Greenhouse gas emissions from globally rewetting drained peatlands

Harmen Severiens

MSc Thesis in Climate Studies

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Preface

After the tough process of writing my BSc thesis, I was not quite looking forward to having to write an even larger MSc thesis. However, during this MSc thesis, I have come to realise how much I actually liked working on it. Using RStudio for the first time, creating my own scenarios in Excel, and deciding halfway through the process to perform another literature review to include more recent emission data, were all experiences that sparked my curiosity and enthusiasm. This thesis really felt like my own project, which gave me a sense of ownership and responsibility combined with a lot of energy and motivation to work on it.

However, this amount of enthusiasm could not have been reached or maintained without the guidance by Jelle ten Harkel and Marjolein Lof, my supervisors. They have stimulated me to be critical about my methods and findings, and they have provided me with many suggestions and extensive feedback, for which I am very grateful. It was a pleasure to work under their supervision. I would also like to thank them for enabling me to combine my thesis with my work as a professional classical singer, which was made possible through their flexibility and understanding.

Finally, I would like to thank Pippelijn Wijnen and Aniek Henken for reviewing my thesis and providing feedback on my presentation, respectively. This thesis was the perfect combination of my BSc in Forest and Nature Conservation, and the MSc in Climate Studies that I aim to finish this year, and I have truly enjoyed working on it.

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Summary

Although peatlands only make up around 3% of land surface area, they are estimated to store 21% of the total global soil organic carbon stock (Leifeld & Menichetti, 2018). Drainage of peatlands leads to peat oxidation and large emissions of CO_2 (Günther et al., 2020). Rewetting is often proposed as a measure to decrease the CO_2 emissions from peatlands and turn peatlands into a carbon sink, although this usually increases CH_4 emissions (Renou-Wilson et al., 2019).

To research the effects of rewetting drained peatlands on a global scale, this study used an atmospheric perturbation model and a literature study to answer the following research question: how is the radiative forcing following greenhouse gas emissions from drained peatlands expected to respond to rewetting on a global scale for different rewetting scenarios? To answer this question, this thesis looked into three different rewetting curves combined with two sets of emission factors, and it researched the effects of future shifting climate zones for four climate scenarios.

The temporal distribution of the adoption of peatland rewetting policy was modelled using three rewetting curve scenarios: one linear scenario that only considered global rewetting, and two scenarios that took into account rewetting per individual country, one following a linear rewetting curve and one following an S-curve. The order in which countries would start rewetting was based on their GDP. The three rewetting curves were combined with two sets of emission factors: one from the 2013 IPCC Wetlands Supplement (IPCC, 2014), which is used by countries to calculate emissions from peatlands for their national greenhouse gas budgets, and one that combined the IPCC emission factors with literature from 2013 onwards, referred to as the updated emission factors. The data for the updated emission factors was collected through a literature review on field and ditch emissions.

Rewetting considering individual countries led to lower radiative forcing over a 100 year period, mostly because the individual countries were ordered by GDP, which led to countries with large drained areas starting to rewet earlier in the rewetting period. Also, rewetting following an S-curve led to similar, but 1.3% or 5.2% higher radiative forcing compared to a linear curve, when the updated and IPCC emission factors were used, respectively.

Using climate zones from climate scenarios with more warming led to increased radiative forcing from rewetting drained peatlands. The climate scenario with the most warming, SSP5-8.5, led to an increase of 6.8% and 4.8% compared to when current climate zones were used, for the updated emission factors and IPCC emission factors, respectively.

Most importantly, this thesis showed very large differences between the IPCC emission factors from 2013, and the emission factors if combined with literature between 2013 and 2024. This resulted in large differences in radiative forcing. Even after correcting for values and weights that strongly affected emission factors, using the updated emission factors resulted in a 81% larger radiative forcing on a 100-year timescale compared to when the IPCC emission factors were used. This was mostly due to larger CO_2 emissions after rewetting, leading to a slower increase in radiative forcing instead of a decrease, the latter being the case when IPCC emission factors were used. Changing the order in which countries started rewetting and changing the steepness of the S-curves used for the scenarios only led to small differences in radiative forcing.

The main limitation of this research was that the exact criteria for including or excluding papers for the emission factors in the IPCC Wetlands Supplement were unknown. Considering that the emission factors from recent literature strongly seem to diverge from the IPCC emission factors, it is recommended that the IPCC emission factors are updated to include recent literature, using the same methodology.

1. Introduction

1.1 Background

Peatlands can play an important role in climate change, storing 21% of the global amount of soil carbon in the first 3 metres (Leifeld & Menichetti, 2018). In a natural peatland system, the groundwater level is close to the surface. This high groundwater level leads to anaerobic conditions under which organic material hardly decomposes, causing the accumulation of organic matter in the form of peat. When these wet conditions are maintained, the carbon can be stored there for thousands of years (Gorham et al., 2012). During the last centuries however, peatlands around the globe have been drained and degraded for various reasons. This drainage has led to substantial emissions of carbon dioxide (CO_2), since lowering the water level made oxygen available for aerobic decomposition of the organic material that peatlands consist of. It is estimated that degraded peatlands account for 5% of the current anthropogenic greenhouse gas (GHG) emissions (Strack et al., 2022). Apart from large CO_2 emissions, the decomposition of peatlands has also lead to soil subsidence and to altered hydrological systems due to the changes in elevation following the soil subsidence (Brouns et al., 2015).

The scenarios from the Intergovernmental Panel on Climate Change (IPCC) that limit the global temperature increase to 1.5 °C of warming require substantial negative emissions, next to cutting current greenhouse gas emissions, especially in the second half of this century (Luderer et al., 2018). Peatlands are often thought of as one way to achieve these negative emissions, by the build-up of organic material in the peat soils. When plants and other organisms die in an ecosystem with high water levels such as a peatland, their remains are broken down very slowly if at all, due to the lack of oxygen. On longer timescales, this process has turned peatlands into a considerable carbon sink. In order to mitigate climate change and make peatlands a GHG sink instead of a source, rewetting of drained peatlands is usually proposed as a measure (Evans et al., 2021; Leifeld & Menichetti, 2018). Depending on the groundwater level, rewetting indeed stops or at least decreases the CO_2 emissions. Furthermore, peatland rewetting leads to the accumulation of organic matter in peat layers, storing carbon in the process. However, rewetting also reestablishes methane emissions (CH_4) (Evans et al., 2021).

CH_4 emissions from peatlands are a product of methanogenesis, a process in which CO_2 or acetate, depending on the pathway, is reduced by archaea to CH_4 (Lai, 2009). This only happens in anaerobic circumstances where alternative electron acceptors have been depleted, because CH_4 is quite an unfavourable electron acceptor. CH_4 emissions from the field will be very low in peatlands that are drained to a groundwater level deeper than 20 cm below the surface, because anaerobically produced CH_4 will be oxidised in the upper aerobic layer (Beyer & Höper, 2015; Peltoniemi et al., 2023). However, this does not mean that CH_4 emission from drained peatlands are zero. CH_4 emissions from the ditches that are created for drainage can still be substantial (Köhn et al., 2021).

CH_4 emissions from peatlands, although produced naturally, may on the short term have a more negative effect on the GHG balance than the CO_2 emissions due to methane's higher Global Warming Potential (GWP) of 27 on a 100-yr timescale (Forster et al., 2021). This means that on a timescale of 100 years, 1 gram of CH_4 emitted to the atmosphere causes 27 times more warming than 1 gram of CO_2. However, CH_4 also has an atmospheric lifetime of 11.8 years, which is much shorter than CO_2 and N_2O. Therefore, rewetting drained peatlands is thought to lead to lower atmospheric GHG concentrations (in CO_2-eq.) on longer timescales (Archer et al., 2009; Günther et al., 2020). In the troposphere CH_4 reacts with the hydroxyl radical OH. In this reaction CH_4 is oxidised into CO, CO_2 and H_2O. Although there are also other ways in which CH_4 is removed from the atmosphere, the reaction with OH is the major sink for atmospheric CH_4 (Stevenson et al., 2020; Wahlen, 1993).

The different timescales, atmospheric lifetimes, and GWPs of CO_2, CH_4, and N_2O result in the observation that rewetted peatlands may take a long time, if at all, to become a net GHG sink again (Schaller et al., 2022; Vanselow-Algan et al., 2015). Especially for N_2O, its relative importance for the GHG balance of a peatland varies substantially compared to CO_2 and CH_4 (Anthony & Silver, 2021). In most studies N_2O emissions seem to be small, just as in the emission scenarios created by Günther et al. (2020), but there are notable exceptions such as found by Hellmann and Vermaat (2012). Due to the large GWP of N_2O, which is 273 on a 100-year timescale, this can have a strong impact on the GHG balance of a peatland (Forster et al., 2021). Peatlands can also emit ozone (O_3), but this greenhouse gas is rarely taken into account in literature and therefore not included here. See Schaller et al. (2022) for a case study where O_3 is included in the greenhouse gas balance.

1.2 Problem statement

Peatlands always emit some GHG, with high CO_2 emissions for drained peatlands and high CH_4 emissions for rewet peatlands. In order to mitigate climate change, it is of great importance to know what the effects will be of rewetting drained peatlands. With CH_4 being a stronger GHG but with a shorter atmospheric lifetime, and CO_2 being a weaker GHG but with a longer atmospheric lifetime, it comes down to the question which is to be preferred in order to limit global temperature increase to 2 °C, and preferably 1.5 °C. How do peatlands under drained and rewetted conditions compare in terms of their GHG balances?

To gain insight into this dilemma, Günther et al. (2020) have modelled different scenarios in which drained peatlands are being rewet on a global scale and compared this to the current situation. For their research, they used data obtained from the Global Peatland Database for the areas identified as peatland, split out per climate zone per land use type (Greifswald Mire Centre, 2022). Thereafter, this data was combined with emission factors from the 2013 IPCC Wetlands Supplement (IPCC, 2014). They found that immediately rewetting all drained peatlands on a global scale within a twenty year period was the most effective scenario to limit the global temperature increase. However, the scenarios that were investigated were limited to the following: to rewet all drained peatlands immediately, to rewet all drained peatlands at a later point in time, to rewet half of drained peatlands immediately, to increase the area of drained peatland at the same rate as between 1990-2017, and to keep the area of drained peatland the same as in 2018. Furthermore, Günther et al. (2020) did not include individual countries in their research, but instead assumed linear rewetting on a global scale at a constant rate. Also, since the emission factors were taken from the 2013 IPCC Wetlands Supplement, literature on emission factors published since 2013 was not taken into account.

Thus, although the study by Günther et al. (2020) provides informative insights into the long-term effects of different global rewetting scenarios, it would be valuable to similarly study the effects of peatland rewetting whilst making additions to the scenarios, leading to a deeper understanding of the long-term effects of rewetting peatlands globally.

1.3 Purpose of the study and research questions

Günther et al. (2020) have studied the effects of globally rewetting drained peatlands on radiative forcing following GHG emissions for different scenarios. This thesis aims to explore a wider range of possible scenarios. This includes the use of different rewetting curves, the impact of multiple future climate scenarios, and comparing the effects of using the initial IPCC emission factors from the Wetlands Supplement with updated emission factors including recent literature. This will be done using the same atmospheric perturbation model that was used and created by Günther et al. (2020) and using updated data from the Global Peatland Database. Therefore, the following research question is proposed:

How is the radiative forcing following greenhouse gas emissions from drained peatlands expected to respond to rewetting on a global scale for different rewetting scenarios?

To answer the main question the following sub-questions (SQs) were defined. SQ1 and SQ3 are answered using a literature study combined with modelling, whereas SQ2 is answered solely through modelling.

1. What is the expected temporal distribution, or rewetting curve, of globally rewetting drained peatlands, and what is the impact of this rewetting curve on radiative forcing?
2. How do future shifting climate zones impact the radiative forcing?
3. What are the effects of using updated emission factors that take into account literature from 2013 onwards?

SQ1: What is the expected temporal distribution, or rewetting curve, of globally rewetting drained peatlands, and what is the impact of this rewetting curve on radiative forcing?

The modelled scenarios by Günther et al. (2020) use a period of twenty years in which all drained peatlands globally are being rewetted at a constant rate. However, it is highly unlikely that the actual global adoption of peatland rewetting policy will take place at a constant rate. The adoption rate might increase or decrease over time, possibly leading to hysteresis effects in the CH_4 emissions. Therefore, this thesis aims to explore what different adoption scenarios, or rewetting curves, could look like. The different rewetting curves are then used to create scenarios. This SQ also explores what the impact of these different scenarios is on the radiative forcing caused by globally rewetting drained peatlands.

SQ2: How do future shifting climate zones impact the radiative forcing?

This SQ simulates the effects of climate change by looking at the changes in climate zone distribution per individual country, using the Köppen-Geiger Explorer (Beck et al., 2023; Haizea Analytics, 2023). This is done for different climate change scenarios, so-called shared socioeconomic pathways, covering a broad range of possible futures. This SQ explores how the different climate zone distributions impact the radiative forcing from globally rewetting drained peatlands.

SQ3: What are the effects of using updated emission factors that take into account literature from 2013 onwards?

A large share of literature on greenhouse gas emissions from drained peatlands has been published after 2013 (Figure 1). Therefore, a literature review is executed aimed at combining the emission factors from the 2013 IPCC Wetlands Supplement with data from newer research. This is done for both the field emissions and the ditch emissions. The radiative forcing from globally rewetting drained peatlands using updated emission factors is compared to scenarios in which the IPCC emission factors are used.

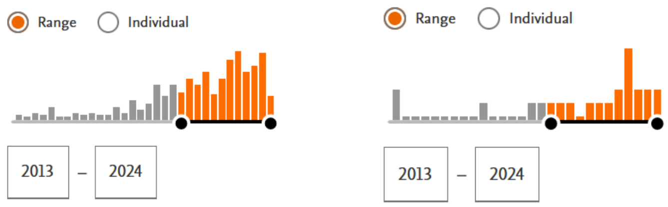

Figure 1: Print screen of Scopus search results showing the number of papers published on field emissions (left) and ditch emissions (right) from drained and rewetted peatlands from 2013 to 2024 (orange) and before (grey). The queries can be found in 2.8.1 (field emissions) and 2.8.2 (ditch emissions).

2. Methods

2.1 Overview of used methods

This section describes the methods that were used in this thesis. An overview of the used data sources, tools and models is provided in Figure 2. To gain insight into possible different rewetting curves, a literature study on policy diffusion was conducted. This literature study was used to answer SQ1, and is described in section 2.2. Using the rewetting curves from this literature study, rewetting scenarios were created using Microsoft Excel. The methods that were used for creating and applying the scenarios in combination with the atmospheric perturbation model by Günther et al. (2020) are described in section 2.3 to 2.6. Section 2.7 describes the methods used to analyse the effects of shifting climate zones, to answer SQ2. Section 2.8 describes the literature study that was used to update the emission factors from the IPCC Wetlands Supplement (IPCC, 2014), to answer SQ3. Finally, section 2.9 describes the methods that were used for conducting the sensitivity analysis.

