Nationaal Onderzoeksprogramma
Broeikasgassen
Veenweiden

Chapter 7 NOBV year report 2022

Climate effect of combined CH_4, N_2O and CO_2 emission change by land use or ecosystem transition.

Climate effect of combined CH_4, N_2O and CO_2 emission change by agricultural system or ecosystem transition – an evaluation of methods.

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Abstract

Changes in agriculture and ecosystems usually result in increase or decrease of the ecosystem greenhouse gas flux. This may include greenhouse gases with different atmospheric lifetimes and radiative properties; besides CO_2, CH_4 and N_2O. Influencing the national greenhouse budgets by land use adaptation is considered for the coastal plain peatlands in The Netherlands and neighboring countries.

However, the common use of the Global Warming Potential (GWP) for evaluating the climate effect of a combination of greenhouse gases by agricultural or ecosystem transition is subject to discussion. The GWP assumes a one-time pulse emission. It does not address the more-or-less stepwise, sustained changes and gradual transitions involved in agriculture or ecosystem change, and uses rather arbitrary time horizons of 20 or 100 years.

Besides the evaluation metric itself a consideration of which elements of the greenhouse gas balance contribute to climate change is necessary. This differs for natural and agricultural ecosystems; for agricultural systems, the life cycle of products may need evaluation.

Several scientifically valid alternatives for GWP (the standard metric for reporting the effect of greenhouse gas emission of land use) have been proposed. In this article, the GWP is compared with other metrics (GWP*, Sustained global warming/cooling potential, radiative forcing. modelling) for evaluation of climate impact of proposed land use transitions. The evaluation is based on five example scenarios that are included within the NOBV project (Baseline dairy farming without changes, dairy farming with reversed drainage, wetland and two Typha paludiculture scenarios). The emission data for these scenarios have been derived from the presently available NOBV data and other published emission data. The evaluation of metrics considers ease of application, relevance to climate forcing, flexibility, and policy relevance.

GWP remains the most policy-relevant metric. GWP* shows deviating results with respect to the other metrics by underestimating the effect of CH_4. Radiative modelling, for which easy to apply model code has been published, performs best. It can calculate climate effects on various time scales without the rigidity of other metrics and allows extensive uncertainty analysis. Given the field data used here for example calculations, all metrics indicate that peatland rewetting reduces the greenhouse gas emission and radiative forcing of the climate on a time scale of less than 20 years.

Key points

- Four approaches to calculate the combined climate effect of CO_2, CH_4 and N_2O emissions from (agro-)ecosystems have been evaluated for various peatland rewetting schemes.
- Global Warming Potential (GWP) and radiative forcing modelling are most relevant for judging mitigation of emissions from agricultural and natural ecosystems. The recently advocated alternative to GWP, GWP* , underestimates the effects of CH_4 emission and is not recommended.
- All approaches show that the methods of peatland rewetting discussed here to mitigate peat oxidation, decrease net greenhouse gas emissions with respect to a traditionally managed peat meadow reference on a timescale of 50 years at most, despite higher CH_4 emissions.

1 Introduction

Agricultural and natural ecosystems emit various amounts of the greenhouse gases CO_2, CH_4 and N_2O, or act as a sink, sequestering CO_2 from the atmosphere in vegetation and soil organic matter. In the Netherlands, a large source of CO_2 emissions is the decomposition of drained peat soils (±3-4% of the national budget, 4.2 megaton CO2 per year; Van den Akker et al., 2008). Adaptations of agricultural practices and change of land use, including rewilding peatlands, have been proposed to mitigate CO_2 emission by oxidation of drained peat soils. However, this also affects the emission of non-CO_2 greenhouse gases. For instance, raising the groundwater table decreases CO_2 emission, but may increase CH_4 emission (Petrescu et al., 2015; Buzacott et al., 2023).

To assess the net climate effect of mitigation measures, the effect on climate of changes in emissions of CO_2, CH_4 and N_2O must be combined. The climate effect of these greenhouse gases differs, since they have different lifetimes in the atmosphere, different radiative properties, and their chemical reactions in the atmosphere may affect the concentration of other greenhouse gases resulting in secondary effects (e.g., oxidation of CH_4 to CO_2).

CO_2 has a radiative efficiency of 1.36×10^{-5} W m^{-2} ppb^{-1}, CH_4 3.77×10^{-4} W m^{-2} ppb^{-1}, about 28 times higher than for CO_2. CO_2 is removed from the atmosphere by several processes, of which some operate on a geological timescale, e.g., peat growth, and uptake of CO_2 by oceans and burial in carbonate sediments. Photosynthesis also removes CO_2 from the atmosphere, but it is largely returned to the atmosphere in short cycles of days to a few years. A part of the human CO_2 emissions will take millennia to be removed from the atmosphere (Inman et al., 2008). CO_2 is therefore a long-lived greenhouse gas. The definition of 'short' and 'long' in this respect depends on the time scale considered; for policy, this is usually a few decennia (Lynch et al., 2020), as is shown by the Paris Climate Agreement timeframe.

The CH_4 is removed from the atmosphere by oxidation by the hydroxyl radical (OH), starting a chain of reactions towards CO_2 and H_2O, both being also greenhouse gases. CH_4 is a short-lived greenhouse gas, with an atmospheric lifetime of about 12 years (IPCC, 2021). Starting with IPCC AR5 (Myrhe et al., 2013) also a difference is made between biogenic CH_4 (from biological decomposition of recent organic material) and fossil CH_4 (from fossil fuel production). Preceding the production of biogenic CH_4, CO_2 has been removed from the atmosphere recently, while fossil CH_4 emission results from the anthropogenic release of carbon that has been stored on a geological timescale.

Starting with the Kyoto Protocol, it is advised to apply the Global Warming Potential (GWP) to evaluate the combined effect of various greenhouse gases for policy purposes. The GWP compares the climate effect of a greenhouse gas X by recalculating it to CO_2 equivalents. It is the time-integrated radiative forcing of the climate, resulting from a *pulse-emission* (emission over a very short time) of a greenhouse gas X with respect to a pulse-emission of an equal mass of CO_2. GWP is calculated over a certain time frame: commonly 100 years (GWP_{100}), but GWP's have been calculated also for shorter time periods (20 years, GWP_{20}) or longer time (500 years, GWP_{500}). Calculation for a specific time frame is necessary for including the effects of the various atmospheric lifetimes of the gases. 'Radiative forcing' is the change in energy flux in the Earth's energy balance, by changes in natural or anthropogenic factors of climate change, such as the concentration of greenhouse gas in the atmosphere.

The GWP_{100} of CO_2 is by definition 1. The CH_4 concentration in the atmosphere mainly decreases by oxidation with the OH^- radical, the starting point of a chain of reactions that produces CO_2. The atmospheric lifetime of CH_4 is estimated at 11.8±1.8 years. Because of evolution of scientific knowledge of CH_4 sinks, the GWP_{100} of CH_4 has increased in successive IPCC reports from 24 (IPCC AR4), to 27.2±11 for biogenic CH_4 and 29.8±11 for fossil CH_4 in the latest IPCC report (AR6, Forster et al., 2021). Over a shorter timescale of 20 years (GWP_{20}) this is 80.8±25.8 for biogenic CH_4 and 82.5±25.8 for fossil CH_4. The differences between the time frame shows the effect of the short lifetime and strong radiative efficiency – over a hundred years, nearly all gas of the pulse emission of CH_4 will have been removed from the atmosphere. The GWP includes the warming effect of the transfer of CH_4 to CO_2. For N_2O, the atmospheric lifetime is 109±10 years, GWP_{100} is 273±130, GWP_{20} is 273±118 (Forster et al., 2021). The GWP values from the latest IPCC report (AR6, Forster et al., 2021) are preferred here. These do not differ substantially from those in AR5 (Myrhe et al., 2013) given the uncertainty ranges given by Forster et al. (2021). Following the rules for reporting greenhouse gas emissions by the UNFCCC (United Nations Framework Convention on Climate Change) the GWP_{100} is still the standard metric to combine the climate effect of greenhouse gases (UNFCCC, 2014). However, there has been a substantial discussion on approaches in recent years, with a focus on the greenhouse gas emission of ecosystems and agriculture. This justifies a consideration of alternatives for GWP for the agricultural practice and land use alternatives that are investigated for the Dutch coastal peatlands. Forster et al. (2021) state below the table of GWP values in IPCC AR6:

> "*Following AR5, this Report does not recommend an emissions metric because the appropriateness of the choice depends on the purposes for which gases or forcing agents are being compared. Emissions metrics can facilitate the comparison of effects of emissions in support of policy goals. They do not define policy goals or targets but can support the evaluation and implementation of choices within multi-component policies (e.g., they can help prioritize which emissions to abate). The choice of metric will depend on which aspects of climate change are most important to a particular application or stakeholder and over which time horizons. Different international and national climate policy goals may lead to different conclusions about what is the most suitable emissions metric (Myrhe et al., 2013)".*

For various reasons, the GWP approach is inadequate in the case of changes in agricultural and natural ecosystems, and can give misleading results (Pierrehumbert et al., 2014; Neubauer & Megonigal, 2015; Lynch et al., 2020; Smith et al., 2021; Collins et al., 2020). The discussion below takes CH_4 as an example.

1. The choice of the timescale is arbitrary. For instance, given the short time that is left to achieve the goals of the Paris Climate Agreement, it may be more logical from a policy viewpoint to use GWP_{20} instead of GWP_{100}, although this would neglect longer term effects. The use of a longer time scale (GWP_{100}) results in a relatively favorable evaluation of the emission of strong short-lived greenhouse gases as CH_4, compared to the shorter time scale of GWP_{20}. The choice of time horizon becomes problematic with rewetting of peat soils for creating wetland carbon sinks or for paludiculture. It takes time to compensate an increase in CH_4 emission by a CO_2 sink, or a decrease of the CO_2 source. This time is longer than the usual policy time horizon (Petrescu et al., 2015). For instance, a peatland rewetting project may result in increased CH_4 emissions, while it starts sequestering CO_2 in vegetation and new peat formation. Initially, it may have a net positive greenhouse gas emission in CO_2 equivalents because of the CH_4 emission if the total emission is calculated using GWP. However, over time (say 50 years) the CH_4 emission may be compensated by the removal of CO_2 from the atmosphere. It will become a net greenhouse gas sink thereafter, because of the continued removal of long-lived CO_2. If a policy goal is set of reducing greenhouse gas emission within 25 years, the short-term effect might lead to rejection of the project since it is still a greenhouse gas source at the end of the policy time horizon, while it would become a significant and continuous sink thereafter.

2. Ecosystem changes such as re-wetting of peatlands or change towards wetland crops do not produce a pulse emission, but an approximate stepwise change, followed by a continuous higher or lower emission level. The effect of such a stepwise change in the emission of a short-lived greenhouse gas is more akin to that of a pulse-emission of a long-lived greenhouse gas, that has a long-term effect on climate (Lynch et al, 2020). The warming effect of a stepwise upwards change of emission of a short-lived greenhouse gas does not decrease over time because of the continued emission (Forster et al., 2021). For a stepwise change of emissions, it is also illogical that the warming effect is strongly dependent on the time scale of the GWP calculation. The duration of the change should be considered (Collins et al., 2020). Alternatively, one could think of stepwise increases as the sum of sequences of many yearly pulse emissions, for each of which a

GWP could be calculated, but that does not avoid the errors resulting from the choice of theGWP time scale either.

The difference in climate effects of a stepwise change of long-lived CO_2 and short-lived CH_4 is illustrated by radiative modelling by Lynch et al. (2020). A stepwise change of CO_2 results in 200 years after the step in a continuous, practically linear increase of the atmospheric CO_2 concentration, because the greenhouse gas has a lifetime that is much longer than two centuries. However, the CH_4 concentration shows a steep increase at first, gradually tapering off until the concentration remains at constant level (Fig. 1). Likewise, the resulting radiative forcing shows a similar pattern. Because of interactions within the climate system and the breakdown products of CH_4, the net warming added by the step CH_4 change still results in a continued temperature rise over 200 years, but at a much slower pace than that caused by CO_2.

Note however, that also a stepwise change in emission is an over-simplification of the emission trajectory at land use change. Transient effects in soil and ecosystem during land use change may create pulse-like emission spikes in the first years for CH_4 (Hahn-Schöfl et al. (2011); Harpenslager et al. (2015); vegetation succession may lead also to gradual changes of CH_4 emission (e.g., Magnússon et al., 2020); the effect of year-to-year weather variability and climate change on emissions is added to that.

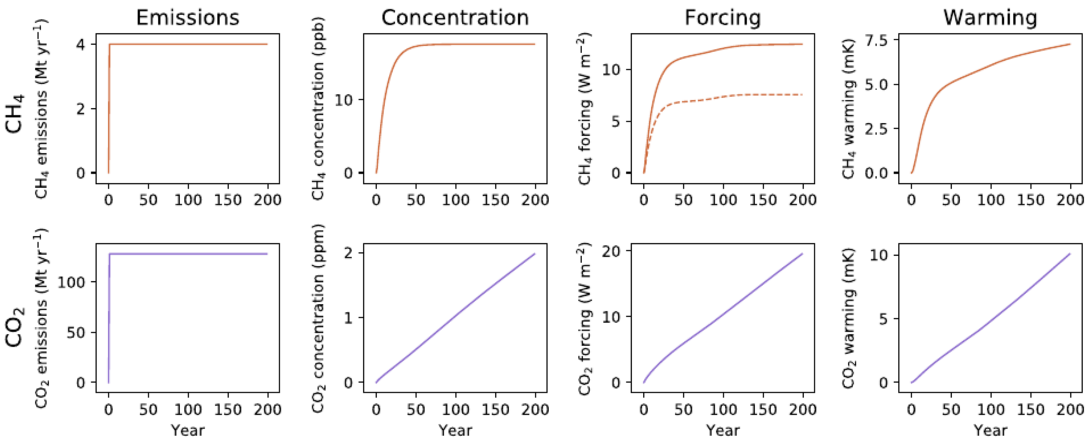

Figure 1. An illustration of the difference in climate effect over a time scale of 200 years of short-lived greenhouse gases (CH_4 as example) and the long-lived greenhouse gas CO_2. The graph shows how a step change in sustained emissions of short-lived CH_4 (top row) and long-lived CO_2 (bottom row) affect the atmospheric concentration of the greenhouse gas, the radiative forcing and global temperature. For CH_4, the dotted line shows the climate forcing from methane alone. However, the total forcing impact (solid line), is greater than this because other greenhouse gases (ozone, water vapour) are produced by CH_4 breakdown (total forcing is approximately 1.65 times that of methane alone). The temperature change is modelled from total forcing. Reproduced from Lynch et al., (2020); reproduced under Creative Commons Attribution 4.0 licence.

2 Methods

2.1 Prospective approaches.

For the Paris Climate Agreement, it is still recommended to use GWP_{100} for national inventories (Collins et al., 2020), but IPCC AR6 (Forster et al., 2021) also discuss other metrics. Of these, we consider here:

*GWP** (Cain et al., 2019; Lynch et al., 2020; Smith et al., 2021). With GWP* the climate effect of a short-lived greenhouse gas is not compared with CO_2, but with a stable base situation over a period of 20 years with a given greenhouse gas emission. The method uses a correction formula on the GWP, in which the magnitude of the stepwise change is considered. The method emphasizes the warming effect of a greenhouse gas and expresses the effect in 'CO_2 warming equivalent' ($CO_{2\ we}$) – a temperature increase instead of a dimensionless ratio. For the comparison of the CH_4 GWP* in $CO_{2\ we}$ with the temperature effect of CO_2 emissions, CO_2 emission can be converted to $CO_{2\ we}$, using the TCRE (Transient Climate Response to cumulative carbon Emissions), 0.42^{o}K per Gigaton CO_2. N_2O is also a relatively long-lived greenhouse gas; an approach for including the climate effect is not included in Lynch et al. (2020) and other papers on GWP*.

