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To cite this article: Janne Rinne *et al* 2025 *Environ. Res. Lett.* **20** 064033

IOP Publishing Environ. Res. Lett. 20 (2025) 064033 https://doi.org/10.1088/1748-9326/add607

ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

RECEIVED
28 November 2024

REVISED
2 April 2025

ACCEPTED FOR PUBLICATION
8 May 2025

PUBLISHED
22 May 2025

LETTER

A practical metric for estimating the current climate forcing of natural mires

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Keywords: peat, wetland, climate, methane, carbon

Supplementary material for this article is available online

Abstract

Commensuration of the radiative effects of different greenhouse gases (GHGs) is crucial for understanding the effects of land cover and ecosystem changes on the global climate. However, none of the current commensuration approaches are suitable for addressing the current climatic effect of mire ecosystems as compared to the situation in which such mires would not exist. The mire ecosystems have accumulated carbon for millennia, creating a negative perturbation to the atmospheric carbon dioxide content, but at the same time they emit methane into the atmosphere. Thus, the functioning of mires involves GHG fluxes with opposing effects on Earth's radiative balance. Here, based on a simple radiative forcing (RF) model, we propose a new metric for commensuration of the effects of accumulated carbon and methane emission (ACME) on Earth's energy balance. This ACME approach is applicable to natural mires with a significant part of their carbon accumulated more than 1000 years ago and requires relatively few input data. We demonstrate the feasibility of the ACME approach by applying it to a set of northern mires. The ACME-based RF estimate indicates that these mires have a cooling effect on the current climate, contrary to what a global warming potential-based calculation suggests, since the climatic effect is dominated by the sustained carbon accumulation. By applying the new metric with varying estimates of the total carbon storage and methane emission of northern mires, we estimate the current RF of these mires to range from −0.49 to −0.26 W m^{-2}.

1. Introduction

By sequestering atmospheric carbon dioxide (CO_2), mire ecosystems have accumulated vast amounts of carbon (C) over several millennia, thus naturally reducing the atmospheric CO_2 content. For example, northern (>45° N) mires contain 250–400 Pg of C (Turunen *et al* 2002). At the same time, these ecosystems act as significant sources of methane (CH_4) into the atmosphere, with current emission of 31–38 Tg(CH_4) yr^{-1} (Peltola *et al* 2019). The ecosystem–atmosphere exchange of these two greenhouse gases (GHGs) has therefore created climate forcing components of opposing directions, CO_2 uptake cooling and CH_4 emission warming the global climate (e.g. Whiting and Chanton 2001, Frolking *et al* 2006).

The atmospheric concentration dynamics resulting from sustained surface fluxes follow very different trajectories for CO_2 and CH_4. For CH_4, with its atmospheric lifetime of about 10 years, a sustained emission will in a few decades create a steady state of a positive but constant concentration perturbation, where the sinks, mainly atmospheric oxidation by hydroxyl radical, are balancing the emission (Frolking *et al* 2006). For CO_2, however, no steady state is established, and a sustained ecosystem sink generates an ever-increasing negative concentration perturbation (Frolking *et al* 2006). This is due to the very long response times of some of the processes equilibrating a perturbance to the atmospheric CO_2 concentration (Joos *et al* 2013). On the other hand, CH_4 has a higher radiative efficiency than CO_2, which means that a CH_4 molecule added to the atmosphere will induce a greater warming effect than an additional CO_2 molecule (Shine *et al* 1990).

While the actual effect of GHGs on climate can be simulated with comprehensive, process-based Earth system models, various simplified approaches have been developed for comparing the climate effects of different GHGs (Fuglestvedt *et al* 2003, Balcombe *et al* 2018, Brandão *et al* 2024). This can be accomplished via a metric that accounts for the different lifetimes and radiative efficiencies of GHGs, typically calculated with a parameterized radiative forcing (RF) model. These models can be used to dynamically calculate the RF due to GHG fluxes, negative or positive, of different ecosystems over a period ranging, for example, from a single forest rotation period (Lohila *et al* 2010) to the whole Holocene (Mathijssen *et al* 2014, 2017, 2022). In applications of this kind, the calculation of RF dynamics requires a reconstruction of the GHG flux history or a scenario for future fluxes.