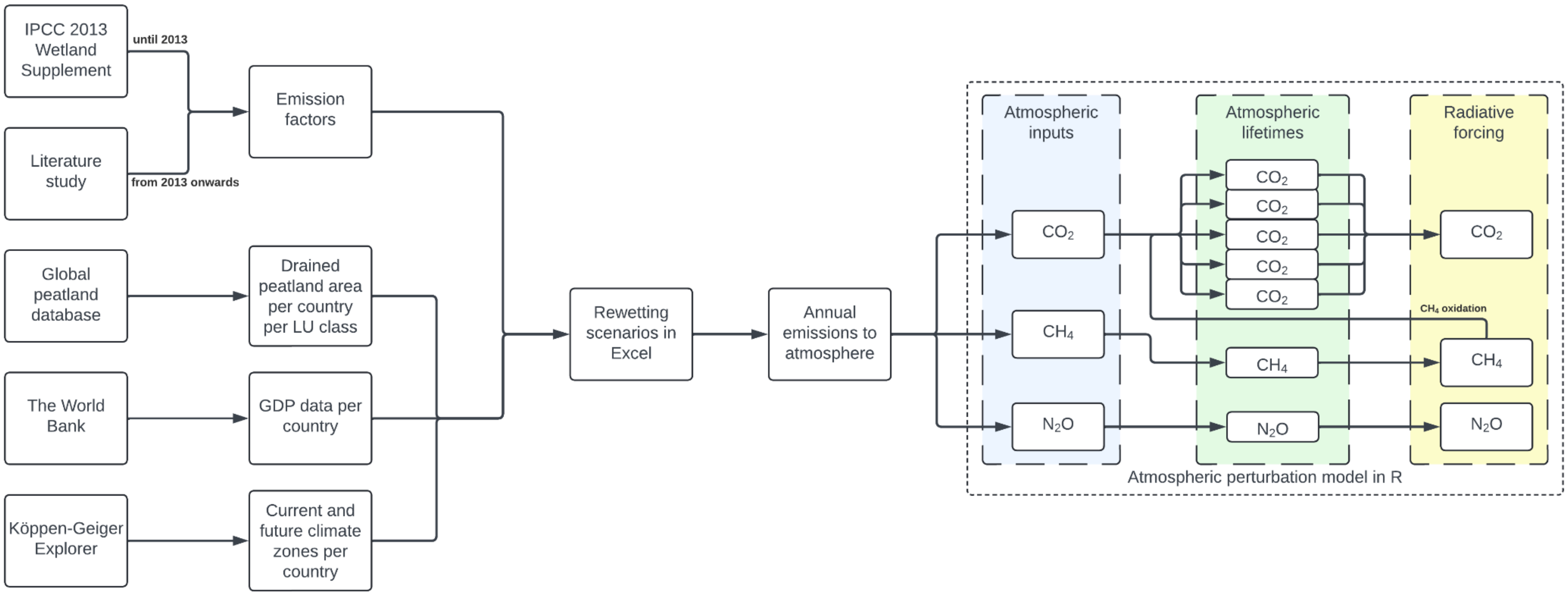

Figure 2: Schematic overview of data sources and processes including the Atmospheric Perturbation Model by Günther et al., 2020.

2.2 Literature research on policy diffusion

In order to predict the temporal distribution of rewetting drained peatlands, it was important to look into the existing literature on so-called policy diffusion. This was done to answer the first part of SQ1: what is the expected temporal distribution, or rewetting curve, of globally rewetting drained peatlands?

In this thesis, policy diffusion was defined as the process of governments influencing each other regarding the implementation of a policy innovation. This meant that "a country or state observes what other countries or states have done and conditions its own policy decisions on these observations" (Graham et al., 2013, p. 675). When this definition of policy diffusion was applied to the subject of this thesis, policy diffusion was considered the process in which governments or countries adopt policies on rewetting the drained peatlands in their countries.

To investigate how the adoption of rewetting policies for individual countries on a global scale could be simulated, a literature research was conducted. In the literature research, the search engines Scopus, Web of Science, and Google Scholar were used to find scientific articles on the subject. Furthermore, snowball sampling was used to find additional literature, meaning that the references of a source and literature citing that source were reviewed for a deeper understanding of the concepts and processes of policy diffusion regarding rewetting drained peatlands and similar environmental policies.

From the literature research it became clear that the diffusion of policy could often, though not always, be described using an S-curve. The reason for this was that in many fields the adoption of policy was more or less normally distributed, leading to a cumulative adoption that had the shape of an S (Gray, 1973). The reasoning behind this S-curve was that a few early adopters would adopt innovative policy, and by doing so, provide information and learning possibilities for other countries to follow in the adoption of similar policy (Simmons & Elkins, 2004). After more and more countries would have adopted the innovative policy, the pool of remaining countries would become smaller, leading to fewer adoptions over time (Berry & Berry, 2007).

In order to make a comparison between different rewetting curves, three different rewetting curve scenarios were included in this thesis. One scenario only considered rewetting globally, not taking individual countries into account. This scenario used a linear rewetting curve, and is explained in more detail in section 2.5. The other two scenarios did take into account individual countries, with one using a linear rewetting curve and the other using an S-curve. These are explained in more detail in section 2.6. See Figure 5 for an example of the S-curve, and Figure 4 for an overview of the three rewetting curve scenarios.

Furthermore, wealth appeared to be one of the factors playing a role in policy diffusion. Research suggests that wealthier countries are more likely to adopt innovative policy. However, this does not mean that early adopters are necessarily wealthy since there are more factors influencing the adoption of new policy (Gray, 1973; Mallinson, 2020).

In this thesis, a countries' GDP was selected as a measure of its wealth to predict the order of countries adopting rewetting policy. This is further described in section 2.6.3. To analyse the sensitivity of the results for different orders of countries, ten random orders were included in the sensitivity analysis (see section 2.9.1 and 3.4.1).

2.3 Model selection

For this thesis, an atmospheric perturbation model in R was used. It was the same model that was used by and created by Günther et al. (2020). The code is provided in Annex 4.

The model calculated the radiative forcing of CO_2, CH_4, and N_2O using exponential functions for atmospheric decay, based on the atmospheric lifetimes and annual inputs. For CO_2, the decrease was simulated by a decay towards equilibria with five different pools with different sizes and residence times. The model included the oxidation of CH_4 into CO_2, that was consecutively spread throughout the five pools. The output of the model was the change in radiative forcing caused by CO_2, CH_4 and N_2O in W/m^2. A schematic overview of the model is shown in Figure 2.

2.4 Selection of emission factors

The atmospheric perturbation model required an input of global annual emissions of CO_2, CH_4, and N_2O in g N or g C per year. In 2013, the IPCC has published an extensive review of greenhouse gas emissions from wetlands, as a supplement to their 2006 report on guidelines for national greenhouse gas reporting (IPCC, 2014). This document will be further referred to as the IPCC Wetlands Supplement, and the emission factors in it as the IPCC emission factors. This report is used by many scholars, amongst which also Günther et al. (2020). The IPCC Wetlands Supplement provides countries with standard emission factors for drained and rewetted organic soils, including emissions from ditches and dissolved organic carbon, for different land use types and boreal, temperate and tropical climate zones, to use for their national greenhouse gas budgets. Since this IPCC Wetlands Supplement is the most complete report on this topic, it was used in this thesis to determine the emissions of drained peatlands per climate zone and per country.

However, many of the emission factors in the IPCC Wetlands Supplement were based on a small number of scientific papers, making them sources of considerable uncertainty. Furthermore, the amount of scientific literature on greenhouse gas emissions from peatlands has been growing rapidly since 2013 (see Figure 1). Therefore, it was decided to similarly conduct two literature reviews that would include scientific literature from 2013 onwards. The first encompassed the field experiments and field measurements of greenhouse gas emissions on drained and rewetted peatlands across all climate zones except polar. The second literature review focused on CH_4 emissions from drainage ditches, since CO_2 and N_2O emissions were rarely included in scientific literature that provided ditch emissions data. Both literature reviews aimed to collect the relevant scientific literature from 2013 until present day. The resulting emission factors from the literature reviews were then combined with the emission factors from the IPCC, to form the updated emission factors. The term 'updated emission factors' is how they will be further referred to in this report.

The details and results of the literature reviews can be found in section 2.8. In order to compare the differences in radiative forcing from using either the IPCC emission factors or the updated emission factors, all scenarios were run with both sets of emission factors.

2.5 Implementation of linear rewetting curve without individual countries

2.5.1 Collection of global drained peatland and climate data

The linear rewetting curve that did not take into account individual countries was created using data on global drained peatlands derived from Table 2 in Günther et al. (2020). This table contained the areas of drained peatland per climate zone, per land use type, without considering individual countries.

Because this data by Günther et al. (2020) was originally derived from the Global Peatland Database (Greifswald Mire Centre, 2022), and the data provided by the Global Peatland Database for this thesis did not contain information on climate zones, the following was done: since the numbers in the Global Peatland Database were updated between the publication of Günther et al. (2020) and the writing of this thesis, the updated total drained peatland area was distributed over the climate zones and land use types following their proportions in Table 2 in Günther et al. (2020). This means that the increase in drained peatland area since the publication of Günther et al. (2020) was assumed to be distributed proportionately over the climate zones and land use types.

2.5.2 Implementing rewetting curve in Excel

The rewetting scenario without individual countries followed a linear increase in rewetting on a global scale over a period of 40 years. This rewetting period started from year 20, to also show radiative forcing from emissions under current drained conditions for the first 20 years. During these first 20 years, emissions were assumed to be constant. It is noteworthy that the rewetting period of 40 years differed from the Günther et al. (2020) paper, where a rewetting period of 20 years was chosen. However, the period of 40 years was more in line with the rewetting period of the scenarios with individual countries, described in 2.6.4, which was needed for the comparison of both.

Since this linear scenario did not consider individual countries, the rewetting curve showing the rewetted fraction per year was truly linear, in contrast to the rewetting curve of the linear scenario that did take into account individual countries (see Figure 4). In other words, this rewetting curve assumed that all drained peatlands around the globe were being rewetted at a constant rate, starting and ending at the same moment.

After the rewetting period of 40 years, all peatlands had been rewet, and the model was run for 40 more years to show the impact of emissions and radiative forcing after rewetting.

2.6 Implementation of rewetting curves with individual countries

2.6.1 Collection of drained peatland data per country

To create the scenarios that considered individual countries, the Global Peatland Database was used as a source of scientific data on drained peatlands per land use type per country (see Annex 6). The database combined data from multiple sources, and was last updated in November 2022. The database was used to create the two rewetting scenarios that considered rewetting by individual countries, one with a linear and one with a logistic rewetting curve. For some countries in the Global Peatland Database, the area of drained peatland was slightly larger than the area of total peatland. In these cases, the total peatland area was adjusted to the drained peatland area. The total drained peatland area from this database was higher than the total area mentioned in Table 2 in Günther et al. (2020). According to personal communication with the coordinator of the database, this was due to updated and more precise numbers rather than only an increase in the drained peatland area.

2.6.2 Collection of climate data per country

Since the data provided by the Global Peatland Database did not include data on a countries' climate zones, this data was collected through the Köppen-Geiger Explorer (Beck et al., 2023; Haizea Analytics, 2023). This is an online tool that shows the historic, current and future climate zones per country. The future climate zones will be discussed more in-depth in section 2.7.

The Köppen-Geiger Explorer shows the relative proportions of climate zones present in a country. To determine the current climate zones, the time interval 1991-2020 was used. The relative climate zone proportions from the Köppen-Geiger Explorer were combined with the drained peatland area data from the Global Peatland Database to determine the drained peatland area per climate zone for a country. This meant that the drained peatlands of a country were assumed to be distributed proportionately over the climate zones present in that country.

In this thesis, emissions were calculated using emission factors for boreal, temperate and tropical climates. However, there were some countries that were completely in the arid climate zone, but still had drained peatlands, such as Egypt, Kuwait, Botswana and Mauritania. For these countries, the climate zone closest to the country (cold, temperate, or tropical) was selected. The Köppen-Geiger Explorer had no data for the Maldives and Kiribati, so these were assigned the tropical climate zone based on their surrounding countries. Last, the Azores were considered part of Portugal by the Köppen-Geiger Explorer, but were visually assigned the climate zone that could be seen on the map.

The Köppen-Geiger Explorer could either show main climate zones, or detailed climate zones per country. The main climate zones were polar, temperate, tropical, arid, and cold. Following the IPCC Wetlands Supplement, the classes polar and arid were excluded. However, the total drained peatland area per climate zone was very different when comparing the numbers from Table 2 in Günther et al. (2020) with the numbers from the Köppen-Geiger Explorer (see Figure 3). Note that the numbers from Günther et al. (2020) were adjusted proportionately to match the updated total drained peatland area from the Global Peatland Database.

The reason for the difference in drained peatland area per climate zone, was that the IPCC used another climate classification system with a boreal climate that was very different from the cold climate from the Köppen-Geiger Explorer (IPCC, 2006). This heavily influenced the distribution of land over the boreal/cold and temperate climate zones. When visually comparing the climate zone maps from the IPCC and the Köppen-Geiger Explorer, the IPCC climate distribution roughly categorised the following climates as temperate instead of cold: Dsa, Dsb, Dwa, Dwb, Dfa and Dfb. These were the continental climates (D) with hot (a) and warm (b) summers. Since the emission factors in the IPCC Wetlands Supplement were divided by the IPCC climate zones, the IPCC climate zones were used in this thesis. Therefore, the Köppen-Geiger Explorer zones Dsa, Dsb, Dwa, Dwb, Dfa, and Dfb were for each country manually moved to the temperate climate zone to be more in line with the IPCC distribution (Figure 3, right column).

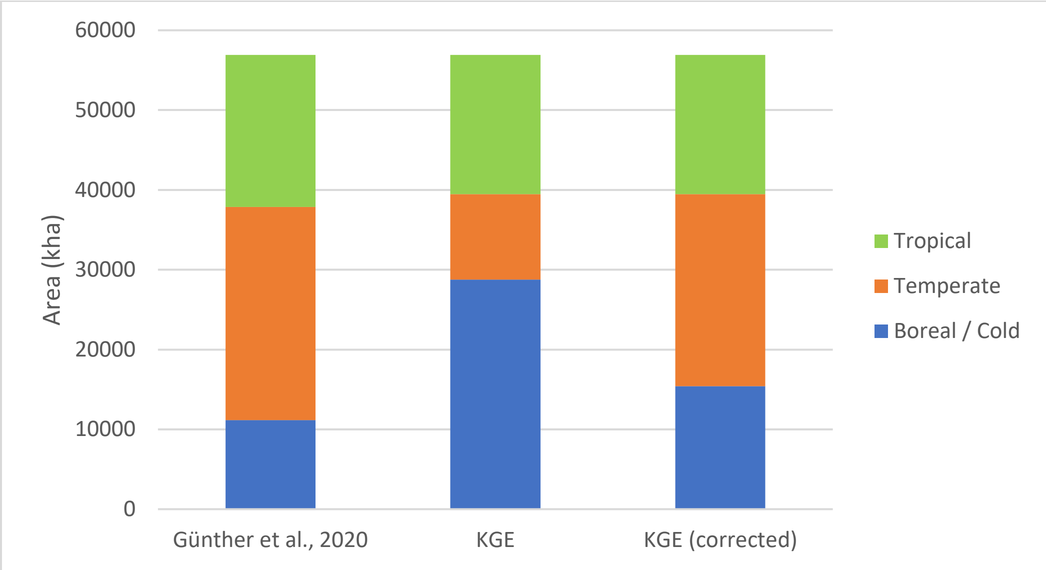

Figure 3: Distribution of drained peatlands across tropical (green), temperate (orange) and boreal/cold climate zones (blue), from left to right: distribution of drained peatlands across climate zones as categorised by the IPCC, using the area numbers from Table 2 in Günther et al. (2020); distribution of drained peatlands across climate zones as categorised by the Köppen-Geiger Explorer, using the area numbers from the Global Peatland Database ; distribution of drained peatlands across climate zones following the Köppen-Geiger Explorer after moving the climates Dsa, Dsb, Dwa, Dwb, Dfa, and Dfb from the cold to the temperate climate zone, to be more in line with the IPCC categorisation, using the area numbers from the Global Peatland Database.

2.6.3 Collection of Gross Domestic Product (GDP) data

For each of the 175 countries with drained peatland, the GDP was collected in order to sort the countries by wealth as a way to predict policy diffusion (Mallinson, 2020). This was done by taking the average GDP of each country from the period 2010 to 2022. This relatively long period was selected because some countries, especially smaller ones, had missing data. The GDP data were taken from The World Bank (2023), except for North Korea, which was taken from Our World in Data (2023a), for Swaziland and Taiwan which were taken from Our World in Data (2023b), and for the Azores, French Guiana, Martinique, and finally Réunion which were taken from Eurostat (2023).

2.6.4 Implementing the rewetting curves in Excel scenarios

Since the atmospheric perturbation model required a total annual input of CO_2, CH_4, and N_2O, these numbers were calculated by combining the data on emission factors, climate zones, drained peatland area per land use type, and GDP. This was done using Microsoft Excel (see also Figure 2). All 174 countries that contained drained peatland according to the Global Peatland Database were put in order of average GDP, from high to low. For each country, its land use categories with drained peatland were distributed proportionately over the climate zones that were present in the country. Consequently, each of these were linked to the emission factor for the corresponding climate zone / land use type combination.