With GWP*, small reductions of CH_4 emission can achieve a cooling effect, compared to GWP, which always assigns a climate warming effect to greenhouse gas emission. A 0.3% annual decrease in CH_4 emissions with respect to a stable emission level, is purportedly sufficient to keep the climate warming effect of CH_4 emission at a stable level (Lynch et al., 2020). With a faster decrease of CH_4, its climate effect is considered by Lynch et al (2020) as equivalent to a removal of atmospheric CO_2. A greater decrease therefore suggests cooling with GWP*; A decline smaller than 0.3% per year, constant emission or increase leads to an increase in the amount of CH_4 in the atmosphere and thus to warming. However, in this way, it is suggested that ongoing CH_4 emissions can have a cooling climate effect, which is an important aspect of criticism on GWP* (Meinshausen and Nicholls, 2022).

GWP* has been used to re-evaluate the climate effect of CH_4 emission by livestock in the USA (Liu et al., 2021) and has been advocated also by farming lobby groups in the Netherlands, under the assumption that feedstock additives could reduce cattle CH_4 emission sufficiently to achieve climate cooling. This included the unjustified claim in the media that cows could cool the climate in (Lamers, 2021), illustrating the criticism of (Meinshausen and Nicholls, 2022) on GWP*.

An advantage of GWP* is that it aligns with GWP and uses a simple correction formula, instead of more complicated modelling of radiative forcing. Lynch et al. (2020) shows that this GWP* approximately tracks climate temperature trajectories. The calculation formula for GWP* for CH_4 according to Lynch et al. (2020) is:

$$E_{CO2weq} = \left(r\ H\frac{\Delta E_{CH4}}{20} - s\ E_{CH4}\right)\ GWP_H$$

E_{CO2weq} is the CO_2 warming equivalent of the CH_4 emission increase in milliKelvin; H the time period in years that is selected; GWP_H the GWP of CH_4 over that period; E_{CH4} the CH_4 emission averaged over 20 years preceding the stepwise increase of CH_4 (Gt CH_4 per year); ΔE_{CH4} the stepwise increase of the CH_4 emission. The factors r and s are weighing factors, representing respectively the contribution to warming by the change in emission rate, and the contribution by the emission stock (the stable emission preceding the rate change). These factors should sum to one and have been estimated by Cain et al. (2019) by fitting to modelled IPCC emission scenarios; their values are r = 0.75 and s = 0.25. To compare with CO_2, the CO_2 emission in the

entire period covered is recalculated into warming equivalents with the TCRE (see above). Note that by its dependence on GWP, GWP* still depends on the time horizons used by GWP.
Combined Global Temperature Change Potential (CGTP) compares the effect of a step change of a short-lived greenhouse gas with that of pulsed CO_2 emissions on the Earth's temperature change (Collins et al., 2020). This is a measure that gives the resulting warming effect after several years, an 'endpoint metric'. The unit is in years, because a continuous emission over a number of years is compared to a pulse emission of CO_2.
Sustained Global Warming Potential (SGWP) and Sustained Global Cooling Potential (SGCP) have been developed by Neubauer & Megonigal (2015) to account for stepwise changes in ecosystems, based on modelling of radiative forcing. These metrics are specifically developed for ecosystem changes. Just as with GWP, these are dimensionless mass-mass ratios. The SGWP represents the quantity of CO_2 (kg m^2 y^{-1}) that must be sequestered by an ecosystem to compensate for an emitted quantity of CH_4 or N_2O. The SGCP indicates how much CO_2 should be sequestered to attain the same cooling effect as the decrease of the other greenhouse gasses. SGWP is considerably higher than GWP. The absolute value of SGCP is much higher than that of SGWP for an emission change of a certain magnitude. Therefore, a comparatively small reduction of non-CO_2 greenhouse gas emission has a much larger climate effect than a pulse emission of CH_4 and N_2O with this method. SGCP and SCWP use the same time horizons as GWP.
Modelling of the radiative forcing (Frolking et al., 2006; Dommain et al., 2018) models the radiative forcing of the climate of greenhouse gas emission over a certain time period. It includes interactions between greenhouse gases and their sources and sinks. The metrics discussed above are based on radiative modelling. Using radiative modelling, Günther et al. (2020) show that rapid reduction of CO_2 emissions from drained peatlands immediately contributes to limiting global warming, despite higher CH_4 emissions. Important in the context of peat conservation by re-wetting is, that in the short term the increase in CH_4 emissions has a warming effect, but on a longer time scale the reduction of CO_2 emissions is more effective (Petrescu et al., 2015; Lynch et al., 2020). Günther et al. (2020) published code of a model, which uses simple impulse-response functions to estimate the radiative forcing effects of greenhouse gas emissions. Input for this model is the yearly balance of greenhouse gas emissions for any number of years; the output of the model is the radiative forcing in W.m^{-2} over time. The yearly greenhouse gas balance of an (agro)ecosystem should ultimately be based on empirical measurements.

2.2 Which components of greenhouse gas budget should be included?

The next question is, which part of the greenhouse gas and carbon balance should be used in calculating climate effects. These should represent real changes of greenhouse gas fluxes to the atmosphere, at the time scale relevant to policy decisions. For instance, daily cycle changes of photosynthetic uptake of CO_2 and its return to the atmosphere by respiration are not relevant in that respect.
Ideally, this is not limited to on-site measurement data of greenhouse gas fluxes in a particular (agro)ecosystem but also needs to consider the greenhouse gas fluxes due to the life cycle of an agricultural product. Most agricultural products, in particular food, have a short life cycle and their carbon is respired back to the atmosphere in less than a year as CO_2 and therefore do not contribute to a net extraction of CO_2 from the atmosphere. However, other products, such as building construction wood or natural insulation material may represent extraction of CO_2 over a much longer timescale of several decennia to centuries, a time range that is relevant for climate mitigation policy. Moreover, it avoids other CO_2 emissions by cement production and heating of buildings (De Jong et al., 2021; Cordier et al., 2022).
It is also crucial to distinguish between the release of soil carbon from short term cycles, such as rapid decomposition of root exudates, plant litter or organic manure that has been produced recently by extraction of CO_2 from the atmosphere by photosynthesis, and carbon that has been in soil storage for a long time and can be considered as ‘fossil’, such as peat and other old soil

carbon that is conserved in the soil environment (Jenkinson and Rayner, 1977). Soil environment changes (temperature, water availability, chemical conditions) determine decomposition or conservation of recently produced carbon, or the re-mobilization of older carbon in the soil (Schmidt et al., 2011). These soil environmental changes contribute to net extraction from, or release of CO_2 to the atmosphere at the time scale that is relevant here. The respiration of old soil carbon increases if significant changes in the soil environment occur that destabilize this carbon (e.g., drastic changes by human intervention such as ploughing, or extreme weather conditions such as drought). Conservation of soil carbon may be fostered by wetter soil conditions and decrease of soil disturbance.

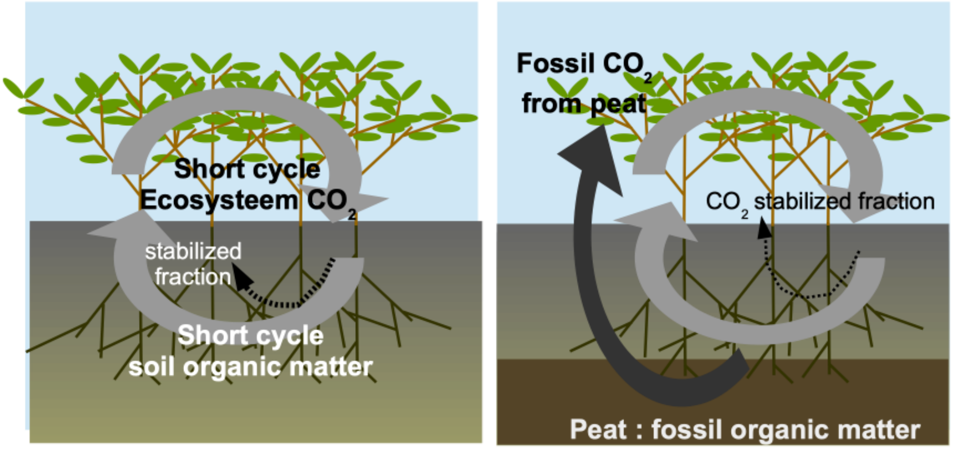

Figure 2. Conceptual diagram of soil organic matter cycling. Left: short cycle of photosynthesis products and soil organic matter, not affecting atmospheric CO_2; right: flux of CO_2 to atmosphere from old soil carbon. The stabilized fraction, resulting from protection against decomposition of short cycle soil organic matter is also known as humus. Net addition of CO_2 to the atmosphere occurs only when fossil organic matter (peat) and the stabilized (humus) fraction is decomposed.

