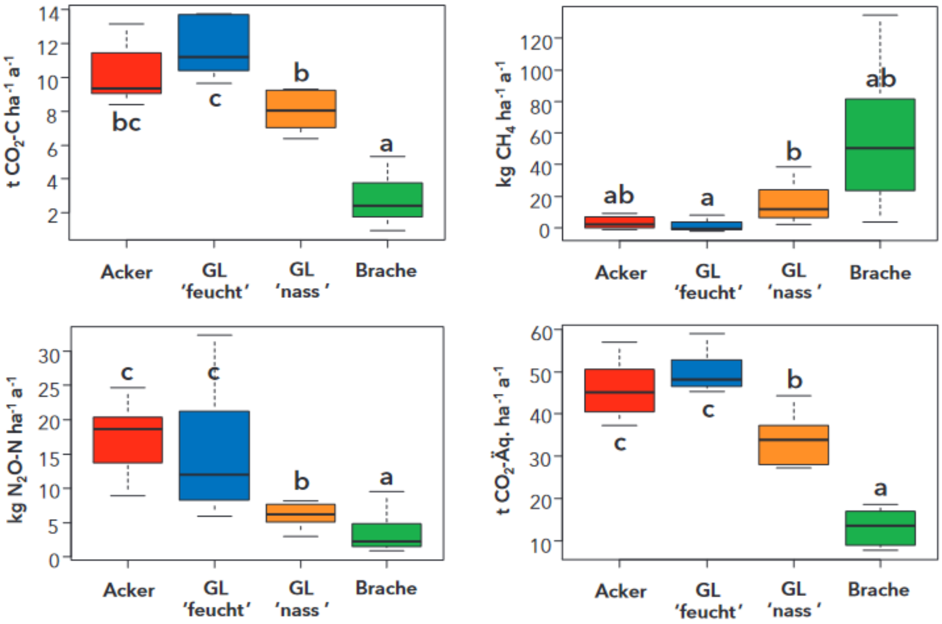


Abbildung 42: Jährliche Emissionen für die Treibhausgase CO_2 (oben links), CH_4 (oben rechts) und N_2O (unten links) im Mittel zweier Versuchsjahre (01. April 2012 – 31. März 2014) sowie die gesamte Klimabilanz (in CO_2-Äquivalenten) der vier Untersuchungsflächen (unten rechts). Unterschiedliche Buchstaben zeigen signifikante Unterschiede zwischen den Untersuchungsflächen.

Figure 26: Emissions of relevant GHGs from peatlands, per gas. (Description → Acker = Arable land, GL = Grünland = Pasture, feucht = semi-wet, nass = wet, Brache = fallow, meaning: a peatland area left wet). From: Böckenhauer et al., 2016, p. 67.

Appendix 5: GHG-Emissions in Relation to Land Use Type

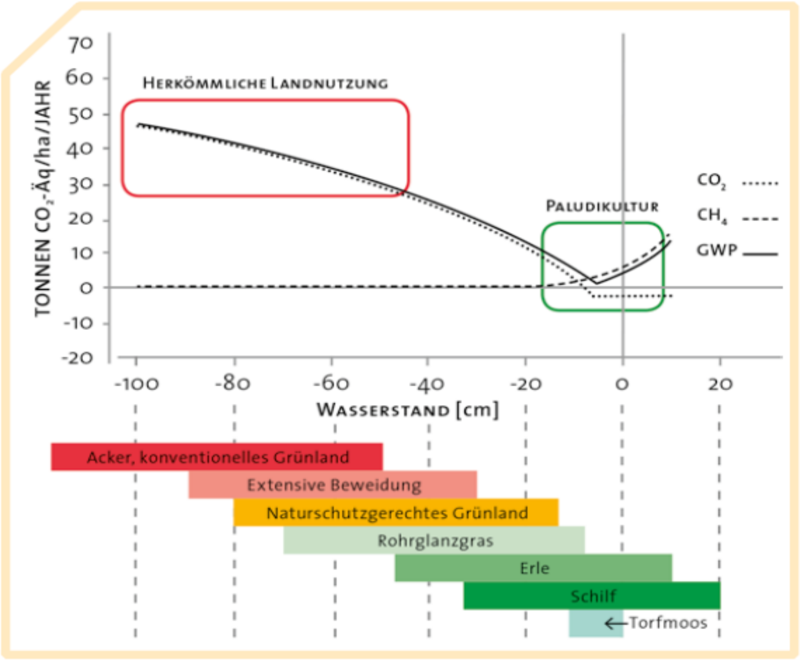


Figure 27: Peatland GHG-Emissions (CO_2e / a) in relation to land use type from dry (conventional, left) to wet (paludiculture, right). From: TEEB DE, 2014, p. 39.