The two rewetting curves that took into account individual countries differed in the way that one used linear functions and the other used logistic functions to simulate the following two things: the rewetting curve per country, meaning the rewet area fraction of a country over time, and the number of countries starting rewetting per year. This meant that the countries started rewetting in different years, based on their GDP. The time that a country needed to rewet was based on the country's ratio between GDP and its drained peatland area, and a maximum time that could be set. The time between the first and last country to start rewetting was set to 15 years, and the maximum time that a country could spend rewetting was set to 25 years. This meant that the total rewetting period could last 40 years, which was the same as for the scenario that did not consider individual countries. The choice for this rewetting period is discussed in section 4.2.

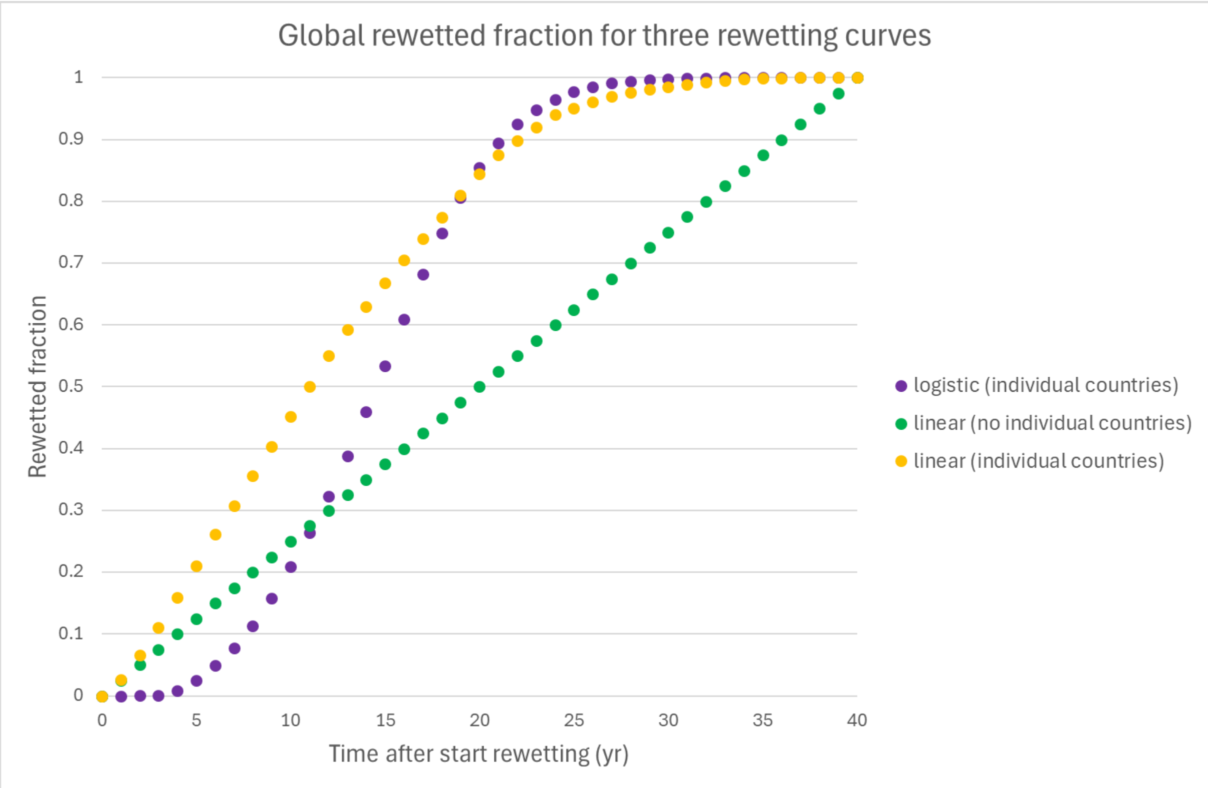

Figure 2: The three different rewetting curves used in this thesis, showing the total rewetted fraction over the 40-year rewetting period: linear without individual countries (green) in which all drained peatlands worldwide are rewetted at a constant rate throughout the whole 40-year period; linear with individual countries (yellow) in which countries are ordered by GDP and the countries with highest GDP start rewetting first, and the number of countries starting rewetting per year and the rewetting speed per country are constant; logistic with individual countries (purple) in which countries are also ordered by GDP and the countries with highest GDP start rewetting first, but the number of countries starting rewetting per year and the rewetting speed per country are following a normal distribution.

Since the countries were rewetting following the order of GDP, the linear scenario with individual countries had a non-linear rewetting curve (Figure 4). The reason for this was that countries with a higher GDP in general had larger areas of drained peatland, whereas the countries with a lower GDP, such as small island states, tended to have smaller areas of drained peatland.

For the rewetting scenarios with individual countries, the duration of rewetting per country could be set. The Excel model was created in such a way that the time needed for rewetting could either be set to one value that was the same for all countries, or that it was dependent on the ratio of GDP per drained area of a country. Based on this ratio, the countries were ranked from 1 to 174 and the rewetting duration was calculated as follows: dividing a country's rank by the total number of countries, multiplied by the maximum set rewetting duration, and then rounded up to a whole number.

To create the S-curves the Normal Distribution function in Excel was used. This function requires a value x, the average of the normal distribution, and the standard deviation of the normal distribution. An overview of the values used for these parameters for both S-curves is provided in Table 1. The average was set to half of the total time period to create a symmetrical S-curve. The standard deviation was set to 1/6th of the total time period, since this led to a well-shaped S-curve (Figure 5). Low standard deviations led to a very sharp increase close to the average, and included few countries starting rewetting at the start or end of the rewetting period. High standard deviations led to the S-curve becoming similar to the linear function that it was to be compared with. However, the effects of changing the standard deviations were assessed in the sensitivity analysis, see section 3.4.2 and 3.4.3. Lastly, since setting a maximum time for rewetting led to the cumulative of the S-curve not adding up to 1, each value was divided by the cumulative value at the maximum set time in order to redistribute the S-curve.

Table 1: Parameters in Normal Distribution function in Microsoft Excel for both S-curves. In the sensitivity analysis other values for the standard deviation were used.

	S-curve for number of countries starting rewetting per year	**S-curve for rewetting for each individual country**
Value x	The n^{th} year of the time period that countries could start rewetting	The n^{th} year of rewetting for that country
Average	Half of total time period that countries could start rewetting	Half of total time period that that country needed for rewetting
Standard deviation	1/6th of total time period that countries could start rewetting	1/6th of total time period that that country needed for rewetting

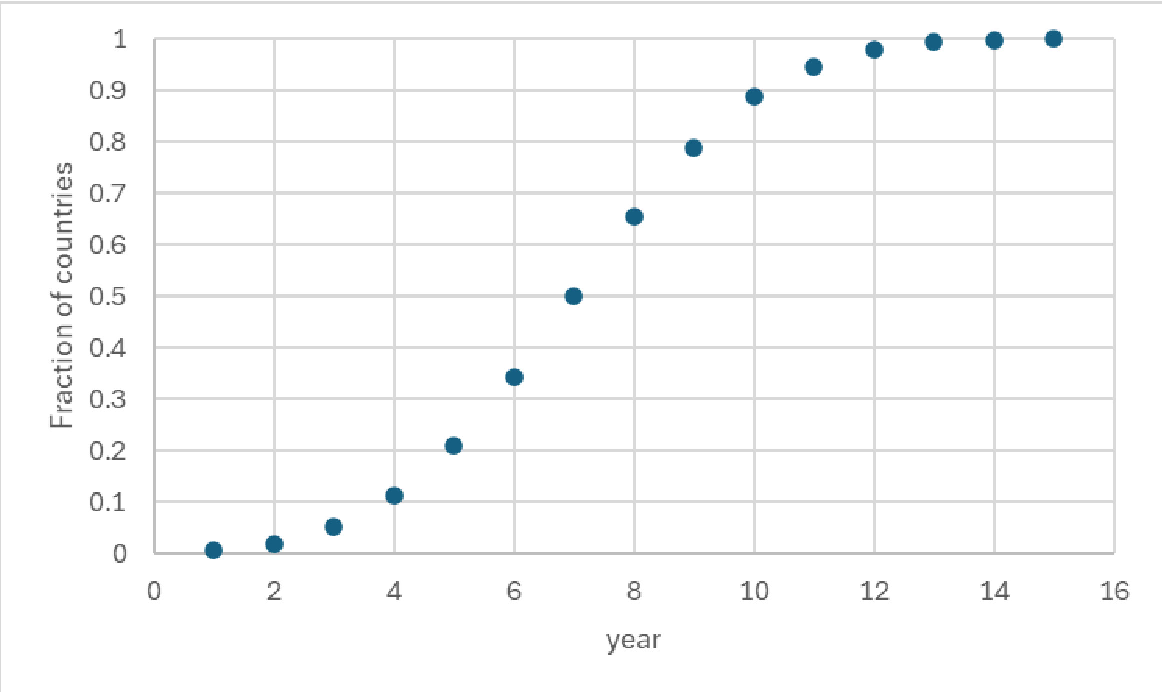

Figure 5: The S-curve used in this thesis for the 15 year period in which individual countries start rewetting. The curve shows the cumulative normal distribution for the fraction of the 174 countries that have started to rewet in a year.

2.7 Climate change scenarios

The impact of different climate scenarios was analysed using the Köppen-Geiger Explorer, which is described in section 2.6.2. In this online tool relative surface areas can be determined for the historical, current and future situations under different Shared Socioeconomic Pathways (SSPs). The Köppen-Geiger Explorer provides seven different SSPs, four of which were used here. The four selected scenarios were, in order of increasing temperature, SSP 1-1.9, SSP 2-4.5, SSP 4-6.0, and SSP 5-8.5. These were expected to cover the broad range of climate change scenarios. The climate zones from these scenarios in "2071-2099" were compared to the current climate zones of "1991-2020". Important note is that the scenarios were run as if these future climate zones were already in place, and did not change over the run time of the model.

The differences between the IPCC climate zones and the climate zones from the Köppen-Geiger Explorer were dealt with in the same way as described in 2.6.2. Also, countries that did not fall into one of the boreal, temperate or tropical climate zones (anymore), were assigned to the nearest climate zone (tropical, temperate, or cold). In case multiple were close, the country's peatland area was divided equally between both climate zones.

2.8 Literature research for emission factors

The literature research for emission factors consisted of two parts: one part aimed at collecting field emission factors, and one part aimed at collecting ditch emission factors. For both literature reviews, literature before 2013 was excluded, because it was assumed that the IPCC had covered all relevant literature in their Wetlands Supplement. All details about the literature review, including a list of all the literature that was included, and the combination of emission factors can be found in Annex 3.

2.8.1 Field emission factors

This literature review was executed on the 7th of March 2024, using Scopus. The following query was entered, aiming to collect as many field emission data as possible whilst filtering out irrelevant literature:

"greenhouse gas" emission AND (methane OR ("nitrous oxide") OR ("carbon dioxide") OR ch4 OR n2o OR co2) AND (drain* OR rewet) AND peat*

This query, using a filter to only show results from 2013 onwards, led to a total of 267 papers. From these papers, a total of 125 were selected based on their title. This excluded papers published in 2013 that were already covered by the IPCC Wetlands Supplement. The 125 papers were analysed for emission data from direct field measurements or experiments using field samples. For the papers containing experiment data, only data from the control samples with natural circumstances were selected. Review papers without own data were excluded to avoid double counting. Also, some of the data appeared in multiple papers, for example when one year later in the experiment the new data was combined with previously published data and published again. In those cases, only the newer paper was used. This resulted in a total of 73 different papers that could provide field emission data on CO_2, CH_4, and/or N_2O.

The emission data were grouped based on the following parameters: 1. Climate zone, which was manually assessed by checking the research location on the Köppen-Geiger Explorer (boreal, temperate, tropical). 2. Land use type (grassland, cropland, forest (including plantations), peat extraction, and rewet. In the case of forest plantations and cropland, the land use was further specified if possible. 3. Mean water table depth (WTD). Following the IPCC standard, a WTD deeper than 0.3m was considered drained or deep-drained, whereas a shallower water table was considered shallow-drained.

Often, papers used multiple land-use categories in their research, so a single paper could provide emission factors for multiple land-use categories or both drainage categories. Also, the number of different locations was noted. This was done so that the emission factors could be combined with those of the IPCC Wetlands Supplement, that used the same methodology. Finally, all the units were converted to g C or g N per kha per year and combined with the IPCC emission factors, that covered literature from 2013 and before. For this, the emission factors were weighted, so if the literature review found for example 2 papers with each 3 locations of a particular climate-land use-drainage combination, then this was weighted as 6. If the IPCC emission factor was retrieved from 4 different locations, that would make total weight 10, the updated emission factor being 4/10th determined by the IPCC emission factor and 6/10th by the literature review. Together, the emission factors from the literature review and the IPCC Wetlands Supplement formed the updated emission factors.

The emission factors from the literature review were compared to the 95% intervals that were provided by the IPCC for each of the 49 emission factors. 25 out of the 49 emission factors from the literature review were outside the corresponding 95% interval, which was one of the reasons that the emission factors were included in the sensitivity analysis (section 2.9.5).

2.8.2 Ditch emission factors

This literature review was executed on the 26th of March 2024, using Scopus. The following query was entered, aiming to collect as many ditch emission data as possible whilst filtering out irrelevant literature:

((TITLE (ditch* OR ("drain* canal")) AND TITLE-ABS-KEY (peat* AND emission)) OR TITLE-ABS-KEY (peat* AND "ditch emission"))

This query, using a filter to only show results from 2013 onwards, led to a total of 19 papers. For these 19 papers, it was assessed whether they actually contained field emission data for CH_4. The other greenhouse gases were not assessed for ditch emissions, and ditch emissions from rewet peatlands were assumed to be zero, following the approach of the IPCC Wetlands Supplement.

From the 19 papers, 11 contained field data on ditch emissions. However, none of the papers contained data from the tropics. In a paper on ditch emissions in tropical climates by Somers et al. (2023), that was excluded because it was a modelling study, two ditch emission factors from other papers published after 2013 were mentioned that did not show up from the Scopus query. The emission data from these two papers was then used for the tropical ditch emission factor.

The ditch emission factors were separated by climate zone, land use category, and drainage depth. The number of sites was used to determine the weights of the emission factors, in a similar way as described for the field emission factors in 2.8.1. Using these weights, the emission factors from the IPCC Wetlands Supplement and the literature review were combined into the updated emission factors.

The emission factors from the literature review were compared to the 95% intervals that were provided by the IPCC for each of the 5 ditch emission factors. 2 out of the 5 emission factors from the literature review were outside the corresponding 95% interval, which was one of the reasons that the ditch emission factors were included in the sensitivity analysis as well (section 2.9.5).

2.9 Sensitivity analysis

The sensitivity analysis consisted of five different sets of runs. For all of these runs, the logistic scenario was used, which took into account individual countries, unless mentioned otherwise. Both the IPCC and updated emission factors were used. The changes made were the following: changing the order of individual countries, changing the standard deviation for the rewetting S-curve of individual countries, changing the standard deviation for the S-curve of the number of countries that start rewetting per year, simulating large fluctuations in the greenhouse gas emissions input for the atmospheric perturbation model, and changing the emission factors derived from the literature review. The methods that were used to do this are briefly described in this section.

2.9.1 The order of individual countries

To find out what the effects were of changes in the order of countries, the Excel random function was used. Each country was assigned a random number between 0 and 1 and the countries were then ordered from low to high accordingly. This was repeated 10 times, so that ten different random orders were created.

2.9.2 The steepness of the S-curve for rewetting per country

During these runs, the standard deviation of the S-curve (see Table 1) of each countries rewetting curve was adjusted, whilst keeping all other factors constant. The standard deviation was changed as a function of the rewetting time (t_i), the time that a country needed for rewetting, since this time differed largely between countries. This was done for five runs, where the standard deviation was changed with a step size of 0.05 between $0.1*t_i$ and $0.3*t_i$.