The following components of the carbon balance are relevant here:

1. CO_2 from peat or other stable soil carbon oxidation. This is the part of soil respiration that transfers carbon from soil storage to the atmosphere and contributes to a real increase of CO_2 in the atmosphere. It is not measured directly with the instrumentation (chambers and eddy covariance) used in the NOBV project that measure the ecosystem greenhouse gas exchange (Net Ecosystem Exchange, NEE) It is also the largest part of the ecosystem respiration, R_{eco}. R_{eco} is usually derived from NEE by modelling or by assuming that it equals CO_2 emission measured at nighttime (Van de Craats et al., 2023). R_{eco} may contain a peat oxidation component and respiration of other old soil carbon, but mostly contains plant respiration, respiration of organic manure, root exudates and plant litter, which is short cycle CO_2 that does do not increase atmospheric CO_2 on the time scale of more than one year. The peat oxidation component of R_{eco} varies strongly over time, since the water table depth and oxygen entrance into the soil strongly influence the amount of old peat that is exposed to oxidation (e.g., Van de Craats et al., 2023). Moreover, CO_2 from oxidation of old soil carbon as part of R_{eco} may be masked by local differences in vegetation. Even for exactly comparable vegetations on test parcels, measurements of NEE and R_{eco} may not represent respiration differences in peat oxidation accurately. Differences in grass growth caused by differences in soil moisture and nutrient availability introduce uncertainty in the short cycle CO_2 emission components, hampering deduction of the old soil carbon components of R_{eco}. Another option is derivation of the old soil carbon component of R_{eco} by modelling based on the decomposition processes from the various soil carbon reservoirs (e.g. Jenkinson and Rayner, 1977; Hendriks, 1992; Van Huissteden et al. 2006; Schädel et al., 2013; Gremmen et al., 2022; Van de Craats et al., 2023). However, also that estimate of peat oxidation is an approximation, because of model and parameter uncertainty (Van Huissteden et al., 2009; Van de Craats et al., 2023).

2. NEE (Net Ecosystem Exchange – gross photosynthesis minus CO_2 produced by soil and plant respiration) may serve to estimate the net CO_2 emission or removal from the atmosphere for natural ecosystems without significant harvest, because much of this CO_2 remains within the soil and vegetation. However, quantification of lateral transport of carbon by organic matter in water and wildlife grazing is necessary. For agricultural systems it depends also on inclusion of the carbon removed by harvest. The harvest carbon is consumed and transferred back to CO_2 in a short cycle of at most a few years and does not count as carbon removed from the atmosphere. Without taking harvest and all other carbon removal into account, NEE overestimates CO_2 sequestration form the atmosphere.

3. If carbon removed by harvest is also removed from the carbon cycle for a long time (for example, for durable construction wood) it could be considered as CO_2 removal from the atmosphere. Life cycle analysis of products should confirm to what extent this is the case (e.g., De Jong et al., 2021; Cordier et al., 2022).

4. CH_4 emissions are a direct addition to the radiative forcing of the climate, although this differs for biogenic CH_4 and CH_4 derived from fossil fuel extraction. For biogenic CH_4 it can be assumed that its carbon has been extracted recently from the atmosphere by photosynthesis. Nevertheless, it adds radiative forcing to the atmosphere during its atmospheric lifetime and is converted to CO_2 in the atmosphere. It therefore needs to be accounted as an emission that adds to climate warming, despite its short lifetime and its derivation from recent photosynthates. With exception of natural ecosystems, it represents also additional greenhouse gas emission that has been caused by human activities. In addition, indirect emissions caused by human influence on natural ecosystems may need to be accounted for. For example, indirect emissions of CH_4 are caused by eutrophication of surface water (Schrier-Uijl et al., 2011; Moss et al., 2017; Downing et al., 2021). Because of this recent photosynthesis origin, biogenic CH_4 has a lower global warming potential than fossil fuel derived CH_4 (Forster et al., 2021). The ecosystem CH_4 flux is composed of plant-mediated flux, ebullition and diffusive flux through the soil/water column (e.g., King and Reeburgh, 2002; Van Huissteden et al., 2006; Gremmen et al., 2022). In agricultural ecosystems, the ruminant emission by cattle and emission from manure storage adds to the ecosystem CH_4 emission (Schrier-Uijl et al., 2014).

5. For N_2O emissions holds the same as for CH_4 emissions; N_2O emissions are largely caused by agricultural and industrial activities. Indirect emissions are caused by nitrogen pollution of natural ecosystems (Hensen et al., 2006). Natural ecosystems generally lack significant N_2O emissions and may even be a N_2O sink in nutrient-poor peatlands (Schlesinger, 2013).

2.3 Evaluation criteria and data.

For NOBV reporting, the following requirements of metrics are important:

1. Ease of use and transparency: elaborate calculations not required and easy to understand for a larger public if properly explained.
2. Climatic forcing agreement: A good agreement with true climatic forcing of sustained emissions and stepwise changes that are caused by land use change, avoiding as much as possible assumptions on emission patterns over time.
3. Ecosystem flexibility: Applicability to both agricultural and natural ecosystems. For instance, SGWP and SGCP are specifically aimed at ecosystems that have a CO_2 sink function, although this does not exclude usage for agricultural land use change.
4. Temporal flexibility: capability to include more complicated emission pathways over time. This includes transient effects of land use or agricultural practice changes such as temporary higher CH_4 emission resulting from rapid rewetting, other temporal variability due to climate and interannual variability and the need for flexibility in the length of the time horizon, to accommodate longer term ecosystem evolution.
5. Policy relevance: relevance to current usage in climate policy, enabling policy makers to judge climate effects of measures in and unbiased way, including uncertainty margins.

The metrics GWP* (Lynch et al., 2020) and SGWP / SGCP (Neubauer & Megonigal 2015) and radiative modelling as applied by Günther et al. (2020) have been evaluated using these criteria and five example land use change scenarios and compared with the standard GWP. CGTP and CGWP of Collins et al. (2020) are not included because of the built-in comparison with a pulse emission of CO_2. The example consists of five scenarios, based on data from Gremmen et al., 2022) and Buzacott et al. (2023). *N.B.: All scenarios are for demonstration purpose only and are based on provisional data; these may not be the same as in other parts of this NOBV report. The scenarios and subsequent analysis are currently not fit for policy decisions.* For a more in-depth and policy-ready analysis, multi-year averages of the greenhouse gas fluxes are necessary. These data were not yet available at the time of writing of this chapter. However, data from recent field measurements were used where possible.