Appendix 6: Map of Peatland Distribution in Schleswig-Holstein

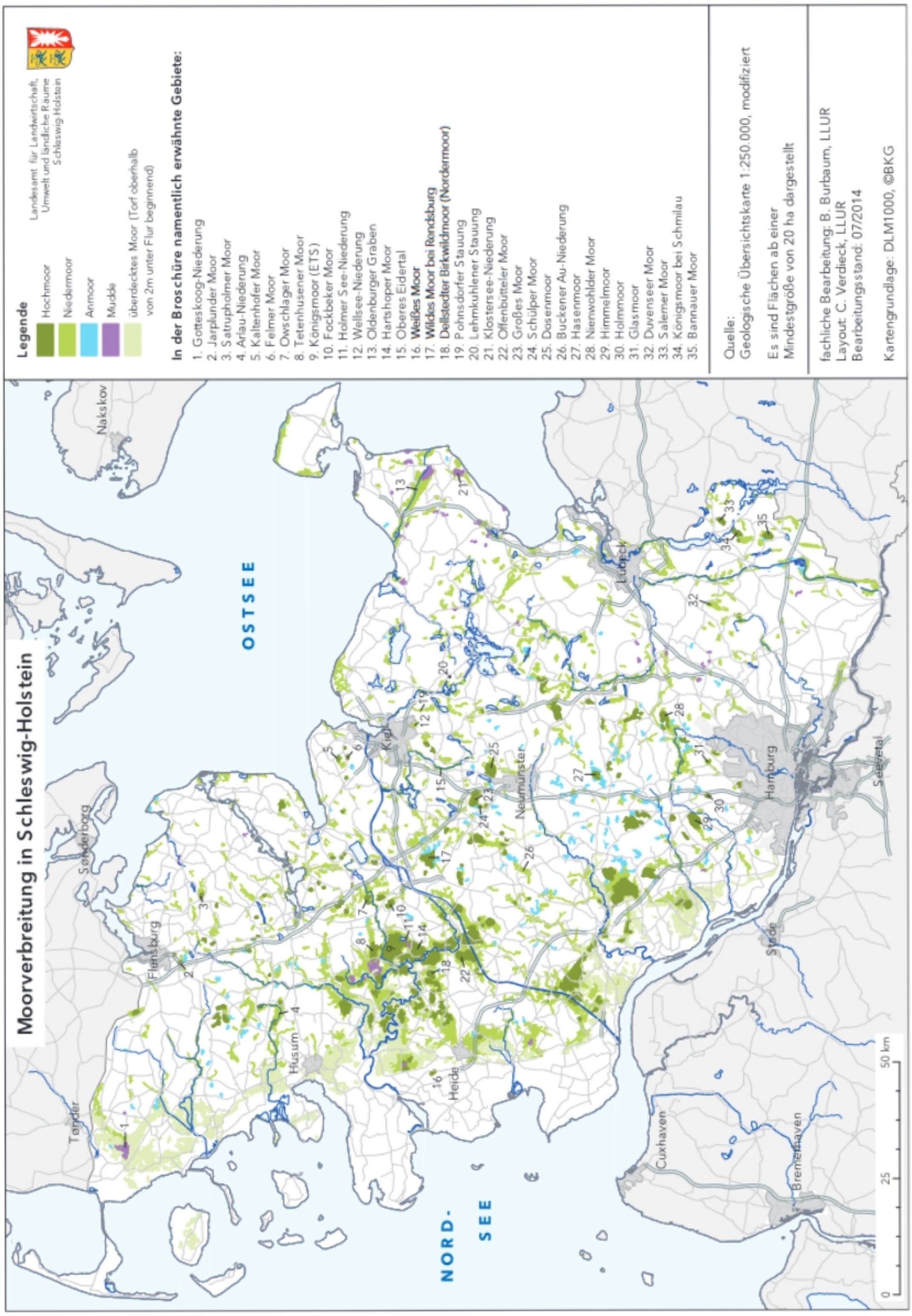


Figure 28: Map of peatlands in Schleswig-Holstein (Hochmoore = Bogs, Niedermoore = Fens, Anmoore = Moist mineral soils with organic content of between 15-30%, Mudde: Organic residue from e.g. drying lakes, überdecktes Moor = covered peatland. From: Böckenhauer et al., 2016, p. 19.

Appendix 7: Relationship of Peatland Area to Precipitation, Temperature and Cloud Cover

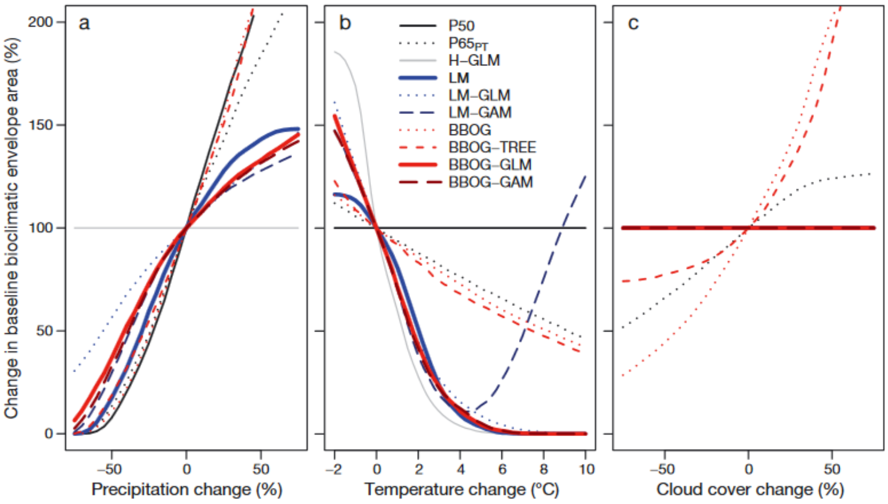
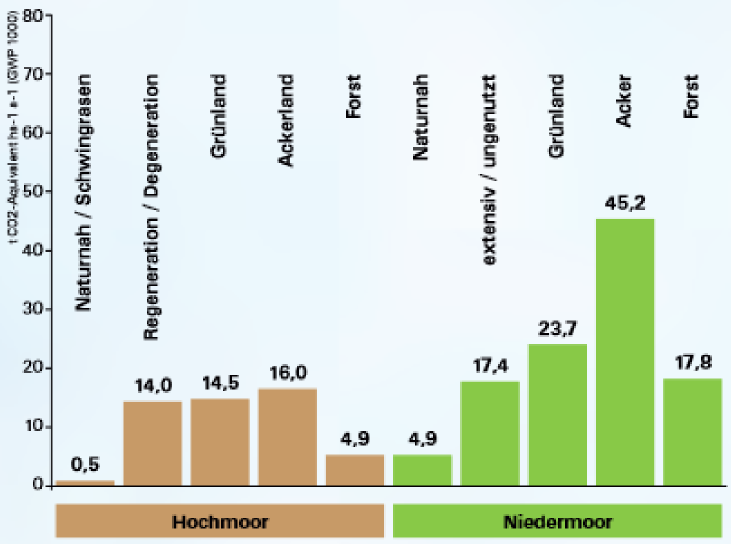


Fig. 4. Sensitivity analysis of bioclimatic envelope models for a single fixed change in either (a) precipitation (b) temperature or (c) cloud cover to 1961–1990 baseline climate data. Changes were applied as single values to the mean monthly data. Models are defined in Tables 1 & 3

Figure 29: Modelled precipitation amount (in %), temperature (in °C) and cloud cover changes (in °C) in relation to peatland area (in % of modelled area). General trends: Increasing precipitation increase leads to peatland areal increases, temperature increases cause peatland decline and cloud cover increases lead to peatland increases. From: Clark et al., 2010, p. 141.