2.9.3 The steepness of the S-curve for number of countries starting rewetting per year

During these runs, the standard deviation of the S-curve (see Table 1) of the number of countries that start rewetting in a year was changed. This standard deviation was changed as a function of the total time between the first and last country to start rewetting (t_n). This was done for five runs, where the standard deviation was changed with a step size of 0.05 between $0.1*t_n$ and $0.3*t_n$.

2.9.4 Emission fluctuations from fluctuating water levels

All emission factors used in this thesis were derived from literature, mostly from long-term field measurements of greenhouse gases. This means that generally, the fluctuations in greenhouse gas emissions caused by fluctuations in water level, either seasonal or following precipitation, were included in the emission factors. However, it was still relevant to investigate the effect of emission fluctuations, considering that the atmospheric decay of the greenhouse gases was calculated using a non-linear model with exponential functions. This meant that emission fluctuations could still have a divergent effect on the radiative forcing without the average emission factor being changed. The possible effects of water level fluctuations were simulated by increasing or decreasing the emissions with 50% of the original value for every other year, since the model was used with annual timesteps.

2.9.5 Sensitivity of inclusion of new data in emission factors

To control for the dependence of the emission factors from the literature review on outliers, the following steps were taken for both field and ditch emission data. Note that the term emission factor here refers to the emission factors from the literature review only, so before the combining with the IPCC's emission factors.

First, for all emission data from the literature review, the impact of their weight – the number of different locations where a paper had measured data from - was assessed. This was done by checking the change in the emission factor when the weight of a value was changed to 1. If this change in weight either increased or decreased the emission factor that this value contributed to by 50% or more, the weight of that value was set to 1 for this sensitivity analysis. This was done to assess the impact of a single paper that had collected data from many locations, thus outweighing other papers that collected data on fewer locations. A second reason to do this was that papers used different methods to collect emission data, for example by using an eddy covariance tower or flux chamber. By changing the weights of a paper that used many locations and strongly influenced an emission factor, the value of an emission factor was impacted less strongly by the methodology used in that paper.

Second, for all emission data from the literature review, the impact of the value itself was assessed. This was done by checking the change in the emission factor when the value was removed. If this either increased or decreased the emission factor by 50% or more, the value was removed for this sensitivity analysis.

If there was only one value determining the emission factor from the literature review, its weight was set to 1 if this was not yet the case. Also, an exception was made for emission factors determined by only two values, because removing one of the two would too easily lead to changes in the emission factor that were larger than 50%. In that case, both values were kept and their weights both set to 1.

Finally, the literature emission factors from the remaining values and their (changed) weights were combined with the emission factors from the IPCC Wetlands Supplement in the same way as described in section 2.8. For these corrected emission factors, the model was run for all three rewetting curves.

For the corrected emission factors, 20 out of 49 field emission factors were outside the IPCC's 95% interval, compared to 25 out of 49 before correction. 3 out of 5 ditch emission factors were outside the IPCC's 95% interval, compared to 2 out of 5 before correction. This is further discussed in section 4.3.

3. The effect of different rewetting scenarios on radiative forcing

3.1 Changes in radiative forcing with different rewetting curves

When comparing the total radiative forcing after the rewetting period for the three different rewetting curves (see Figure 4), the radiative forcing was highest for the linear rewetting scenario that did not take into account individual countries, in which all drained peatlands globally were rewetted linearly over the same period (Figure 6). The radiative forcing after the rewetting period was more similar for the two scenarios that included individual countries, with radiative forcing being 4.6% and 1.3% higher for the logistic scenario, using IPCC and updated emission factors, respectively. The differences between using the IPCC emission factors versus the updated emission factors are discussed in section 3.3.

In most climate zone / land use type combinations rewetting led to lower greenhouse gas emissions. Consequently, the linear scenario without individual countries, that was slower to rewet in the first half of the rewetting period (see Figure 4), showed the highest radiative forcing of the three scenarios for both the IPCC and the updated emission factors (Figure 6).

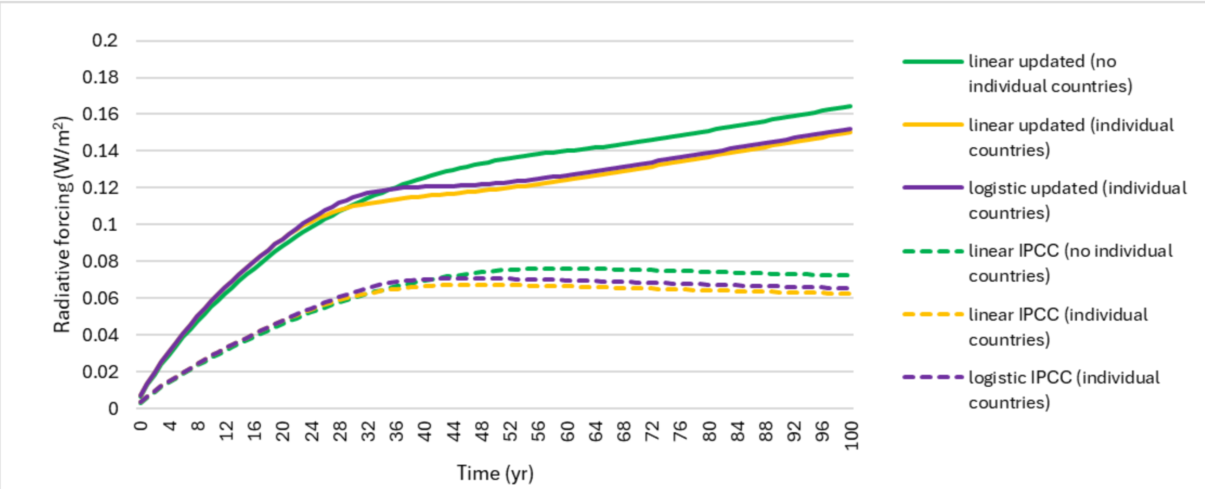

Figure 6: The total radiative forcing for three rewetting curves; linear without individual countries (green) in which all drained peatlands worldwide are rewetted at a constant rate throughout the whole 40-year period; linear with individual countries (yellow) in which countries are ordered by GDP and the countries with highest GDP start rewetting first, and the number of countries starting rewetting per year and the rewetting speed per country are constant; logistic with individual countries (purple) in which countries are also ordered by GDP and the countries with highest GDP start rewetting first, but the number of countries starting rewetting per year and the rewetting speed per country are following a normal distribution. and two sets of emission factors; the IPCC emission factors (dashed lines) and the updated emission factors (solid lines). Rewetting period from year 20 to 60.

3.2 The effect of changing climate zones under different future warming scenarios

Running the scenarios for future changes in climate zones due to climate change, it was found that climate scenarios with stronger global warming led to higher total radiative forcing if rewetting were to be executed during that climate regime. This was the case both when the updated emission factors were used (Figure 7) and when the IPCC emission factors were used (Figure 8). The scenarios for future changes in climate zones and the current scenario were run using the logistic rewetting curve that included individual countries.

The difference in total radiative forcing between the warmest future scenario (SSP5-8.5) and the current scenario was 6.8% for the updated emission factors at the end of the model run, and 4.8% for the IPCC emission factors at the peak value. Furthermore, in the SSP5-8.5 scenario with IPCC emission factors, the peak in radiative forcing was five years later than when the current climate zones were used.

The total radiative forcing for the warmest future scenario (SSP5-8.5) was 5.1% higher than for the coolest future scenario (SSP1-1.9) at the end of the model run when using the updated emission factors. It was 3.8% higher at the peak value when using the IPCC emission factors. Also, in the SSP5-8.5 scenario with IPCC emission factors, the peak in radiative forcing was four years later compared to the SSP1-1.9 scenario.

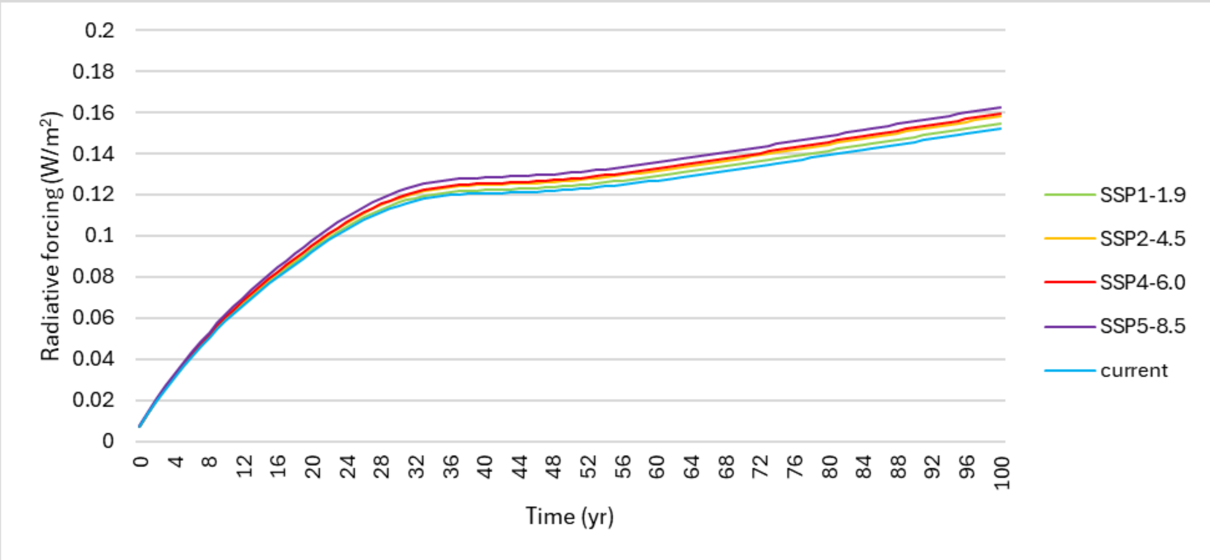

Figure 7: Total radiative forcing for shifting climate zones in 4 different future scenarios compared to the current situation: SSP1-1.9 (green), SSP2-4.5 (yellow), SSP4-6.0 (red), SSP5-8.5 (purple), and the current climate zones (blue). SSP1-1.9 is the coolest future scenario, SSP5-8.5 the warmest. The logistic rewetting curve is used with updated emission factors. Rewetting period from year 20 to 60.

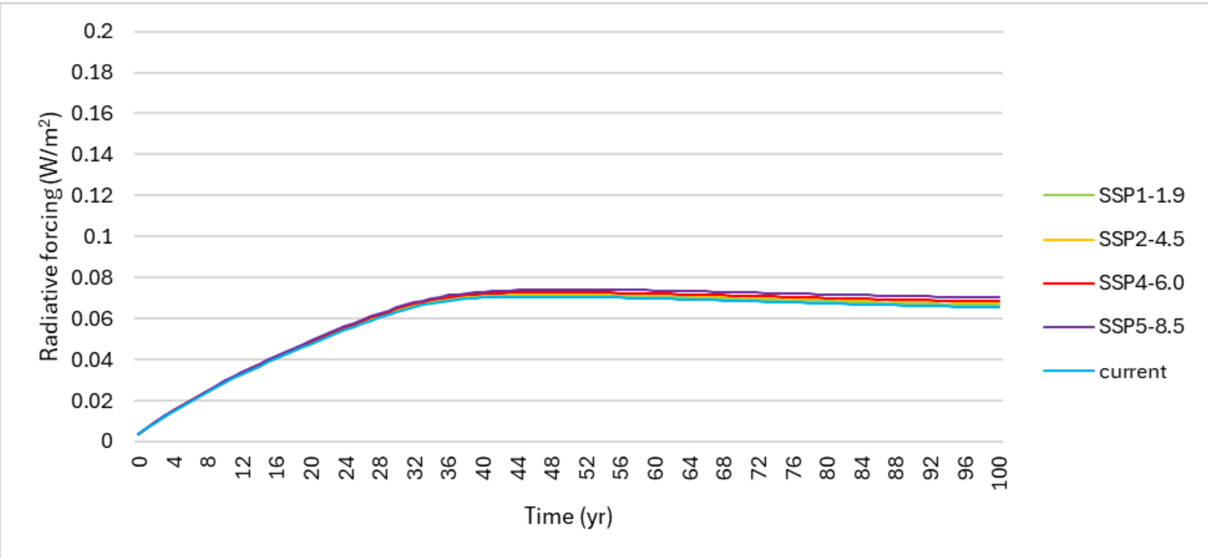

Figure 8: Total radiative forcing for shifting climate zones in 4 different future scenarios compared to the current situation: SSP1-1.9 (green), SSP2-4.5 (yellow), SSP4-6.0 (red), SSP5-8.5 (purple), and the current climate zones (blue). SSP1-1.9 is the coolest future scenario, SSP5-8.5 the warmest. The logistic rewetting curve is used with IPCC emission factors. Rewetting period from year 20 to 60.

3.3 Comparing updated and IPCC emission factors

Compared to the small differences in radiative forcing for different rewetting curves (section 3.1) and different climate scenarios (section 3.2), differences in radiative forcing were large when the two sets of emission factors were compared. The two sets of emission factors are shown in Table 2, showing substantial differences for some emission factors.

Table 2: Two sets of greenhouse gas emission factors for drained and rewetted peatlands, per climate zone and per land use type: the IPCC emission factors from the IPCC Wetlands Supplement (IPCC, 2014) adapted following the land use types from the Global Peatland Database (Greifswald Mire Centre, 2022), and the updated emission factors that combine the IPCC emission factors with results of the literature review from this thesis. Note the different unit for CO_2-C.

		Updated Emission Factors			IPCC Emission Factors		
Climate zone	Land use type	CO2-C (kt/kha/yr)	CH4-C (t/kha/yr)	N2O-N (t/kha/yr)	CO2-C (kt/kha/yr)	CH4-C (t/kha/yr)	N2O-N (t/kha/yr)
Boreal	Forest	0.8	5.2	2.3	0.7	7.4	1.7
Boreal	Cropland	8.0	317.1	13.0	8.0	43.7	13.0
Boreal	Grassland	6.3	323.7	7.3	5.8	44.7	9.5
Boreal	Peat extraction	2.9	55.0	1.5	2.9	24.7	0.3
Boreal	Agriculture	7.2	320.4	10.2	6.9	44.2	11.3
Boreal	Agriculture (shallow-drained)	7.2	20.4	10.2	6.9	20.3	11.3
Temperate	Forest	4.4	3.2	3.1	2.9	5.9	2.8
Temperate	Cropland	9.5	866.9	8.5	8.2	43.7	13.0
Temperate	Grassland	8.8	194.6	4.3	5.3	45.2	4.7
Temperate	Peat extraction	2.6	49.4	0.6	3.1	24.7	0.3
Temperate	Agriculture	9.2	530.7	6.4	6.8	44.5	8.9
Temperate	Agriculture (shallow-drained)	4.1	53.1	1.5	3.9	47.6	1.6
Tropical	Forest	12.7	37.1	44.6	8.9	39.2	2.3
Tropical	Cropland	11.0	82.4	32.0	12.5	89.2	2.7
Tropical	Grassland	10.4	33.2	5.0	10.4	39.0	5.0
Tropical	Peat extraction	2.8	32.6	3.6	2.8	38.4	3.6
Tropical	Agriculture	11.6	53.3	41.2	11.5	56.4	3.3
Tropical	Agriculture (shallow-drained)	9.3	100.3	73.3	6.3	96.2	1.9
Boreal	Rewet	0.0	87.3	11.1	-0.4	89.0	0.0
Temperate	Rewet	1.3	163.7	3.4	0.4	154.0	0.0
Tropical	Rewet	9.6	90.0	33.0	0.5	41.0	0.0

The large differences in results when using IPCC or updated emission factors appeared for the total radiative forcing (Figure 6 and Figure 9), but also for radiative forcing from the individual greenhouse gases (Figure 9). Figure 9 only shows the results from the logistic rewetting scenario, but the patterns considering individual greenhouse gases that were observed for this scenario were similar when the other two (linear) rewetting curves were applied.