1. *Baseline.* A baseline scenario of unmitigated peat oxidation on a typical drained peatland in the Western part of the Netherlands, based on the Assendelft reference site. Peat oxidation amounts to 4.09 ton CO_2 ha^{-1} year^{-1}. This is an average based on two-year data from field measurements with automatic chambers. These data have been upscaled to a yearly balance with the Peatland-VU model, calibrated on the field data. Based on the methodology described in Chapter 10 (Van de Craats et al., 2023), an estimate of the amount of peat oxidation has been made (Gremmen et al., 2022). The estimate of peat oxidation ranges from 3.60 ton CO_2 ha^{-1} year^{-1}(2019) to 4.58 ton CO_2 ha^{-1} year^{-1} in 2020; an average of these two figures has been used. It is assumed that CH_4 emission from the soil or uptake into the soil is negligible, which is confirmed by measurement data. The cattle ruminant CH_4 emission of the dairy farm is estimated at 0.25 ton CH_4 ha^{-1} year^{-1} (based on emission factors by Šebek et al., 2014). CH_4 emissions from manure storage and from ditches are not included. Neither are CO_2 emissions from the farm and CO_2 emission compensation by its solar power array included. N_2O emission has not been measured at Assendelft; based on emission data from the Zegveld experimental farm, an emission for N_2O of 0.0464 ton N_2O ha^{-1} year^{-1} is assumed (Pleijter et al., 2011).
2. *Reversed Drainage.* Application of pressurized reversed drainage in scenario 1, resulting in higher groundwater tables and reduction of peat oxidation. Modelled CO_2 emission due to peat oxidation is 2.31 ton CO_2 ha^{-1} year^{-1}. The cattle CH_4 emission is the same as in baseline. The N_2O emission is lower at higher water table based on data from the Zegveld experimental farm (Pleijter et al., 2011); 0.0182 ton N_2O ha^{-1} year^{-1} is assumed.
3. *Wetland.* Replacement of dairy farming (baseline scenario) by a wetland dominated by grasses, *Typha* and *Phragmites* as would result from peat meadow rewetting and rewilding (Hendriks et al., 2010). This results in highly productive, high CH_4 emission wetland, with high uptake of CO_2 which would be added as carbon to a peat soil. For the emission data an average of the Onlanden and Camphuis sites in Buzacott et al. (2023) is taken. Peat oxidation and N_2O emission are reduced to zero, net carbon uptake (net ecosystem exchange) amounts to -11.5 ton CO_2 ha^{-1} year^{-1} (this includes avoided CO_2 emission by peat oxidation with respect to baseline). CH_4 emission is 0.441 ton CH_4 ha^{-1} year^{-1}. There are no transient high CH_4 emissions on rewetting, nor a decrease of CH_4 emission by vegetation succession.
4. *Typha Harvest* is paludiculture with harvest; in this scenario it is assumed that all carbon uptake by the ecosystem is harvested and is applied in such a way that it returns within a short time back to the atmosphere as CO_2, similar as food crops. Only the avoided peat oxidation with respect to baseline (4.09 ton CO_2 ha^{-1} year^{-1}) counts as a decrease of emission; the CH_4 emission is 0.568 ton CH_4 ha^{-1} year^{-1} based Typha latifolia paludiculture at Zegveld (Buzacott et al., 2023) there is no N_2O emission.
5. *Typha Life cycle.* Typha paludiculture, but taking life cycle effects of isolation panel production into account (9.73 ton CO_2 eq. ha^{-1} year^{-1} for harvest and panel production, -8.36 ton CO_2 eq. ha^{-1} year^{-1} for avoided CO_2 emission of glass/rockwool isolation panel production, -2.6 ton C ha^{-1} year^{-1} for carbon storage in panels, assumed permanent over 50 years, based on De Jong et al., 2021); together with the avoided CO_2 emission from

peat oxidation this results in a net decrease of CO_2 emission by 12.25 ton CO_2 eq. ha^{-1} $year^{-1}$. CH_4 and N_2O emission are the same as in scenario 4.

3 Results

Table 1.1 shows the results of the climate impact metrics discussed above for the land use scenarios. In all cases, these are calculated for 1 ha of each scenario, except for the radiative forcing modelling which is calculated on m^2 scale. The results include the effect of CO_2 from peat oxidation, sequestration or avoided emissions, and net ecosystem exchange of CH_4 and N_2O wherever possible (see below).

Table 1. Climate effect according to four different metrics for comparing the effect of CO_2 and CH_4. GWP_{20} and GWP_{100} are the Global Warming Potentials at a time horizon of 20 and 100 years; GWP based on Lynch et al. (2020); SGWP, SGCP sustained global warming/cooling potentials based on Neubauer and Megonigal (2015). The columns 'Diff' indicate the difference between SGWP and SGCP. The radiative forcing is calculated cf. Günther et al. (2020) and represents the summed radiative forcing over 100 years of 1 m^2. The year of max. forcing is the number of years it takes before a decline of radiative forcing starts after an initial increase. Radiative forcing units are nanoWatt/m^2*

climate effect per hectare	**GWP_{20} (CO_2 eq)**	**GWP_{100} (CO_2 eq)**	**GWP^*_{100} CO_2 warming eq. nano-Kelvin**	**$SGWP_{20}$ (CO_2 eq)**	**$SGCP_{20}$ (CO_2 eq)**	**Diff.**	**$SGWP_{100}$ (CO_2 eq)**	**$SGCP_{100}$ (CO_2 eq)**	**Diff.**	**Radiative forcing ($nW.m^{-2}$) 100 years**	**Year of max. forcing**
Baseline	36.9	23.5	1.70e04	39.7	0.0	39.7	27.9	0.0	27.9	0.0214	-
Reversed drainage	27.5	14.1	0.95e04	9.3	0.0	9.3	7.3	0.0	7.3	0.0126	-
Wetland	24.1	0.5	-4.64e04	42.3	11.5	30.8	11.5	8.3	3.2	0.0051	28
Typha harvest	41.8	11.4	-1.43e04	54.5	0.0	54.5	25.6	0.0	25.6	0.0121	51
Typha life cycle	33.6	3.2	-4.86e04	54.5	0.0	54.5	25.6	0.0	25.6	0.0079	31

The GWP calculations use a GWP_{20} of 80.8 for CH_4 and 273 for N_2O, and GWP_{100} of 27.2 for CH_4 and 273 for N_2O, according to Forster et al. (2021). The same GWP's have been used to calculate GWP* according to eq. 1. For GWP*, the Baseline scenario has been taken as the required 20-year stable baseline. The N_2O emission could not be included since the given calculation formula for GWP* is valid for CH_4 only. The GWP* value for this baseline results from the CO_2 emission only since there is no change in the CH_4 emission for that scenario. The constants used for the calculation of SGWP and SGCP of Neubauer and Megonigal (2015) have been derived from Table 1 in that paper ($SGWP_{20}$; CH_4 96, N_2O 250; $SGCP_{20}$: CH_4 153, N_2O 264; $SGWP_{100}$: CH_4 45, N_2O 270; $SGCP_{100}$: CH_4 203, N_2O 349). For the SGCP, only the uptake of greenhouse gases by the ecosystem soil or vegetation is included in the method, because it is unclear how avoided greenhouse gas emissions related to the life cycle of agricultural products should be included. Therefore, avoided CO_2 emissions have not been included in the calculation of Table 1. For the radiative forcing modelling cf. Günther et al. (2020) the 100-year sum of the total radiative forcing of all three greenhouse gases is given in Table 1, and for scenarios that display a decline to radiative forcing within 100 years, the year of the maximum radiative forcing.

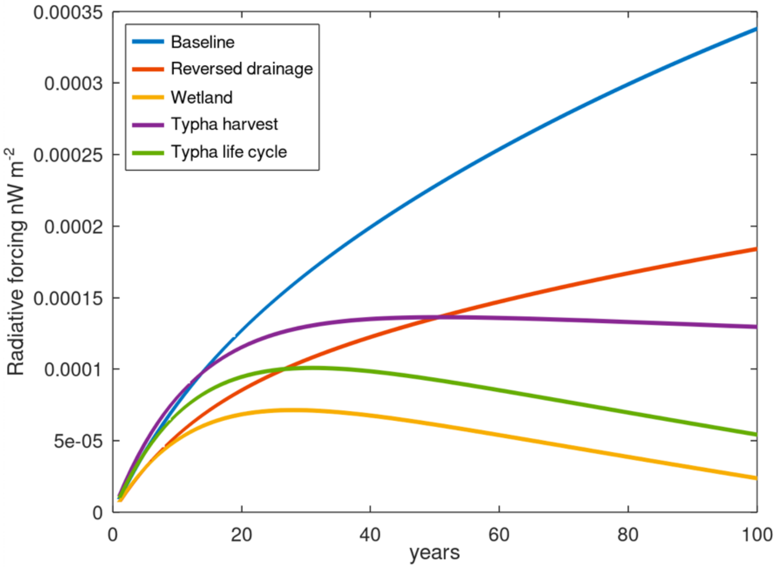

Figure 3. Radiative forcing modelling for the scenarios in Table 1 cf. Günther et al. (2020). In Table 1 the summed radiative forcing over 100 years and the year of maximum forcing is listed.