Appendix 8: GHG-Emissions According to Land Use Type in Schleswig-Holstein



Hoch- und Niedermoore setzen je nach Nutzungsintensität und Entwässerungstiefe unterschiedlich stark Treibhausgase frei.
Quelle: nach Höper 2007

Figure 30: Different emissions from bogs and fens, according to land use type, for the case of SH. From: LLUR, 2013, p. 6.

Appendix 9: Peatland Management and According Warming Potential

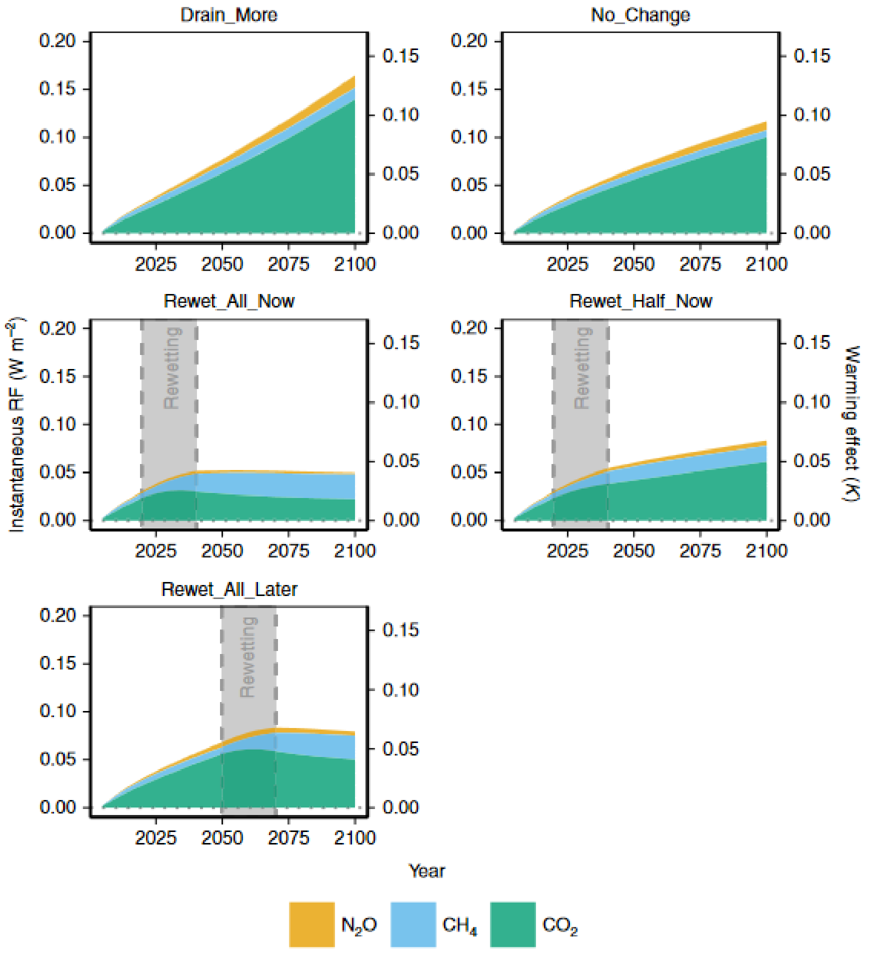


Figure 31:Peatland GHG-emissions according to land use management type and time of implementation (over the course of 2020-2100), in relation to radiative forcing (RF in watt / m^2) and resulting warming effect (in °K). From: Günther et al., 2020, p. 3.