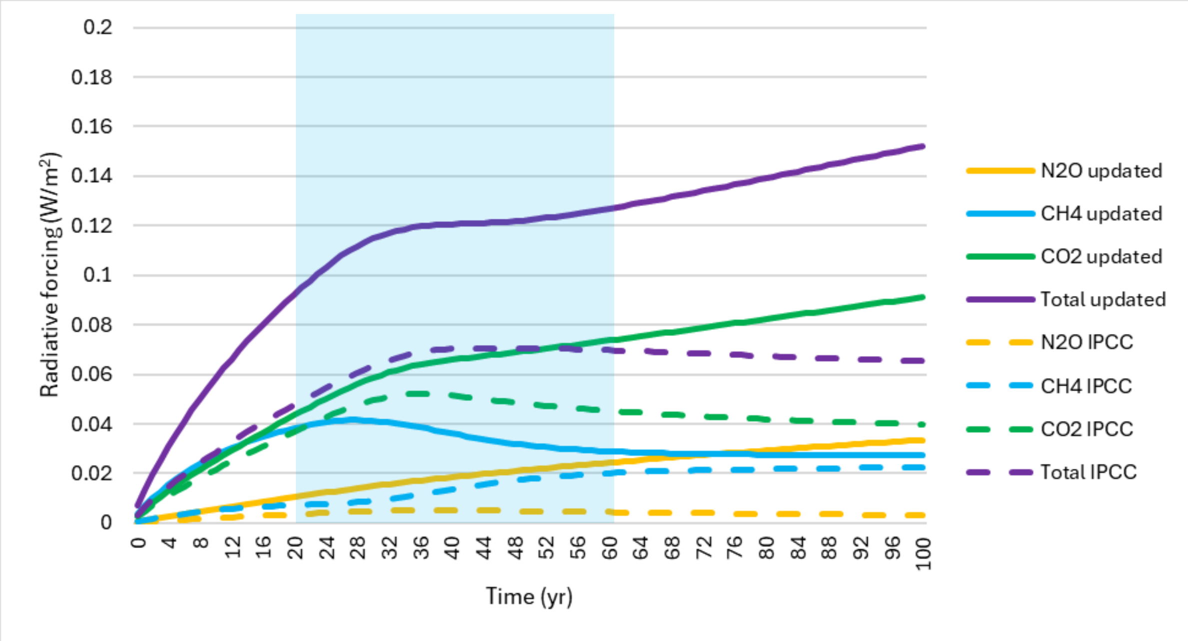

Figure 9: Radiative forcing per greenhouse gas (CO_2 in green, CH_4 in blue, N_2O in yellow) and total (purple) for IPCC emission factors (dashed lines) and updated emission factors (solid lines), using the logistic rewetting curve. Rewetting period from year 20 to 60 in light blue.

3.3.1 Radiative forcing from CO_2

The radiative forcing from CO_2 was higher for the updated emission factors than for the IPCC emission factors throughout the entire 100 year period. However, the divergence between the two sets of emission factors increased during and after the rewetting period. The main difference seemed to be that rewetting led to a decrease in radiative forcing for the IPCC emission factors, whereas using the updated emission factors rewetting led to a slower increase in radiative forcing compared to pre-rewetting.

3.3.2 Radiative forcing from CH_4

The radiative forcing from CH_4 was also higher for the updated emission factors than for the IPCC emission factors throughout the entire 100 year period. However, for this greenhouse gas the rewetting period appeared to lead to contrasting effects for the two sets of emission factors. Before rewetting, radiative forcing from CH_4 increased much faster for the updated emission factors than for the IPCC emission factors. Yet, during the rewetting period, radiative forcing decreased for the updated emission factors, whereas it increased for the IPCC emission factors, leading to a small and stabile difference in radiative forcing after the rewetting period.

3.3.3 Radiative forcing from N_2O

Finally, the radiative forcing from N_2O was also higher for the updated emission factors than for the IPCC emission factors throughout the entire 100 year period. One of the reasons for this is that N_2O emissions after rewetting are assumed to be zero in the IPCC Wetlands Supplement, whereas the literature review found large N_2O emissions after rewetting for all three climate zones. Thus, when the updated emission factors were used, radiative forcing from N_2O increased throughout the entire 100 year period, compared to a slow decrease after rewetting for the IPCC emission factors.

3.3.4 Total radiative forcing

In total, radiative forcing was much higher when the updated emission factors were used than when the IPCC emission factors were used. Moreover, using the updated emission factors showed that total radiative forcing was still increasing at the end of the modelled period, whereas total radiative forcing was decreasing for the scenario using IPCC emission factors. The highest total radiative forcing value using the updated emission factors was 116% higher than the peak value of the scenario using the IPCC emission factors. The difference in total radiative forcing between the two sets of emission factors was mostly caused by CO_2, and to a lesser extent by N_2O.

3.4 Sensitivity analysis

3.4.1 The order of individual countries

When with the logistic rewetting scenario the order of countries was changed at random instead of basing the order on GDP, the biggest difference in peak total radiative forcing value was 8.0% between the ten runs when using the IPCC emission factors (Figure 11). Using the updated emission factors led to the biggest difference of 0.9% in the total radiative forcing value at the end of the run (Figure 10). Furthermore, the biggest difference in the timing of the peak year was five years when using the IPCC emission factors. Compared to the radiative forcing when using the GDP-based country order, the radiative forcing from the random orders was between 1.2% and 2.1% higher for the updated emission factors and between 2.3% and 10.5% higher for the IPCC emission factors, both at the end of the 100 year model period.

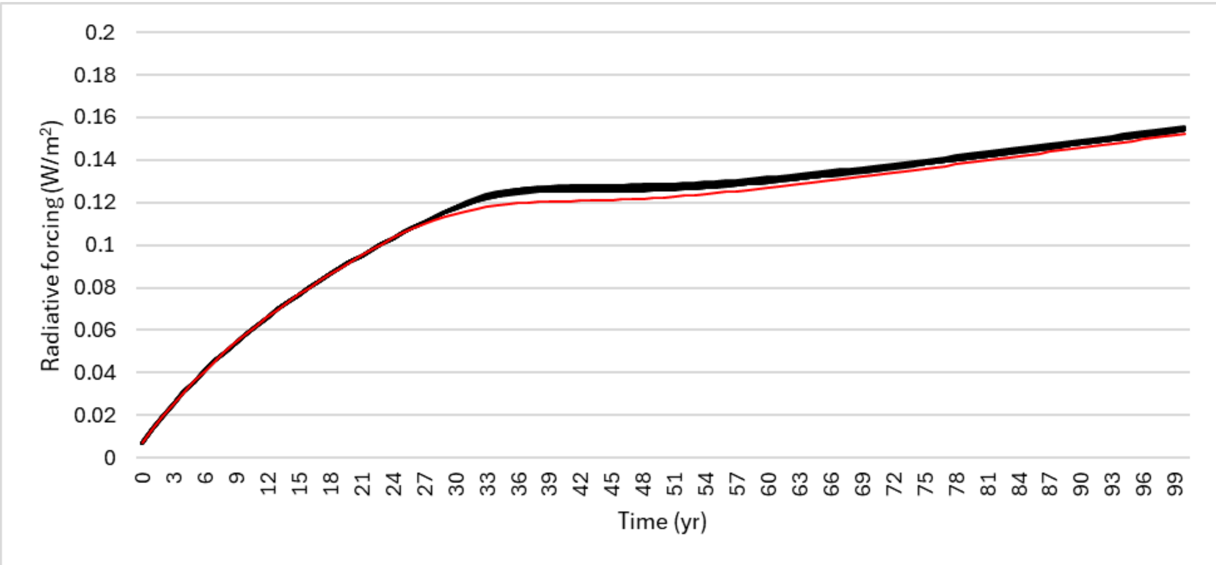

Figure 10: Total radiative forcing for ten random country orders (black) and for the order based on GDP (red), using the logistic rewetting curve and updated emission factors. Rewetting period from year 20 to 60.

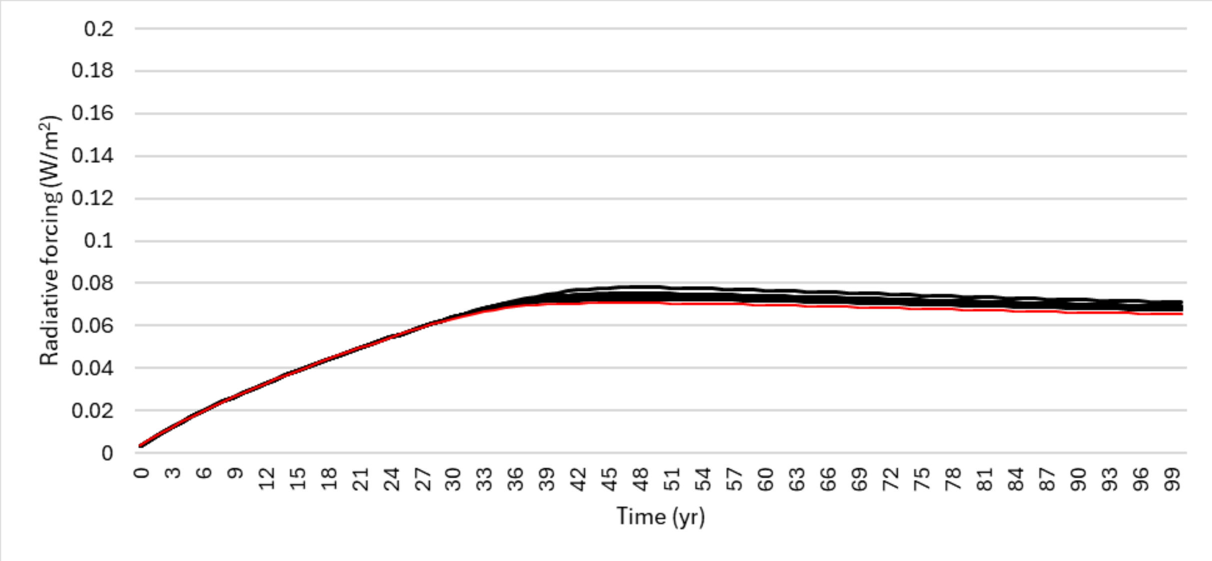

Figure 11: Total radiative forcing for ten random country orders (black) and for the order based on GDP (red), using the logistic rewetting curve and IPCC emission factors. Rewetting period from year 20 to 60.

3.4.2 The steepness of the S-curve for rewetting per country

When the steepness of the S-curve for rewetting per country was adjusted by changing the standard deviation (SD) of the normal distribution, the differences in total radiative forcing for the different SD values were very small, with slightly lower radiative forcing with larger standard deviations. The highest value at the end of the model run was 0.26% higher than the lowest value for the updated emission factors, and the highest peak value was 1.1% higher than the lowest peak value for the IPCC emission factors, with a largest difference in peak year of only one year.

3.4.3 The steepness of the S-curve for number of countries starting rewetting per year

When the steepness of the S-curve of the number of countries that start rewetting in a year was changed by changing the standard deviation (SD) of the normal distribution, the differences in resulting total radiative forcing for the tested standard deviations were small, with slightly lower radiative forcing with larger standard deviations. This was similar to the pattern that was found for changing the standard deviation of the S-curve of rewetting per country. The highest value at the end of the model run was 1.2% higher than the lowest value for the updated emission factors (Figure 12), and the highest peak value was 4.3% higher than the lowest peak value for the IPCC emission factors, with again the largest difference in peak year being one year (Figure 13).

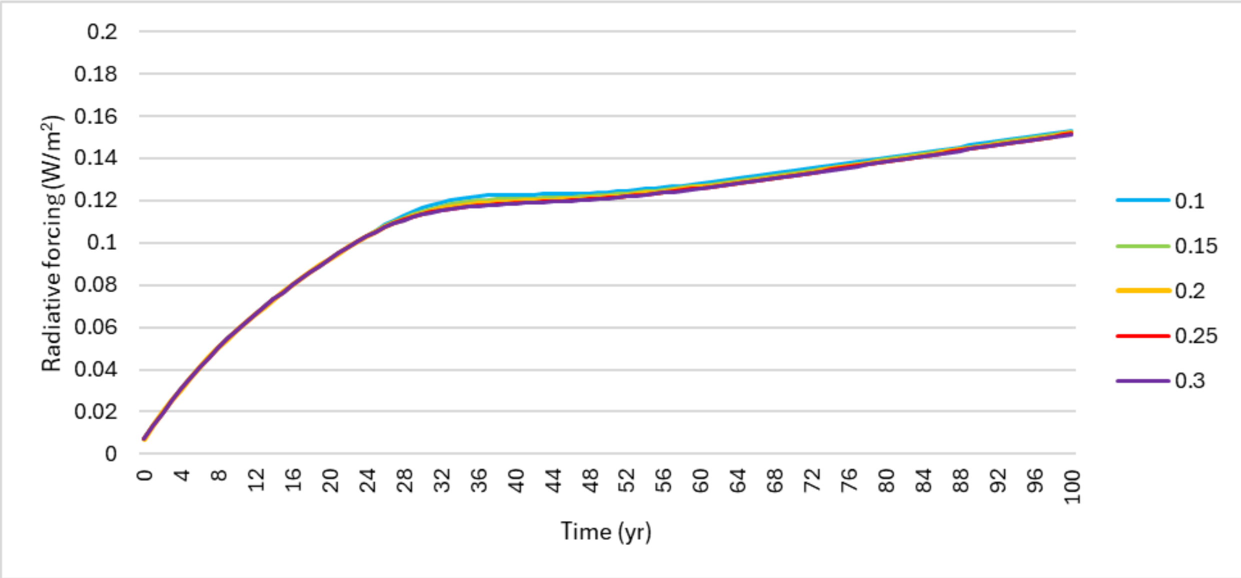

*Figure 12: Total radiative forcing for different standard deviations of the normal distribution used for the S-curve that determines the amount of countries starting rewetting per year, changing the steepness of the S-curve. The standard deviations are based on the total time period in which countries could start rewetting of 25 years: 0.1*25 years (light blue), 0.15*25 years (green), 0.2*25 years (orange), 0.25*25 years (red), and 0.3*25 years (purple). Using the logistic rewetting curve with updated emission factors. Rewetting period from year 20 to 60.*

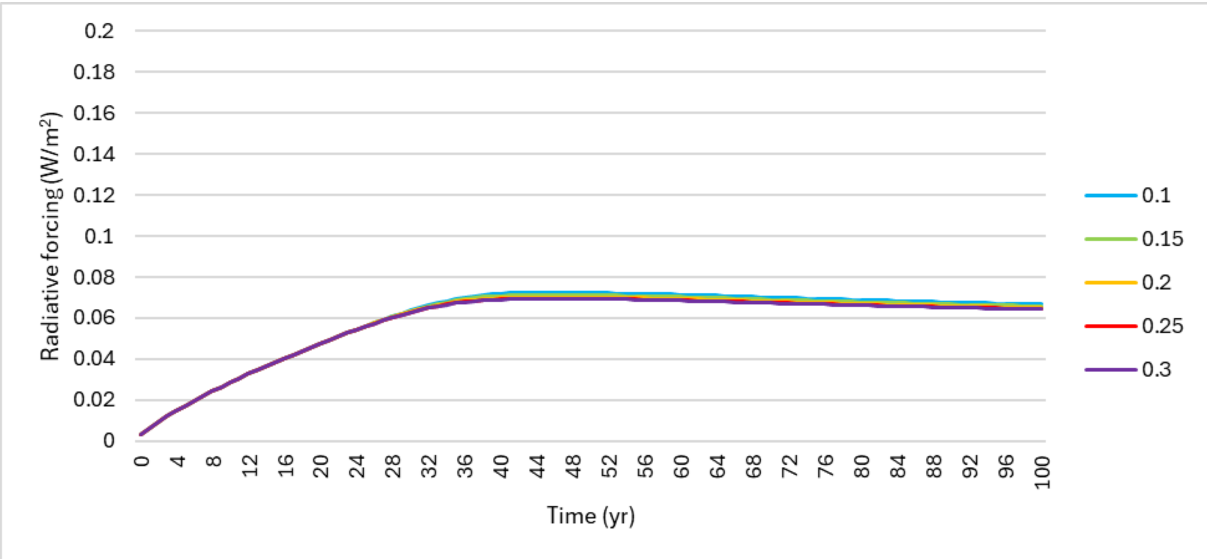

*Figure 13: Total radiative forcing for different standard deviations of the normal distribution used for the S-curve that determines the amount of countries starting rewetting per year, changing the steepness of the S-curve. The standard deviations are based on the total time period in which countries could start rewetting of 25 years: 0.1*25 years (light blue), 0.15*25 years (green), 0.2*25 years (orange), 0.25*25 years (red), and 0.3*25 years (purple). Using the logistic rewetting curve with IPCC emission factors. Rewetting period from year 20 to 60.*

3.4.4 Emission fluctuations from fluctuating water levels

When water level fluctuations were simulated for the logistic rewetting scenario, by increasing or decreasing the greenhouse gas emissions with 50% of the original value for every other year, the differences in total radiative forcing between running the model with and without fluctuations were negligible for both sets of emission factors (Figure 14).