The modeled RF can be processed into the global warming potential (GWP) that provides conversion to a unit of CO_2 equivalent (CO_2-eq), which is the most commonly used metric for commensuration[4] of climatic effects of different GHGs (Shine *et al* 1990, Fuglestvedt *et al* 2003). The practical usage of GWPs avoids an explicit calculation of RF, as GWP represents a constant equivalence factor between a non-CO_2 GHG and CO_2. This coefficient is obtained by integrating the RF following a pulse emission of the GHG in question, typically over 20, 100 or 500 years, and relating this to the integrated RF of a similar mass pulse of CO_2 (Shine *et al* 1990). The GWP approach is most appropriate for expressing anthropogenic emissions in commensurate units, in which case an annual emission, for example, can be well expressed as an individual, short-term pulse. However, GWPs continue to be used for the sustained GHG fluxes of natural ecosystems as well (e.g. Nykänen *et al* 1995, Johansson *et al* 2006, Rinne *et al* 2007, Hugelius *et al* 2023, Virkkala *et al* 2024) despite the justified criticism against this (Frolking *et al* 2006, Neubauer and Megonigal 2015).

As an alternative to the GWP, Neubauer and Megonigal (2015, 2019) recommended the so-called sustained global warming potential (SGWP), originally called the step-change GWP (e.g. Johnson and Derwent 1996), to be preferred if the GHG exchange should be considered a continuous process rather than a short-term event. Obviously, this is the case with natural ecosystems. Similarly to the GWP, the SGWP refers to a single number per GHG and time horizon. However, it is important to note that also any SGWP-based conversion to CO_2-eq implicitly or explicitly refers to a reference state, be it the GHG exchange before a land use or land cover change, or a nominal zero GHG exchange. Hence, such calculation corresponds to the climatic effect of a constant step change in GHG flux rather than that of an actual long-term GHG flux, whether constant or variable, as such. Similarly to the GWP-based approach, the SGWP has been used to answer questions for which it is not fully applicable for (e.g. Yuan *et al* 2021, Virkkala *et al* 2024). Another alternative to the GWP is its modification known as the GWP* (Allen *et al* 2018, Lynch *et al* 2020), in which the cumulative CO_2-eq exchange, calculated from CO_2 and CH_4 exchange with a 20 year time horizon, is used to quantify the climatic effect of the changes in these GHG fluxes. However, this approach requires data or assumptions on the temporal trajectories of the exchange of these GHGs.

In conclusion, neither the GWP- nor the SGWP-based conversion to CO_2-eq adequately represents the actual flux dynamics and related climate forcing in the case of sustained GHG exchange of natural ecosystems. On the other hand, the use of GWP* requires long-term trajectories for GHG fluxes, which are not often readily available, and explicit calculation of RF additionally depends on modeling resources. Hence, our aim here is to present a simple metric for quantifying the current climatic effect that can be justifiably attributed to the past and present GHG exchange of natural mire ecosystems. Our approach is based on the important notion that these ecosystems have accumulated carbon for millennia, which should be accounted for when assessing their climatic effects. It has been suggested that the current RF of natural mires depends mainly on the accumulated C storage and the current CH_4 emission rate and thus could be quantified with these parameters with some information on peat initiation date (Frolking *et al* 2006, Mathijssen *et al* 2022). As some cryoturbated permafrost peatlands have been observed to emit nitrous oxide (N_2O, Repo *et al* 2009) we supplement the new metric with this GHG for completeness' sake.