Figure 3 shows the radiative forcing per year for all scenarios. Uncertainty ranges on the radiative forcing arising from measurement methods, models and year-to-year variability has deliberately not been included, since these uncertainties would be still quite hypothetical given the short data time series on which the scenarios have been based. Also, at the time range of Figure 3, uncertainty due to future climate trajectories should be included. The radiative may seem very small (nanoWatt/m^2), but the calculation is based on a m^2 scale. On a larger hectare or country-wide scale, contributions by land use change may become more significant.

The five scenarios show that the effect of CO_2 emission reduction in combination with a change of CH_4 and N_2O emission varies depends on the magnitude of the emissions, which type of emissions are included, and on the metrics used for comparison.

For GWP, all scenarios have a net warming effect (net increase of total greenhouse gas in CO2 equivalent) within a time horizon of 20 years. However, there is a clear decrease of warming with all scenarios that attempt mitigation of peat oxidation with respect to Baseline. The Reversed Drainage results in a comparatively strong reduction of the GWP than could be expected from differences in peat oxidation alone, because it is assumed here that under wetter conditions also the N_2O emission decreases (Pleijter et al., 2015). This is corroborated by literature reference in Chapter 9 of this report. However, N_2O measurement data comparing the effect of water table management at NOBV experimental sites are not yet available. Chapter 9 also reports a larger incidence of N_2O emission peaks due to the combination of manure application and rainfall in a wetter year with higher groundwater table than in a dry year, which indicates that higher water tables also could enhance N_2O emissions.

The Wetland scenario has a positive GWP at 20 years, but near zero at 100 years, indicating that at a longer time scale the sequestration of carbon by the ecosystem becomes dominant over the high CH_4 emission. However, CH_4 emission and NEE vary strongly between natural wetland ecosystems. Saarnio et al., (2009) found a large range of CH_4 emissions in European wetlands, ranging from 53 kg CH_4 ha^{-1} yr^{-1} for ombrotrophic mires with precipitation as the only water source to 467 kg CH_4 ha^{-1} yr^{-1} for freshwater marshes, receiving nutrient-rich water from surrounding water courses. The Onlanden and Camphuis sites from Buzacott et al (2023) used for the Wetland scenario classify as freshwater marshes, and therefore represent a high CH_4 scenario. The uncertainty resulting from vegetation type is discussed more extensively below.

The Typha harvest and life cycle scenarios have similar GWP's as Baseline on the 20-year time scale because of the high CH_4 emissions, but perform better on a longer time scale, although they remain a net greenhouse gas source. The Zegveld paludiculture site which has been used for the Typha scenarios is fertilized (Buzacott et al., 2023). The amount and quantity of manure or fertilizer application to Typha culture may affect its CH_4 and N_2O emission (Chapter 6 on paludiculture, Fritz et al., 2023). Unfortunately, there is no data yet to quantify the effects of fertilization.

The GWP* (100-year time scale) approach indicates that reversed drainage strongly decreases the warming effect with respect to Baseline but does not result in cooling. All wetland and Typha scenario's result in net cooling, because of the absence of CO_2 emission from peat oxidation. The cooling effect of Wetland and Typha Life Cycle are 2.5-3 times stronger than that of Typha Harvest. A drawback of GWP* is that it calculates the effect with respect to an existing baseline scenario; in this example the Baseline has a relatively high level of emission of CH_4 from cattle, which is not included in its GWP* because there is no change.

The SGWP and SGCP show similar results as GWP. The Reverse Drainage scenario shows a net decrease of the greenhouse gas emissions with respect to Baseline. However, on a 20-year timescale the Typha Harvest scenario has an even higher warming effect than the Baseline, because the avoided emission of peat oxidation has not been included in the SGCP, and all sequestered CO_2 is assumed to be removed by harvest. Nevertheless, on a timescale of 100 years, the paludiculture scenarios do perform slightly better. Also, the Wetland has a higher warming effect than Baseline at the 20-year time scale, but at the 100-year time scale considerably lower.

The result of the radiative forcing modelling (Fig. 3) compares well with the GWP and SGWP/SGCP. Here also, the Reversed Drainage results in less warming than the Baseline. However, the net warming effect keeps rising throughout the 100-year period over which the radiative forcing is calculated (Fig. 3). By contrast, the more drastic rewetting scenarios show a decrease of the warming effect after an initial steep rise. For the Wetland scenario, this decrease starts after 28 years; for the paludiculture scenarios later. The Wetland scenario results in net near-zero greenhouse gas emission after 100 years, with a further trend towards cooling. The Wetland scenario has the lowest warming contribution of all scenarios. The Typha Harvest has a similar net warming effect after 100 years as Reverse Drainage; the climate effect of Typha Life Cycle is comparable to that of Wetland.

In general, the GWP, SGWP/SGCP and radiative forcing modelling show broad agreement in results. Reverse Drainage has an immediate effect by reducing CO_2 emission from peat oxidation and lower N_2O emission. The effect of complete rewetting scenarios (Wetland and paludiculture) starts counting at longer time scales then 20 years. SGWP/SGCP appears more pessimistic in the effect of rewetting than the other scenarios because a restriction on the greenhouse gas budget components that can be included. GWP* deviates from the other metrics by indicating a much more positive effect of the rewetting scenarios. The radiative forcing modelling shows considerably more information on the evolution of the climate effect over time, which is missed in the other single number metrics.

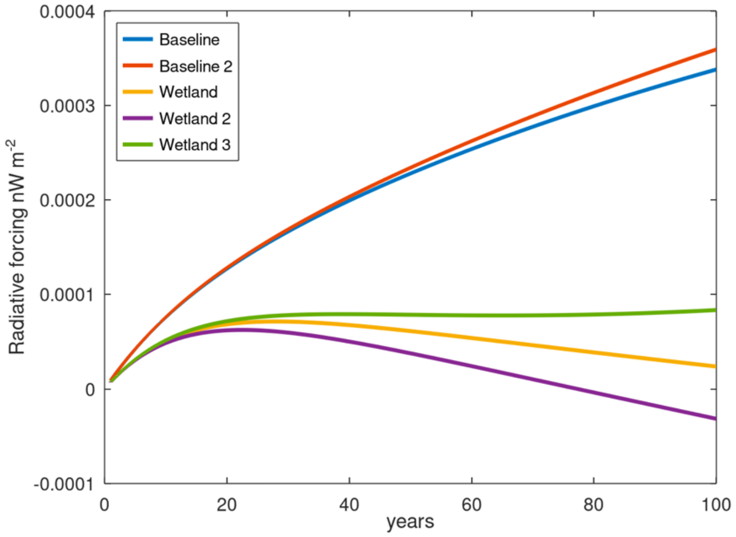

Figure 4. Radiative forcing modelling for the Baseline and Wetland scenarios, showing the effects of climatic and vegetation succession uncertainty at longer time scale. Baseline and Wetland scenarios as in Fig. 3. Baseline 2 includes a climate change driven 1% per year increase of CO_2 emission from peat; Wetland 2 a hypothetical 0.5% per year decrease of CH4 emission driven by vegetation succession; Wetland 3 a climate change driven hypothetical1% per year increase of CO_2 emission from peat and a 0.75% decrease of CH_4 emission.