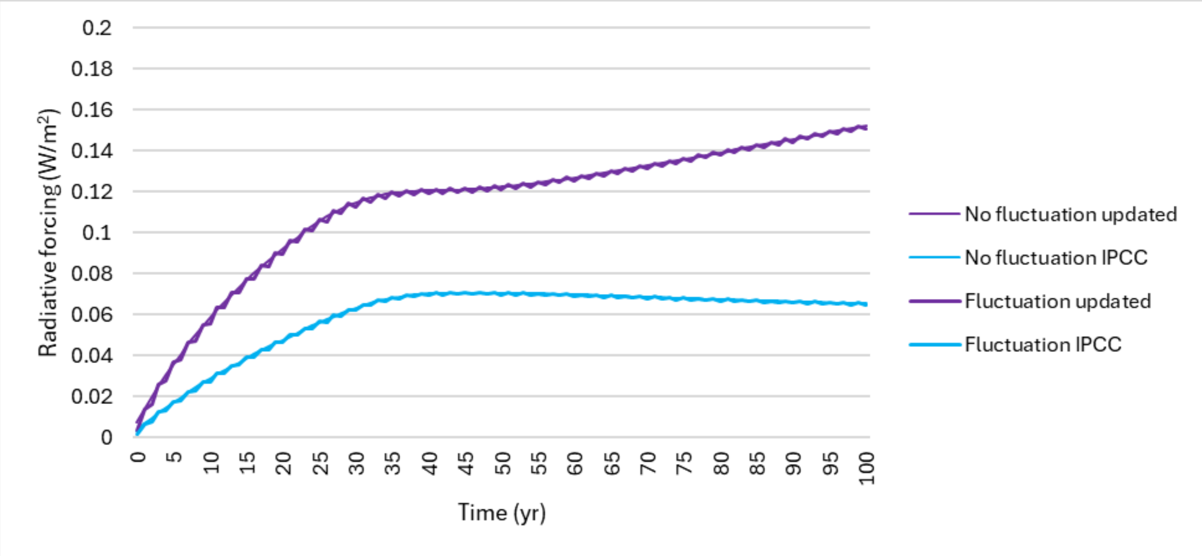

Figure 14: Total radiative forcing with and without emission fluctuations for both sets of emission factors, using the logistic rewetting curve. Rewetting period from year 20 to 60.

3.4.5 Sensitivity of inclusion of new data in emission factors

Running the model with the corrected updated emission factors for the logistic scenario that included individual countries resulted in some noteworthy changes (Figure 15).

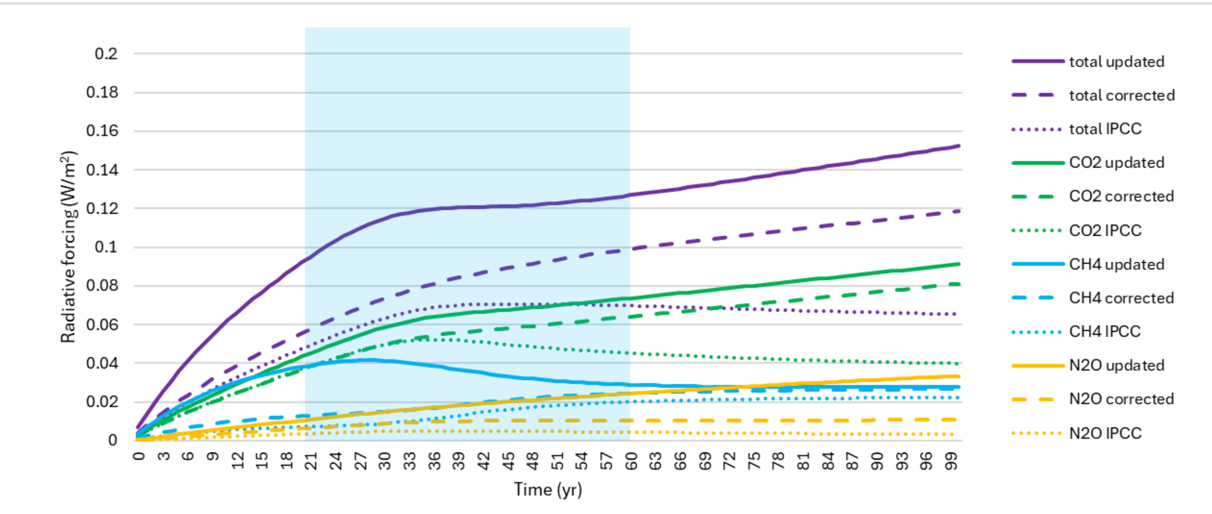

Figure 15: Radiative forcing per greenhouse gas (CO_2 in green, CH_4 in blue, N_2O in yellow) and total (purple) for IPCC emission factors (dotted lines), updated emission factors (solid lines), and corrected updated emission factors (dashed lines), using the logistic rewetting curve. Rewetting period from year 20 to 60 in light blue.

Considering CO_2, using the corrected updated emission factors led to a lower pre-rewetting radiative forcing than when the updated emission factors were used. The pre-rewetting radiative forcing was comparable to the radiative forcing for when the IPCC emission factors were used. However, during the rewetting period, the radiative forcing from CO_2 changed, and became similar to when the updated emission factors were used, following the same trend but with lower radiative forcing. This meant that for the corrected updated emission factors too, the radiative forcing from CO_2 was still increasing after rewetting until the end of the 100 year period.

Considering CH_4, using the corrected updated emission factors led to a radiative forcing from CH_4 that followed a comparable trend as when the IPCC emission factors were used, but with slightly higher radiative forcing throughout the entire 100 year period. Compared to the updated emission factors, the corrected updated emission factors led to a much lower pre-rewetting radiative forcing. Consequently, when using the corrected updated emission factors rewetting caused an increase in radiative forcing from CH_4 instead of the decrease that was the case when the updated emission factors were used. At the end of the 100 year period, radiative forcing from CH_4 stabilised at almost the same level as when the updated emission factors were used.

Considering N_2O, using the corrected updated emission factors led to a radiative forcing that was lower than when the updated emission factors were used, but higher than when the IPCC emission factors were used. After the rewetting period, the N_2O radiative forcing stabilised, which increased the difference compared to when the updated emission factors were used.

The total radiative forcing using the corrected updated emission factors was lower than when the updated emission factors were used, but higher than when the IPCC emission factors were used. Before the rewetting period, total radiative forcing from the corrected updated emission factors was closer to radiative forcing from when the IPCC emission factors were used than when the updated emission factors were used, which was mostly due to the large difference in radiative forcing from CH_4 between the corrected updated and the updated emission factors. During and after the rewetting period, the total radiative forcing from the corrected updated emission factors diverged from when the IPCC emission factors were used, and maintained a steady increase until the end of the 100 year period. This was mostly due to the radiative forcing from CO_2, which kept increasing after the rewetting period, contrasting to when the IPCC emission factors were used.

At the end of the 100 year period, the total radiative forcing when using the corrected updated emission factors was 81% higher than when the IPCC emission factors were used, and 29% lower than when the updated emission factors were used.

4. Discussion

4.1 The atmospheric perturbation model

Multiple models were considered during the selection of an appropriate model for this thesis, such as PEATLAND-VU (Mi et al., 2014), IMAGE (Doelman et al., 2023), JULES (Clark et al., 2011), WAD2M (Zhang et al., 2021), and the atmospheric perturbation model by Günther et al. (2020). The choice for the atmospheric perturbation model was made because the other models were deemed too complex for this MSc thesis. The atmospheric perturbation model created by Günther et al. (2020) was able to perform the necessary tasks whilst still being comprehensible and requiring less computing power than the other models.

The atmospheric perturbation model is aimed at modelling changes in radiative forcing over time from greenhouse gas emissions, more specifically considering emissions as continuous fluxes instead of single pulses (Dommain et al., 2018; Günther et al., 2020; Neubauer & Megonigal, 2015). As described by Dommain et al. (2018), this approach has been used by multiple scholars to analyse greenhouse gas emissions from peatlands. During the use of the model, no unexpected outcomes were observed regarding the functionality of the model. The model calculates the radiative forcing of CO_2, CH_4, and N_2O using exponential functions for atmospheric decay. It includes the oxidation of CH_4 into CO_2, but no other interactions that could take place in the atmosphere. The output is the change in radiative forcing caused by said greenhouse gases in W/m^2.

Although it was not possible within the scope of this thesis to compare the results from running the scenarios with multiple models, the accuracy of the results using this model was increased by including an extensive sensitivity analysis covering a broad range of input parameters (see section 3.4 and 4.4).

4.2 Limitations and assumptions in the scenarios

A few assumptions were made when creating the scenarios. Considering the climate zones, emission factors from the IPCC Wetlands Supplement were only available for three climate zones (boreal, tropical, and temperate). Therefore, the peatlands and land use types within a country were assumed to be distributed over these three, following the proportions of these climate zones in a country. Arid and polar zones were not included, even though some countries had drained peatlands despite being labelled as fully in an arid climate zone. This meant that areas of peatland in a polar or arid climate zone were assumed to be in one of the other three climate zones. Since there is hardly any literature on greenhouse gas emissions in polar or arid climates, using the emission factors from other nearby climate zones is expected to provide the most reliable estimate possible considering the lack of data. Furthermore, the areas of drained peatland in polar and arid climates are small, making up around 0.2% of the total drained peatland area (Günther et al., 2020). Considering possible shifts in climate zones, it could however be valuable for further research to analyse greenhouse gas emissions from peatlands that are in a climate zone that is changing or already has changed into an arid climate.

Regarding the rewetting scenarios, a rewetting period of 40 years was chosen after a 20-year period in which the current situation was maintained.

The 40-year global rewetting period was based on the 20-year rewetting period from Günther et al. (2020), yet taking into account the fact that individual countries would start rewetting at different moments, some needing more time to rewet than others depending on a countries' GDP and the area of drained peatland to be rewet. Nonetheless, this 40-year rewetting period remains an estimate, and it might turn out that rewetting, either for individual countries or globally, takes more (or less) time in reality. However, this thesis is aimed at showing general trends from rewetting drained peatlands for different scenarios. Considering that the model used does not include feedback mechanisms, using different rewetting periods is expected to result in generally the same trends but on different timescales.

During the first 20 years of each model run, the total emissions from drained peatlands were assumed to be constant. This is unlikely considering that peatland drainage (and rewetting) are ongoing processes, with an average increase in drained area of around 5000 kha per year between 1990 and 2017 (Günther et al., 2020). Due to the nature of the model, adding an expected increase in peatland drainage would lead to higher radiative forcing, but is not expected to lead to different trends when comparing the scenarios analysed in this thesis. Günther et al. (2020) used the same model to compare a scenario with increased area of drained peatland to a scenario in which this area is kept stable.

Lastly, calculating greenhouse gas emissions using constant emission factors assumes that the emissions are stable after rewetting. However, Kalhori et al. (2024) have shown that it might take a substantial amount of time after rewetting until the emission factors used by the IPCC are reached, and they argue that emission factors should take into account this temporally dynamic nature. If a slow (instead of immediate) transition from the drained to the rewet emission factors were to be applied in this thesis, rewetting drained peatlands globally would lead to higher radiative forcing compared to the scenarios that were used in this thesis, as rewetting slows down or halts the increase in radiative forcing (see Figure 6). This means that the results in this thesis potentially underestimated the radiative forcing from rewetting drained peatlands. However, to provide reliable estimates on the development of greenhouse gas emissions over time after rewetting, more research is needed with regard to different land use types, water levels and climate zones, before such thing could be implemented in global estimates. Therefore, temporally dynamic emission factors after rewetting were not included in these thesis, but could be integrated in the future when there is more scientific clarity on this topic.

4.3 Emission factors and literature research

The differences between the IPCC and updated emission factors and consequently the difference in radiative forcing is the most unexpected outcome of this thesis, with many emission factors being outside the corresponding IPCC's 95% intervals (see section 2.9.5).

As described in section 2.9.5, outliers were removed and weightings were adjusted to check whether there were particular values or weights having a large impact on emission factors. This was done for both field and ditch emission data. However, after doing this, still 20 out of 49 of the field emission factors were outside the 95% interval from the IPCC Wetlands Supplement. Some emission factors even moved from the outside on one side of the interval to the other after the removal of outliers and changing of weights. The reasons for the large differences in measured greenhouse gas emissions are unknown, and a more in-depth analysis of the literature was not possible within the timeframe of this thesis. Part of the differences might be related to methodological choices, such as the use of different measuring equipment (flux chambers versus eddy covariance towers) and different temporal and spatial scales of the measurements. However, the large number of measured emissions that are outside the IPCC 95% interval might also suggest that the increased amount of literature on the subject is revealing a wider range of possible emissions and uptakes than previously measured.

Something unexpected that came up before removing the outliers, is that the CH_4 emissions decreased over time after rewetting on a global scale (Figure 9). This is not in line with most of the rewetting literature, and was caused by a few high emission values from both drained field and ditch literature, especially from temperate cropland and from boreal cropland and grassland. Removing the outliers resulted in lower drained CH_4 emissions, so that rewetting lead to an increase in emissions, as would be expected from most literature (Evans et al., 2021; Koskinen et al., 2016).

Considering the IPCC emission factors, an interesting point is that the IPCC Wetlands Supplement assumes N_2O emissions to be zero after rewetting, stating that "raising the water table will cause N_2O emissions to decrease rapidly, and fall practically to zero if the depth of the water table is less than 20cm below the surface". (Blain, 2014, p. 3.19). The literature review is not in line with this statement, showing 24 values ranging from -25 to 260 tonnes N /kha/yr, with an unweighted average of 13 tonnes N /kha/yr. This average value is higher than all of the IPCC emission factors of N_2O for drained peatlands. After removing the outliers however, the average value is negative, indicating an N_2O uptake. On a global scale, emissions of N_2O were still modelled to be positive after rewetting, caused by the emission factors of the boreal and temperate climate zones.

Another element of conflict is the CO_2 emissions after rewetting a tropical peatland. Here, too, emissions are assumed to be zero, with the following remark: "For tropical rewetted organic soils where decayed organic material is not oxidised due to saturated conditions." (Blain, 2014, p. 3.12) Results from the literature review would suggest that providing a CO_2 emission factor for rewet tropical peatlands could be valuable, with emissions ranging from 0.3 to 14.3 kt C /kha/yr, with an average of 9.1 kt C /kha/yr. This value was not changed by removing the outliers, indicating that emissions from rewet tropical areas might be considerable, especially because after removing outliers, the emission factor for tropical CO_2 emissions after rewetting is 6.2 and 5.9 times higher than the emission factor for boreal and temperate climate zones, respectively.

The major limitation for updating the emission factors was that the procedure that was followed by the IPCC to derive the emission factors from scientific literature is unknown. It is unknown how the literature was selected, what criteria were used for including or excluding papers, and how for example laboratory experiments, mesocosms and modelling studies were handled. Furthermore, the exact definitions of the different land-use categories from both the IPCC and the Global Peatland Database were unknown.

To keep the validity of this thesis as high as possible whilst acknowledging this limitation, the criteria used for the literature review in this these were quite strict, only including direct field measurements and measurements using control field samples in mesocosm studies. This meant that modelling studies and laboratory experiments manipulating the water level or other parameters were not included. The reasons for exclusion or selective inclusion of data are provided in Annex 3.

Despite the considerable limitation of not knowing the exact criteria for including literature, there was such an amount of individual values and emission factors outside the IPCC's 95% intervals that this suggests that the IPCC 95% intervals are too narrow and should be widened to cover the broad range of measured greenhouse gas emissions.