Appendix 10: Drivers of Peatland Changes in the Past

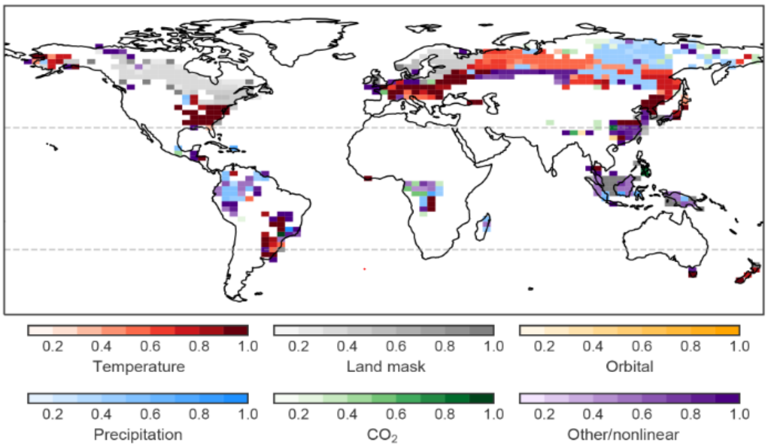


Figure 6. Drivers of the change in peatland area from LGM to present. Colors indicate the most important driver, and colored shading shows the contribution of the respective driver on a scale from 0 (no contribution) to 1 (only contributor).

Figure 32: Main drivers of peatland changes, in the past. From: Müller & Joos, 2020, p. 5296.

Appendix 11: Annual Net Profits of EU Agriculture (examples)

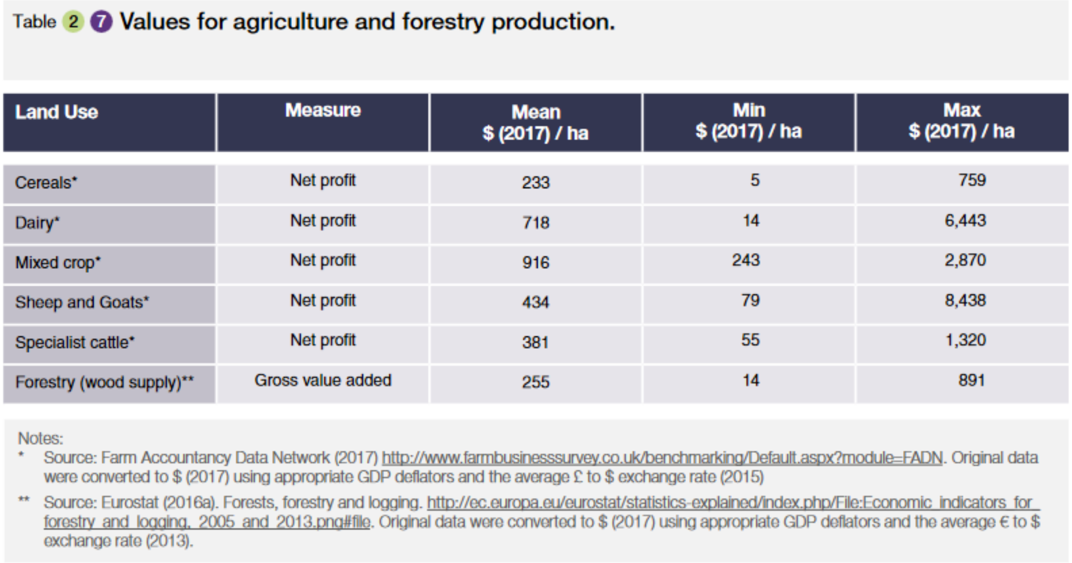


Table ② ⑦ **Values for agriculture and forestry production.**

Land Use	Measure	Mean $ (2017) / ha	Min $ (2017) / ha	Max $ (2017) / ha
Cereals*	Net profit	233	5	759
Dairy*	Net profit	718	14	6,443
Mixed crop*	Net profit	916	243	2,870
Sheep and Goats*	Net profit	434	79	8,438
Specialist cattle*	Net profit	381	55	1,320
Forestry (wood supply)**	Gross value added	255	14	891

Notes:

* Source: Farm Accountancy Data Network (2017) http://www.farmbusinesssurvey.co.uk/benchmarking/Default.aspx?module=FADN. Original data were converted to $ (2017) using appropriate GDP deflators and the average £ to $ exchange rate (2015)

** Source: Eurostat (2016a). Forests, forestry and logging. http://ec.europa.eu/eurostat/statistics-explained/index.php/File:Economic_indicators_for_forestry_and_logging,_2005_and_2013.png#file. Original data were converted to $ (2017) using appropriate GDP deflators and the average € to $ exchange rate (2013).

Figure 33: Net annual profits from EU agriculture in 2017 From: IPBES, 2018, p. 147.

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