The outcomes of GWP and SGWP/SGCP show large difference depending on a short time horizon of 20 years and the longer time horizon of hundred years. The radiative forcing modelling shows that after the first 10-20 years the climate effect of the various scenarios start to deviate strongly. This shows that the climate effect of decisions on land use change may have a considerably longer time scale than the typical policy time horizon. With a longer time horizon, uncertainty will be introduced by climate change and, for rewilding to natural wetlands, by vegetation succession. Next, as the data of Buzacott et la. (2023) show, there is a large variation in CH_4 and CO_2 ecosystem exchange among similar ecosystems. Therefore, additional radiative forcing modelling may explore these uncertainties (Fig. 4). Three *hypothetical* scenarios were added:

Baseline 2. The same as Baseline, but with a hypothetical 1% increase of CO_2 emission from peat oxidation per year, caused by climate change: in increase in incidence and length of dry and hot summer periods, causing more frequent deep oxygen penetration and higher soil temperatures.

Wetland 2. A decrease of CH_4 emission by a hypothetical 0.5% per year due to a succession towards less nutrient-rich (eutrophic towards meso/ombrotrophic), less CH_4 emitting vegetations.

Wetland 3. A hypothetical decrease of CH_4 emission by 0.75% per year, and an increase of peat oxidation by 1% per year caused by climate change as in Baseline 2.

Additionally, an uncertainty analysis has been done on the Wetland scenario. This scenario is based on average emissions of two sites in Buzacott et al. (2023), Camphuys and Onlanden; in the analysis in Fig. 5, the emissions of these sites are taken as lower and upper uncertainty boundaries. *For comparison, also a radiative forcing calculation of a Sphagnum-dominated minerotrophic/ombrotrophic blanket bog in northern Scotland (Forsinard, Levy and Gray, 2015) has been added.*

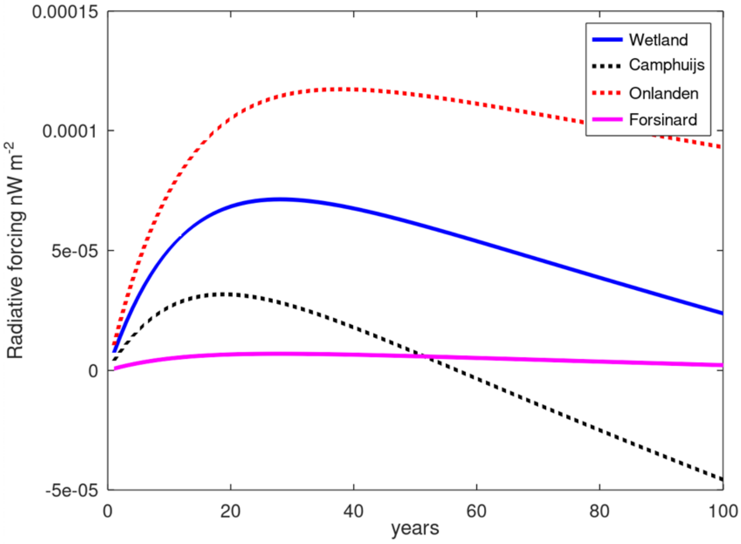

Figure 5. Radiative forcing modelling for Wetland, with uncertainty boundaries based on the sites with highest and lowest emissions. For comparison, a radiative forcing calculation of a Sphagnum-dominated blanket bog in northern Scotland (Forsinard, Levy and Gray, 2015) has been added.

The radiative forcing modelling is very well capable to show the effects of these scenarios and indicates that small perturbations of future emissions may be particularly large for the Wetland scenario. The yearly 1% increase of peat oxidation is small compared to the high emissions of

Baseline, and therefore has a noticeable but relatively small additional warming effect in Baseline 2 (increase of 0.0007 nW.m^{-2}, 3.6%). For Wetland, the climate cooling effect of vegetation succession is strong (Wetland 2; decrease of radiative forcing by 0.0025 nW.m^{-2}, 49%). The total radiative forcing over 100 years remains positive (0.0026 nW.m^{-2}), but its decline starts somewhat earlier (22 years), and cooling is reached after 77 years. However, an increase of peat oxidation by climate change in Wetland 3 results in a continued high warming effect (summed over 100 years of 0.0073 nW.m^{-2}, an increase by 0.0022 nW.m^{-2}, 49%), despite a decrease in CH_4 emissions. This suggests that the success of the Wetland scenario depends on vegetation succession and water management.

The uncertainty range for wetland is large (Fig. 5), based on the data of Buzacott et al. (2023). This results in a large uncertainty range for the sum of the total radiative forcing in Table 1 of 0.0051 ±0.0050 nW.m^{-2}. At the lowest uncertainty range, cooling is reached at 57 years. Note however, that the wetlands included in the Wetland scenario represent a type of wetland with the highest CH_4 emissions on a national and European scale (Saarnio et al., 2009); the CH_4 emissions of ombrotrophic and minerotrophic wetlands that do not receive a supply of nutrients from surface water import are substantially lower. Also, the data are based one year of observations only. The minerotrophic / ombrotrophic blanket bog site in northern Scotland (Levy and Gray, 2015) has a CO_2 uptake of -114 g CO_2 m^{-2}yr^{-1}, and a CH_4 emission 4.3 g CH_4 m^{-2}yr^{-1}. This site is a CO_2 sink, albeit at an approximately ten times lower rate than the Wetland scenario. However, it is a very small greenhouse source because of the CH_4 emissions compensate for the CO_2 uptake. This illustrates nicely the difference between the greenhouse gas balance and carbon balance. Fig. 5 also shows the large range of radiative forcing trajectories over time for various wetland sites, and the potential effect of vegetation succession and management on the greenhouse gas balance of wetland reconstruction.

4 Discussion

First, important restrictions on the results apply. it should be stressed that the scenarios above, are only partly based on data collected within the NOBV project. Insofar these data have been used, these are provisional data from short time periods of two years at most and therefore subject to considerable statistical uncertainty. This article is a provisional exploration of methods. The basic data may change during the NOBV research project, and conclusions are therefore not definitive, but in the future will include sufficient observations to evaluate uncertainties in the data. For the dairy farming scenarios Baseline and Reversed Drainage, CH_4 emissions from ditches and farm emissions (CH_4 from manure storage and farm CO_2) have not been included. Based on Schrier-Uijl et al. (2014), the manure storage emissions are small compared to the cattle emissions, but nevertheless cause an underestimate of the Baseline and Reverse Drainage emissions. The emissions from ditches are more substantial (Schrier-Uijl et al., 2014), but are also expected to occur in approximately the same amount in the other scenarios. For N_2O, emission data from earlier reports have been used. Also in this respect there is considerable uncertainty in the emissions for Baseline and Reversed Drainage. Data on the effect of water table management on N_2O emissions at the NOBV sites are not yet available; Chapter 9 of this report (Velthof et al., 2023) did not include a reversed drainage experiment.

Second, for each scenario and each metric it should be considered carefully which part of the greenhouse gas fluxes are a legitimate entry for the metric under consideration. This is not straightforward and may be subject to politicized controversy. For instance, it has been advocated in advertising that the CO_2 uptake by grass in dairy farming should be taken as CO_2 extraction from the atmosphere, not realizing that this extracted carbon is returned in a short cycle of a year at most to the atmosphere again as greenhouse gas, including CH_4 from cattle with its strong radiative forcing.

Only the additions or extractions that increase/decrease greenhouse gas radiative forcing in the atmosphere matter. E.g., gaseous soil carbon losses from the soil or water increase radiative forcing from CO_2 and CH_4 in the atmosphere. CO_2 extracted from the atmosphere by photosynthesis that results in increased soil carbon storage (peat growth or increase of stable humus) decreases radiative forcing. Incidentally, agriculture also can result in soil carbon gains (e.g., Sun et al., 2020). However, it should be known what the source of this carbon is: local photosynthesis, or extraction from other environments (e.g. peat cutting, sludge, fodder production), with due accounting of the greenhouse gas emissions resulting from that extraction. However, in the case of peat soils, this needs to overcome any oxidation losses of peat, which is unlikely.

The scale of the analysis is also important here. With greenhouse gas emission reporting on a national scale, agricultural emissions like CH_4 from emissions from cattle are reported separately from land use emissions. Including these emissions in those resulting from land use change (LULUCF reporting) on a national scale would result in double counting. However, on the scale of a particular project, also the changes in farm emissions do matter for judging the potential climate effects of the project.