4.4 Uncertainties covered by sensitivity analysis

This thesis used GDP as a measure to predict which countries are likely to start rewetting drained peatlands first. This is, of course, a large simplification, that ignores cultural, political and social aspects of rewetting drained peatlands. Therefore, the sensitivity analysis included a trial in which ten different random country orders were used. As shown in the section 3.4.1, the differences in radiative forcing between the country orders (0.9% to 8%) were much smaller than the differences between the use of updated or IPCC emission factors (116%). The duration of rewetting of an individual country was still determined by GDP per drained area. Changes in this value are expected to only lead to slightly different outcomes whilst showing the same trends.

The effects of changing the standard deviation of the normal distribution for both S-curves were included in the sensitivity analysis, which showed (section 3.4) that changes in the individual country's S-curve led to very small differences in radiative forcing (0.26% to 1.1%). Changes in the S-curve for the number of countries starting rewetting slightly larger differences (1.2% to 4.3%), with lower standard deviations leading to slightly higher peak values for both S-curves. However, the differences were again much smaller than the differences between the use of updated or IPCC emission factors (116%). That changes in the steepness of the S-curve for rewetting an individual country led to only small changes in radiative forcing can be explained: changes in the steepness of this S-curve only created differences within the rewetting period of each of the 174 countries; in other words, each country started its rewetting period with 100% drained peatlands and ended with 100% rewet peatlands, regardless of the steepness of the curve, whilst the duration or the place of the rewetting period of a country within the total 40 year period did not change. Thus, only small differences in radiative forcing resulted from changes in the steepness of this S-curve.

To conclude, the factors of uncertainty analysed in the sensitivity analysis had a much smaller effect on the radiative forcing than the choice of which emission factors were used.

4.5 Policy implications

Despite the fact that this thesis presents a less hopeful view following the rewetting of drained peatlands, it is important to stress that rewetting still leads to a considerable decrease in greenhouse gas emissions compared to a scenario where the drained state is maintained or expanded (see Supplementary Figure 1 (Annex 1) and Günther et al. (2020)). Considering that degraded peatlands are estimated to account for 5% of the current anthropogenic greenhouse gas emissions, rewetting remains a mitigation measure not to be overlooked (Strack et al., 2022). Furthermore, alternative policy measures could enhance the reduction of GHG emissions. Rewetting in combination with a *Sphagnum* cover can lead to lower CH_4 emissions, further increasing the benefits of rewetting (Kip et al., 2010; Raghoebarsing et al., 2005).

For countries using the *Tier 1* emission factors from the IPCC Wetlands Supplement – which are the general emission factors used in this research – it would be very helpful if an updated version of these emission factors was created that included more recent research on the subject, including N_2O emissions after rewetting and CO_2 emissions from tropical climates after rewetting. The *Tier 1* emission factors are to be used when no country-specific data is available. However, if there is one thing that has become clear from the literature review in this thesis, it is that emissions and uptake of greenhouse gases in peatlands can vary enormously, both temporally and spatially. Consequently, local circumstances can differ from the IPCC emission factors, but also from national emission factors, as emissions are influenced by precipitation, temperature, water table depth and vegetation (see for example Sturtevant et al. (2016) and Lai (2009)). Countries containing drained peatlands should therefore continuously research their peatland emissions and the factors influencing them, whilst increasing their effort to reduce greenhouse gas emissions in other fields as a precautionary measure against the uncertainties of peatland emissions.

5. Conclusions

This study uses an atmospheric perturbation model and a literature study to answer the following research question: how is the radiative forcing following greenhouse gas emissions from drained peatlands expected to respond to rewetting on a global scale for different rewetting scenarios? This is researched using three different rewetting curves (SQ1), two sets of emission factors (SQ3), and looking at the effects of shifting climate zones for future climate scenarios (SQ2).

Based on Gray (1973), the temporal distribution of the adoption of peatland rewetting policy can be modelled using an S-curve, or logistic curve. This S-curve is, amongst other factors, influenced by GDP.

Rewetting considering individual countries leads to lower radiative forcing over a 100 year period, mostly due to a faster decrease of CO_2 emissions. The reason for this is that individual countries were ordered by GDP, which led to countries with large drained areas starting to rewet earlier in the rewetting period. Also, rewetting following an S-curve leads to similar, but 1.3% to 5.2% higher radiative forcing compared to a linear curve over a 100 year period, when the updated and IPCC emission factors are used, respectively.

Climate change is likely to influence more factors than just climate zone distribution. Nevertheless, using multiple climate warming scenarios and the according climate zones leads to a 6.8% and 4.8% higher radiative forcing for the updated emission factors and IPCC emission factors, respectively.

Most importantly, this study shows large differences between the IPCC emission factors from 2013, and the emission factors if combined with literature between 2013 and 2024. Even after removing single values and weights that strongly affected emission factors from the literature review, using the updated emission factors results in a 81% larger radiative forcing on a 100-year timescale compared to when the IPCC emission factors were used. This is mostly due to larger CO_2 emissions after rewetting, leading to a slowed increase in radiative forcing compared to before rewetting, whereas rewetting led to a decrease in radiative forcing when using the IPCC emission factors. Changing the order in which countries start rewetting, changing the steepness of the two S-curves used for the scenarios, and including strong emission fluctuations to simulate water level fluctuations only leads to small differences in radiative forcing. Larger standard deviations for the S-curves lead to slightly lower radiative forcing.

Recommendations for further research include creating a model that combines future peatland emissions with other effects of climate change, such as expected changes in vegetation composition. This will help to gain insight into the combined effects of climate change on peatland greenhouse gas balances. Furthermore, future research could include temporally dynamic instead of static emission factors, provided that more data is then available on this topic.

This research shows that the choice of emission factors is very important for the resulting radiative forcing after rewetting drained peatlands. Because the exact methodologies behind the IPCC emission factors are unknown, and because the amount of literature on the topic has increased considerably since 2013, it is strongly recommended that the emission factors from the IPCC are updated with the latest research, including N_2O emissions after rewetting.

In general, increasing the amount of research on the greenhouse gas balance from drained and rewetted peatlands will help to shed light on the large differences between land use types, climate zones and water table depths, and improve the reliability of the emission factors for countries that use them in their national greenhouse gas budgets.

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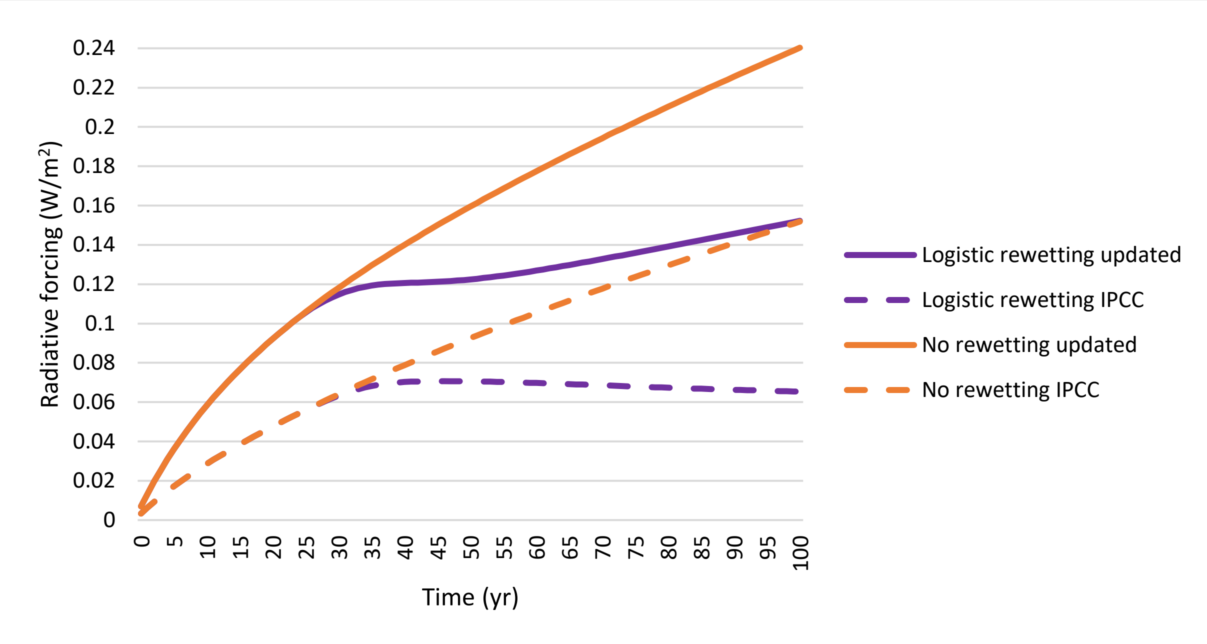
Annexes

Annex 1: Supplementary figure 1



Supplementary figure 1: Total radiative forcing for the IPCC emission factors (dashed line) and updated emission factors (solid line) for the logistic rewetting scenario (purple) and a scenario without rewetting (orange) in which the total drained peatland area is assumed to be constant. Note that the Y-axis is longer than in the other figures in the report.

Annex 2: Output from Atmospheric Perturbation Model

This dataset is shared as a separate Microsoft Excel document.

Annex 3: Dataset from the literature review on emission factors

This dataset is shared as a separate Microsoft Excel document.

Annex 4: Code of the Atmospheric Perturbation Model

This code is shared as a separate R-file.

Annex 5: Excel scenario builder

This dataset/tool is shared as a separate Microsoft Excel document.

Annex 6: Raw data from Global Peatland Database (updated November 2022)

This dataset is shared as a separate Microsoft Excel document.

Annex 7: The use of artificial intelligence

In this thesis, the artificial intelligence tool ChatGPT was almost exclusively used to solve problems with RStudio and Microsoft Excel, such as occurring errors and questions about formulas. ChatGPT was not used to generate written text for the report. ChatGPT is not expected to have influenced the outcomes of this thesis. The links to the 'conversations' are the following:

https://chatgpt.com/share/19b0162e-2191-47ba-bac0-b21b78a707df

https://chatgpt.com/share/cd90a6d2-201f-4f01-8dcb-4f6afecd4df3

https://chatgpt.com/share/aeb0ed10-d499-48b6-91ff-c79847abec77

https://chatgpt.com/share/515f9c50-56c8-47c4-9830-8784d81d5a44

The lists of prompts are as follows:

1st list of prompts in ChatGPT

- export Rstudio data into excel
- add legend in ggplot
- I have four different lines in a plot with four different colours. I have used scale_color_manual to create a legend, but no legend is shown. I do not get any errors. What is going wrong?
- solve a^40=1
- How can I change this line plot into a stacked line plot?
- What does %>% mean in the example above?
- Can you provide an exmaple of the pivot_longer function?
- I get this error message: Error in `pivot_longer()`: ! Arguments in `...` must be used. ✖ Problematic arguments: • ..1 = ch4totrf • ..2 = co2rf ℹ Did you misspell an argument name? Run `rlang::last_trace()` to see where the error occurred.
- How can I select columns in a similar way that are not sequential? Like cols = 3:5
- How can I assign colours to a stacked graph?
- How can I adjust the names in the legend in this example?
- What does theme_minimal() do?

2nd list of prompts in ChatGPT

- In RStudio, I have made a stacked line chart. Now, I want to change the order of the stacked layers. How can I do that?
- Can you give an example where you change the order in aes manually?
- Error in aes(x = i, y = radiativeforcing, fill = GHG) + geom_area(position = "stack") + : non-numeric argument to binary operator
- output_long <- output %>% #this converts output to a long format pivot_longer(cols = c(n2orf,ch4totrf,co2rf), names_to = "GHG", values_to = "radiativeforcing") #the

following creates a stacked graph ggplot(output_long, aes(x=i, y=radiativeforcing, fill=GHG, order=GHG))+ geom_area(position="stack")+ labs(title = "RF of GHG linear rewetting 2020to2040", x = "time (years)", y = "radiative forcing (W/m2)")+ scale_fill_manual(name = "GHG emissions", values = c("cornflowerblue","blue2","blue4"), breaks = c("ch4totrf", "co2rf", "n2orf"), labels = c("CH4", "CO2", "N2O"))+ ylim(0, 0.1)+ theme_minimal(base_size = 14)

- Then how can I change the order?
- I am working in Excel. I want to use a formula that is different for every nth value in a series that has no logical order. How can I do this?
- I actually meant that the series is as following: 10 19 29 38 48 58 67 77 86 96 106 115 125 134 144 154 163 173 182 192 So the formula should change for these values
- Can I use a cell reference in excel to get a number of cells displaying a particular value? For example if I have the number 3, that means I want 3 consecutive cells filled with that number.
- This is not exactly what I meant. I want an empty row to display the number (in this case 3) 3 times, This number itself is positioned in a different cell. If I change the number to a number n, I want to have that number displayed n times in the empty row.
- Thanks, this is what I meant. Now, I want to have the first 3 cells display 3, the next 3 display 6, the next 3 display 9 etc.
- What is wrong in this excel formula in the Dutch version of Excel:
- =ALS(C$3>$A4;0;ALS((C$3+(ALS(parameters!$B$6="YES";country_data!B$10;parameters!$B$2))>$A4;'rew country with formulas'!C$2*($A4-C$3+1)/(ALS(parameters!$B$6="YES";country_data!B$10;parameters!$B$2);C$2)))
- ggplot()+ geom_line(data = output, mapping = aes(x=i, y=totalforcing, color="Total"))+ geom_line(data = output, mapping = aes(x=i, y=co2rf, color="CO2"))+ geom_line(data = output, mapping = aes(x=i, y=ch4totrf, color="CH4"))+ geom_line(data = output, mapping = aes(x=i, y=n2orf, color="N2O"))+ ylim(0, 0.08)+ labs(title = "RF of GHG linear rewetting", x = "time (years)", y = "radiative forcing (W/m2)")+ scale_color_manual(name = "GHG emissions", breaks = c("Total", "CH4", "CO2", "N2O"), values = c("Total" = "blue", "CH4" = "cadetblue1", "CO2" = "aquamarine3", "N2O" = "darkgoldenrod1"))+ How can I change the thickness of the lines in this graph?
- I have a sheet in excel. There are two rows. The first row contains my data. The second row has given all these values a number. Now I want excel to calculate the average of the values that have the same number assigned to their values. The cells are already ordered by the numbers in the second row. How can I do this?
- How could I shorten this formula in excel?
- =ALS(G$12/$B$1<$E$15;$A$15;ALS(G$12/$B$1<$E$16;$A$16;ALS(G$12/$B$1<$E$17;$A$17;ALS(G$12/$B$1<$E$18;$A$18;ALS(G$12/$B$1<$E$19;$A$19;ALS(G$12/$B$1<$E$20;$A$20;ALS(G$12/$B$1<$E$21;$A$21;ALS(G$12/$B$1<$E$22;$A$22;ALS(G$12/$B$1<$E$23;$A$23;ALS(G$12/$B$1<$E$24;$A$24;ALS(G$12/$B$1<$E$25;$A$25;ALS(G$12/$B$1<$E$26;$A$26;ALS(G$12/$B$1<$E$27;$A$27;ALS(G$12/$B$1<$E$28;$A$28;ALS(G$12/$B$1<$E$29;$A$29;ALS(G$12/$B$1<$E$30;$A$30;ALS(G$12/$B$1<$E$31;$A

$31;ALS(G$12/$B$1<$E$32;$A$32;ALS(G$12/$B$1<$E$33;$A$33;ALS(G$12/$B$1<$E$34;$A$34;ALS(G$12/$B$1<$E$35;$A$35;ALS(G$12/$B$1<$E$36;$A$36;ALS(G$12/$B$1<$E$37;$A$37;ALS(G$12/$B$1<$E$38;$A$38;ALS(G$12/$B$1<$E$39;$A$39;ALS(G$12/$B$1<$E$40;$A$40;ALS(G$12/$B$1<$E$41;$A$41;ALS(G$12/$B$1<$E$42;$A$42;ALS(G$12/$B$1<$E$43;$A$43;ALS(G$12/$B$1<$E$44;$A$44;ALS(G$12/$B$1<$E$45;$A$45;ALS(G$12/$B$1<$E$46;$A$46;ALS(G$12/$B$1<$E$47;$A$47;ALS(G$12/$B$1<$E$48;$A$48;ALS(G$12/$B$1<$E$49;$A$49;ALS(G$12/$B$1<$E$50;$A$50;ALS(G$12/$B$1<$E$51;$A$51;ALS(G$12/$B$1<$E$52;$A$52;ALS(G$12/$B$1<$E$53;$A$53;ALS(G$12/$B$1<$E$54;$A$54;ALS(G$12/$B$1<$E$55;$A$55;ALS(G$12/$B$1<$E$56;$A$56;ALS(G$12/$B$1<$E$57;$A$57;ALS(G$12/$B$1<$E$58;$A$58;ALS(G$12/$B$1<$E$59;$A$59;ALS(G$12/$B$1<$E$60;$A$60;ALS(G$12/$B$1<$E$61;$A$61;ALS(G$12/$B$1<$E$62;$A$62;ALS(G$12/$B$1<$E$63;$A$63;ALS(G$12/$B$1<$E$64;$A$64;ALS(G$12/$B$1<$E$65;$A$65;ALS(G$12/$B$1<$E$66;$A$66;$B$2))

- Is there a way to copy cells with formulas to another sheet without getting the VALUE! error?
- =ALS(H$12/$B$1<$C$15;$A$15;ALS(H$12/$B$1<$C$16;$A$16;ALS(H$12/$B$1<$C$17;$A$17;ALS(H$12/$B$1<$C$18;$A$18;ALS(H$12/$B$1<$C$19;$A$19;ALS(H$12/$B$1<$C$20;$A$20;ALS(H$12/$B$1<$C$21;$A$21;ALS(H$12/$B$1<$C$22;$A$22;ALS(H$12/$B$1<$C$23;$A$23;ALS(H$12/$B$1<$C$24;$A$24;ALS(H$12/$B$1<$C$25;$A$25;ALS(H$12/$B$1<$C$26;$A$26;ALS(H$12/$B$1<$C$27;$A$27;ALS(H$12/$B$1<$C$28;$A$28;ALS(H$12/$B$1<$C$29;$A$29;ALS(H$12/$B$1<$C$30;$A$30;ALS(H$12/$B$1<$C$31;$A$31;ALS(H$12/$B$1<$C$32;$A$32;ALS(H$12/$B$1<$C$33;$A$33;ALS(H$12/$B$1<$C$34;$A$34;ALS(H$12/$B$1<$C$35;$A$35;ALS(H$12/$B$1<$C$36;$A$36;ALS(H$12/$B$1<$C$37;$A$37;ALS(H$12/$B$1<$C$38;$A$38;ALS(H$12/$B$1<$C$39;$A$39;ALS(H$12/$B$1<$C$40;$A$40;ALS(H$12/$B$1<$C$41;$A$41;ALS(H$12/$B$1<$C$42;$A$42;ALS(H$12/$B$1<$C$43;$A$43;ALS(H$12/$B$1<$C$44;$A$44;ALS(H$12/$B$1<$C$45;$A$45;ALS(H$12/$B$1<$C$46;$A$46;ALS(H$12/$B$1<$C$47;$A$47;ALS(H$12/$B$1<$C$48;$A$48;ALS(H$12/$B$1<$C$49;$A$49;ALS(H$12/$B$1<$C$50;$A$50;ALS(H$12/$B$1<$C$51;$A$51;ALS(H$12/$B$1<$C$52;$A$52;ALS(H$12/$B$1<$C$53;$A$53;ALS(H$12/$B$1<$C$54;$A$54;ALS(H$12/$B$1<$C$55;$A$55;ALS(H$12/$B$1<$C$56;$A$56;ALS(H$12/$B$1<$C$57;$A$57;ALS(H$12/$B$1<$C$58;$A$58;ALS(H$12/$B$1<$C$59;$A$59;ALS(H$12/$B$1<$C$60;$A$60;ALS(H$12/$B$1<$C$61;$A$61;ALS(H$12/$B$1<$C$62;$A$62;ALS(H$12/$B$1<$C$63;$A$63;ALS(H$12/$B$1<$C$64;$A$64;ALS(H$12/$B$1<$C$65;$A$65;ALS(H$12/$B$1<$C$66;$A$66;$B$2))
- =ALS(H$12/$B$1<$C$15;$A$15;ALS(H$12/$B$1<$C$16;$A$16;ALS(H$12/$B$1<$C$17;$A$17;ALS(H$12/$B$1<$C$18;$A$18;ALS(H$12/$B$1<$C$19;$A$19;ALS(H$12/$B$1<$C$20;$A$20;ALS(H$12/$B$1<$C$21;$A$21;ALS(H$12/$B$1<$C$22;$A$22;ALS(H$12/$B$1<$C$23;$A$23;ALS(H$12/$B$1<$C$24;$A$24;ALS(H$12/$B$1<$C$25;$A$25;ALS(H$12/$B$1<$C$26;$A$26;ALS(H$12/$B$1<$C$27;$A$27;ALS(H$12/$B$1<$C$28;$A$28;ALS(H$12/$B$1<$C$29;$A$29;ALS(H$12/$B$1<$C$30;$A$30;ALS(H$12/$B$1<$C$31;$A$31;ALS(H$12/$B$1<$C$32;$A$32;ALS(H$12/$B$1<$C$33;$A$33;ALS(H$12/$B$1<$C$34;$A$34;ALS(H$12/$B$1<$C$35;$A$35;ALS(H$12/$B$1<$C$36;$A$36;ALS(H$12/$B$1<$C$37;$A$37;ALS(H$12/$B$1<$C$38;$A$38;ALS(H$12/$B$1<$C$39;$A$3

9;ALS(H$12/$B$1<$C$40;$A$40;ALS(H$12/$B$1<$C$41;$A$41;ALS(H$12/$B$1<$C$42;$A$42;ALS(H$12/$B$1<$C$43;$A$43;ALS(H$12/$B$1<$C$44;$A$44;ALS(H$12/$B$1<$C$45;$A$45;ALS(H$12/$B$1<$C$46;$A$46;ALS(H$12/$B$1<$C$47;$A$47;ALS(H$12/$B$1<$C$48;$A$48;ALS(H$12/$B$1<$C$49;$A$49;ALS(H$12/$B$1<$C$50;$A$50;ALS(H$12/$B$1<$C$51;$A$51;ALS(H$12/$B$1<$C$52;$A$52;ALS(H$12/$B$1<$C$53;$A$53;ALS(H$12/$B$1<$C$54;$A$54;ALS(H$12/$B$1<$C$55;$A$55;ALS(H$12/$B$1<$C$56;$A$56;ALS(H$12/$B$1<$C$57;$A$57;ALS(H$12/$B$1<$C$58;$A$58;ALS(H$12/$B$1<$C$59;$A$59;ALS(H$12/$B$1<$C$60;$A$60;ALS(H$12/$B$1<$C$61;$A$61;ALS(H$12/$B$1<$C$62;$A$62;ALS(H$12/$B$1<$C$63;$A$63;ALS(H$12/$B$1<$C$64;$A$64;ALS(H$12/$B$1<$C$65;$A$65;ALS(H$12/$B$1<$C$66;$A$66;$B$2)) Can you update this formula so that all the cells refer to a sheet called "parameters" ? I am using the dutch version of excel.

- Can you do this for all the conditions in the formula so I can copy it?
- Can you copy this sequence and continue it until row 114? Please do it completely, so I can copy it as well. =ALS(B$3/parameters!$B$1 < parameters!$C$15; parameters!$A$15; ALS(B$3/parameters!$B$1 < parameters!$C$16; parameters!$A$16; ALS(B$3/parameters!$B$1 < parameters!$C$17; parameters!$A$17; ALS(B$3/parameters!$B$1 < parameters!$C$18; parameters!$A$18; ALS(B$3/parameters!$B$1 < parameters!$C$19; parameters!$A$19; ALS(B$3/parameters!$B$1 < parameters!$C$20; parameters!$A$20; ALS(B$3/parameters!$B$1 < parameters!$C$21; parameters!$A$21; ALS(B$3/parameters!$B$1 < parameters!$C$22; parameters!$A$22; ALS(B$3/parameters!$B$1 < parameters!$C$23; parameters!$A$23; ALS(B$3/parameters!$B$1 < parameters!$C$24; parameters!$A$24; ALS(B$3/parameters!$B$1 < parameters!$C$25; parameters!$A$25; ALS(B$3/parameters!$B$1 < parameters!$C$26; parameters!$A$26; ALS(B$3/parameters!$B$1 < parameters!$C$27; parameters!$A$27; ALS(B$3/parameters!$B$1 < parameters!$C$28; parameters!$A$28; ALS(B$3/parameters!$B$1 < parameters!$C$29; parameters!$A$29; ALS(B$3/parameters!$B$1 < parameters!$C$30; parameters!$A$30; ALS(B$3/parameters!$B$1 < parameters!$C$31; parameters!$A$31; ALS(B$3/parameters!$B$1 < parameters!$C$32; parameters!$A$32; ALS(B$3/parameters!$B$1 < parameters!$C$33; parameters!$A$33; ALS(B$3/parameters!$B$1 < parameters!$C$34; parameters!$A$34; ALS(B$3/parameters!$B$1 < parameters!$C$35; parameters!$A$35; ALS(B$3/parameters!$B$1 < parameters!$C$36; parameters!$A$36; ALS(B$3/parameters!$B$1 < parameters!$C$37; parameters!$A$37; ALS(B$3/parameters!$B$1 < parameters!$C$38; parameters!$A$38; ALS(B$3/parameters!$B$1 < parameters!$C$39; parameters!$A$39; ALS(B$3/parameters!$B$1 < parameters!$C$40; parameters!$A$40; ALS(B$3/parameters!$B$1 < parameters!$C$41; parameters!$A$41; ALS(B$3/parameters!$B$1 < parameters!$C$42; parameters!$A$42; ALS(B$3/parameters!$B$1 < parameters!$C$43; parameters!$A$43; ALS(B$3/parameters!$B$1 < parameters!$C$44;

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parameters!$A$46; ALS(B$3/parameters!$B$1 < parameters!$C$47;
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parameters!$A$61; ALS(B$3/parameters!$B$1 < parameters!$C$62;
parameters!$A$62; ALS(B$3/parameters!$B$1 < parameters!$C$63;
parameters!$A$63; ALS(B$3/parameters!$B$1 < parameters!$C$64;
parameters!$A$64; ALS(B$3/parameters!$B$1 < parameters!$C$65;
parameters!$A$65; ALS(B$3/parameters!$B$1 < parameters!$C$66;
parameters!$A$66; parameters!$B$2)))

- My plots in Rstudio using ggplot suddenly have a gray layer over them. I can still see the plot but the background is grey and all other elements also appear to be behind a grey transparant layer
- Error in if (ch4inv[i - 1] > 0) { : missing value where TRUE/FALSE needed'
- [reached 'max' / getOption("max.print") -- omitted 2 rows] What does this mean?
- Removed 3 rows containing non-finite values (`stat_align()`).
- The function to find the maximum in Rstudio (max) leads to NA. Why?
- If you get the message that a number of rows is removed because of non-finite values, how can you see which rows are removed?
- Error in is.finite(output) : default method not implemented for type 'list'
- If the outcome is FALSE for a column in my list, does it mean that it contains non-finite values? And how can I see where these values are?
- > non_finite_rows <- which(!is.finite(output$co2rf)) > print(output$co2rf[non_finite_rows]) [1] NA
- Hi!
- I would like excel to create a line chart, but to create it in a separate sheet
- How can I change the number of decimals in the axis of an excel chart?

3rd list of prompts in ChatGPT

- Hi, I am using RStudio and I would like to download my output as an excel or csv file.
- I used writexl. However, my laptop does not recognise the created file as an excel file.
- Can you give an example in R how I can mention a specific place where the excel should be saved?

4th list of prompts in ChatGPT

- I am working in R and made a graph using GGplot. In the legend of the graph there are multiple chemicals, such as CO2 and N2O. I would like the legend to use subscript for the numbers in these chemicals. How can I do that?
- ggplot(output_long, aes(x=i, y=radiativeforcing, fill=GHG))+ geom_area(position="stack")+ labs(#title = "test with emission fluctuation", x = "time (years)", y = "radiative forcing (W/m2)")+ scale_fill_manual(name = "GHG", values = c("darkgoldenrod1","cadetblue1","aquamarine3"), breaks = c("n2orf", "ch4totrf", "co2rf"), labels = c("N2O", "CH4", "CO2"))+ ylim(0, 0.2)+ theme_minimal(base_size = 14)
- It says "expected , after expression"
- It still gives the same error, but now only for the N[2]O
- The parentheses were not necessary, only adding * did the trick
- ggplot()+ geom_line(data = output, mapping = aes(x=i, y=totalforcing, color="Total"), linewidth=1)+ geom_line(data = output, mapping = aes(x=i, y=co2rf, color="CO2"), linewidth=1)+ geom_line(data = output, mapping = aes(x=i, y=ch4totrf, color="CH4"), linewidth=1)+ geom_line(data = output, mapping = aes(x=i, y=n2orf, color="N2O"), linewidth=1)+ ylim(0, 0.2)+ labs(#title = "test with emission fluctuation", x = "time (years)", y = "radiative forcing (W/m2)")+ scale_color_manual(name = "GHG", breaks = c("Total", "CH4", "CO2", "N2O"), values = c("Total" = "blue", "CH4" = "cadetblue1", "CO2" = "aquamarine3", "N2O" = "darkgoldenrod1"))+ theme_minimal(base_size = 14)
- geom_area(position="stack")+ labs(title = "test with emissions fluctuation", x = "time (years)", y = "radiative forcing (W/m2)")+ scale_fill_manual(name = "GHG", values = c("darkgoldenrod1","cadetblue1","cornflowerblue", "aquamarine3"), breaks = c("n2orf", "ch4rf", "ch4oxrf", "co2rf"), labels = c(expression(N[2]*O), expression(CH[4]), expression(CO[2] from CH[4]), expression(CO[2])))+ ylim(0, 0.1)+ theme_minimal(base_size = 14)
- Error in `+.gg`: ! Cannot add <ggproto> objects together ℹ Did you forget to add this object to a <ggplot> object? Run `rlang::last_trace()` to see where the error occurred. >
- The problem with this is that it does not recognize the subscript 4 in "from CH[4]"
- No, it should read CO2 from CH4 with the 2 and 4 as subscript
- How does the # in R work exactly?

- Can you use # in a way that R ignores multiple lines of code?
- In excel I am having trouble with the conditional formatting
- I am using the following condition formula: =EN(country_data!B$52<C5;C5<country_data!B$49)
- This works perfectly for all the columns that have multiple values inbetween country_data!B$49 and country_data!B$52. However, if a column has only one value inbetween these, it does not format despite being inbetween the values mentioned
- I am now working in excel. After following your advice on how to change some labels into subscript, the labels do not match the corresponding lines anymore. CO2 and CH4 are now switched. This is my code: ggplot()+ geom_line(data = output, mapping = aes(x=i, y=totalforcing, color="Total"), linewidth=1)+ geom_line(data = output, mapping = aes(x=i, y=co2rf, color="CO2"), linewidth=1)+ geom_line(data = output, mapping = aes(x=i, y=ch4totrf, color="CH4"), linewidth=1)+ geom_line(data = output, mapping = aes(x=i, y=n2orf, color="N2O"), linewidth=1)+ ylim(0, 0.25)+ labs(#title = "test with emission fluctuation", x = "time (years)", y = "radiative forcing (W/m2)")+ scale_color_manual(name = "GHG", breaks = c("Total", "CH4", "CO2", "N2O"), labels = c("Total", expression(CO[2]), expression(CH[4]), expression(N[2]*O)), values = c("Total" = "blue", "CH4" = "cadetblue1", "CO2" = "aquamarine3", "N2O" = "darkgoldenrod1"))+ theme_minimal(base_size = 14)
- Warning message: In length(vp) : reached elapsed time limit
- Can I use subscript in the legend of an excel graph?
- Can I change the layout for multiple lines in a line graph at once? In excel
- can you give synonyms for "in this way"?
- I am writing my MSc thesis. What is a good way to structure the discussion?
- In excel, is there a way in which to change all formulas in a sheet at once? For example if you want to keep all the formulas the same, but only from a different sheet