Third, the metrics also differ with respect to what is included in the climate effect calculation, as shown by SGWP/SGCP, which focusses on ecosystem change only.

The methods for climate effect calculation have different outcomes and measurement units when the effects of land use changes are considered. Nevertheless, GWP, SGWP/SGCP and radiative modelling show broadly comparable results for the scenarios considered above. These approaches show that (given the caveats discussed above):

- Reversed drainage decreases the total greenhouse gas emission with respect to Baseline;
- Conversion to natural wetland has the strongest effect on reduction of greenhouse gas emission of all scenarios at a time scale > 20 years (at a shorter time scale, SGWP/SGCP

suggests more effectiveness for Reversed drainage). However, the uncertainty in natural wetland emissions is large, and this uncertainty is exacerbated by potential changes induced by vegetation succession and climate change.

- Paludiculture likely decreases greenhouse gas emission, but the effectiveness depends on the life cycle of the products and the effect of fertilization on the amount of CH_4 and related N_2O emission.

The GWP* deviates by marking all wetland and paludiculture scenarios as cooling, because of a less strong effect of an increase in CH_4 in this metric. Again, the Wetland scenario results in the strongest reduction of warming. This suggests that the GWP* approach is over-optimistic in its weighing of CH_4 emission. Moreover, the climate effect of the CH_4 emissions from cattle could, by definition, not included the Baseline scenario since GWP* requires a stepwise change in emissions, which is not included for Baseline.

Meinshausen and Nicholls (2022) criticized the GWP* approach, for climatic and policy reasons. Their criticism on the climate warming aspect holds that including a baseline CH_4 emission of 20 years in their model may result in a negative contribution of CH_4 to radiative forcing. This is caused by factoring the decreasing warming effect of past CH_4 emissions into the warming effect of future emissions. However, any cooling effect of CH_4 is physically unjustified, since every amount of CH_4 added to the atmosphere will contribute to climate warming during its lifetime in the atmosphere. As such, Meinshausen and Nicholls (2022) consider GWP* as a metric that is biased, when they state that “*GWP* however is not a ‘neutral’ metric as it weighs emissions differently depending on what the emission history of the country, project or facility has been*”, adding perverse incentives to using it. Another point of criticism is, that it is not possible to include variability and uncertainty of emissions in a meaningful way in GWP*.

The SGWP/SGCP is technically the strictest approach. The paper of Neubauer & Megonigal (2015) considers only uptake of greenhouse gases by ecosystems resulting in an immediate decrease of the atmospheric greenhouse gas concentration, but appears to exclude avoided emissions, such as occur in Typha Life Cycle scenario.

For evaluating the effect of land use changes, the radiative modelling approach of Dommain et al. (2018) and Günther et al. (2020) appears to be the most appropriate. Its main advantage is not exactness on calculating climate effects, but its versatility. It does not rely on assumed pulse emissions or stability of emissions over time. It allows to include emission changes due to transient effects, agricultural system changes, ecosystem succession and climate change, which may be expected to influence emissions within policy time horizons. It is therefore better suited to rigorous uncertainty analysis, including coupling to model experiments.

Table 2. Assessment of applicability of the metric / models for climatic effect evaluation of NOBV land use measures.

Metric or model	**Ease of use, transparancy**	**Climatic forcing agreement**	**Ecosystem flexibility**	**Temporal flexibility**	**Policy relevance**
GWP	++	+	++	-	++
GWP*	+/-	+/-	++	-	--
SGWP/SGCP	+	+	-	-	-
Radiative forcing modelling (RFM)	-	++	++	++	+

In Table 2 an ordinal scale assessment of the applicability of the four metrics/models of the climatic effect evaluation is given. GWP scores best on the criterium of ease of use and transparency since it is well established and does not require modelling. Radiative forcing modelling (RFM) requires the use of model code and may be somewhat less transparent for a larger public, although this easily can be overcome; the code is publicly available and easy to understand and operate. GWP* has an extra data requirement with respect to GWP and SGWP/SGCP: stable baseline data, which is often not available. As shown above, the climate forcing agreement is good and converges to similar conclusions for GWP, SGWP/SGCP and

RFM. Although it is claimed that GWP* approaches the climate effect better than GWP (Lynch et al., 2020), the objections of Meinshausen and Nicholls (2022) against the potential inclusion of an artificial cooling effect of CH_4 emissions are a serious drawback. SGWP/SGCP is less flexible with respect to agricultural systems than the other approaches.

The single number metrics (GWP, SGWP/SGCP, GWP*) are not flexible with respect to including temporal variations and uncertainty and have fixed time horizons. It is recommended to calculate these metrics on both short (20 years) and long (100 years) time horizons. As shown above, beneficial climate effects on longer time scales may be missed by considering a short time scale only. RFM shows more detail in the temporal evolution of the climate effect and can handle temporal variability.

The policy relevance of GWP is high, since it is still the recommended policy instrument to judge the effect of climate mitigation measures; other metrics and models may result in sometimes major re-evaluation of past climate policy (for GWP*, see Meinshausen and Nicholls, 2022). Because of its unbiased and flexible evaluation, RFM should be considered as a useful additional instrument to evaluate climate change mitigation policy, in particular when longer time scales than policy horizons of a few decennia need to be considered.

5 Conclusions

GWP remains relevant, because of its climate policy relevance. However, the time horizons for which it is evaluated are rather arbitrary. It is recommended that GWP values are calculated on the 20 to 100 year’s time horizon at least. This represents the presence of short and long-term effects of land use change better. The SGWP/SGCP are designed for natural ecosystem change, not for agricultural systems with harvest. Rigidity holds also for the GWP* approach because of its adherence to stepwise changes and the assumed stable baseline. Moreover, GWP* requires more data and is a biased metric that tends to underestimate the effect of CH_4.

Radiative forcing modelling is a very useful and relatively easy to use additional instrument, that allows to evaluate the effects of climate mitigation over a flexible time scale, showing short term and long evolution of climate effects and allowing uncertainty analysis. Transparency and ease of use could be improved.

As the examples above have shown, climate change, water management and nature management will influence future greenhouse gas emission from peat soils. It is necessary to include uncertainty analysis on future emissions, by process modelling of emissions under future climate and management scenarios, and by extending measurement time series. Radiative forcing modelling is than an excellent instrument to assess the climate effect of these uncertainties.

Besides the choice of metrics and models, a careful consideration of all greenhouse gas balance elements to be included in climate effect evaluation is necessary. If possible, this should include life cycle analysis of agricultural products; this is shown by the inclusion of life cycle analysis in the Typha paludiculture scenario above. The climate effect of wetland rewilding schemes is shown to vary strongly due to large variability of measured emissions, and is very sensitive to future climate change, water management and vegetation management; investment on data collection from a wider range of ecosystems is necessary for a better understanding of the climate effect of wetland restoration in the Netherlands.

All metrics indicate that, given the data used here, all rewetting options result on a 100-year time scale in a reduction of greenhouse gas emission relative to the baseline of unmitigated peat oxidation, although for high CH_4 emitting paludiculture it may take some ten years’ time. However, data collection and analysis is still ongoing and the input data for the example calculations are subject to considerable uncertainty.

6 Acknowledgements

This study was part of the Netherlands Research Programme on Greenhouse Gas Dynamics of Peatlands and Organic Soils (NOBV), which was launched in 2019 by the Dutch ministry of Agriculture, Nature management and Food quality (LNV) as part of the Climate Agreement. Its objective is to research the effectiveness of measures in peatland areas and to be able to better predict emission levels. The effect on subsidence is also researched. The programme is directed by the Foundation for Applied Water Research (STOWA). The research is conducted by Wageningen University (WU), Wageningen Environmental Research (WENR), Vrije Universiteit Amsterdam (VU), Utrecht University (UU), Radboud University, Deltares research institute.

Prof. dr. ir. Sander Houweling, Pui Mee Chan, Frouke Hoogland and Anne Marieke Motelica-Wagenaar are thanked for their constructive comments on this article.

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