2. RF due to atmospheric GHG perturbations

The RF due to a perturbation to the atmospheric mixing ratio of a well-mixed GHG, denoted by χ, can be expressed as

$$\Delta RF_{\chi} = \varepsilon_{\chi} \Delta c_{\chi}\,, \tag{1}$$

where ε_{χ} is the radiative efficiency and Δc_{χ} the mixing ratio change of χ (Shine *et al* 1990). Assuming

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[4] Commensuration is defined as the comparison of different entities according to a common metric (Espeland and Stevens 1998).

perfect mixing, c_χ is related to the atmospheric mass of χ, m_χ, by $c_\chi = (M_a/\mu M_\chi) m_\chi$, where M_a is the mean molar mass of air, μ is the total mass of the atmosphere and M_χ is the molar mass of χ. We derived the radiative efficiencies from the RF parameterization of Meinshausen *et al* (2020) as $\varepsilon_\chi = \partial RF_\chi / \partial c_\chi$ at a fixed reference c_χ of 420 ppm, 1920 ppb and 340 ppb for $\chi = \mathrm{CO_2}$, $\mathrm{CH_4}$ and $\mathrm{N_2O}$, respectively. For details, see Supplement I.

The dynamics of m_χ associated with the mass flux F_χ to the atmosphere can be modeled as

$$m_\chi(t) = m_\chi(0) R_\chi(t) + \int_0^t F_\chi(s) R_\chi(t-s)\,\mathrm{d}s, t > 0 \tag{2}$$

where t is time and R_χ the atmospheric impulse–response function of χ (Oeschger and Heimann 1983, Enting 2007). The impulse-response functions of GHGs can be described by a series of exponential functions. For $\mathrm{CH_4}$ and $\mathrm{N_2O}$, we adopted first-order decay with atmospheric lifetimes of $\tau_{\mathrm{CH4}} = 11.8$ yr and $\tau_{\mathrm{N2O}} = 109$ yr (Forster *et al* 2021). For $\mathrm{CO_2}$, the dynamics are more complex as there are processes acting in widely differing time scales. Thus, we modeled the atmospheric $\mathrm{CO_2}$ mass, m_{CO2}, affected by the net atmosphere–ecosystem $\mathrm{CO_2}$ flux F_{CO2}, with the following impulse–response formulation:

$$\begin{aligned} m_{\mathrm{CO2},i}(t) &= m_{\mathrm{CO2},i}(0)\,\mathrm{e}^{-t/\tau_{\mathrm{CO2},i}} \\ &\quad + \int_0^t \alpha_i F_{\mathrm{CO2}}(s)\,\mathrm{e}^{-(t-s)/\tau_{\mathrm{CO2},i}}\mathrm{d}s, \\ &\quad i = 0,\ldots,n \end{aligned} \tag{3}$$

$$m_{\mathrm{CO2}}(t) = \sum_{i=0}^{n} m_{\mathrm{CO2},i}(t). \tag{4}$$

Which shows that the total $\mathrm{CO_2}$ mass is divided into $n+1$ compartments, each carrying a mass of $m_{\mathrm{CO2},i}$. One of these compartments has a very long perturbation time scale ($\tau_{\mathrm{CO2},0} = \infty$), thus resulting in a permanent change, while in the others an atmospheric mass pulse decays with a characteristic, finite time scale ($\tau_{\mathrm{CO2},i}, i = 1,\ldots,n$). The $\mathrm{CO_2}$ flux is divided into these conceptual reservoirs according to the fractions α_i. Here, $n = 3$, and we parameterized the model according to Joos *et al* (2013); for further details, see supplement I.

Equation (2) can be numerically integrated in time, starting from an arbitrary initial mass and assuming any temporal flux trajectory. Figure 1 shows examples for hypothetical flux trajectories, for which it was assumed that F_{CO2} corresponds to the carbon accumulation rate (CAR) of the mire and $F_{\mathrm{CH4}} = 0.2 \times \mathrm{CAR}$ in terms of C (e.g. Rinne *et al* 2018); for further examples, see supplement II. The model results for these flux scenarios, extending well beyond the range of realistic cases, present a robust picture of the climate effect of the $\mathrm{CO_2}$ exchange of a mire ecosystem: the perturbation to the current atmospheric $\mathrm{CO_2}$ concentration depends mostly on the total amount of C accumulated during the history of the mire and is largely insensitive to any variations in the CAR trajectory followed more than about 1000 years ago. This shows that the radiative effect of the carbon exchange of a mire ecosystem can be estimated from its total carbon storage, as earlier suggested by Frolking *et al* (2006) and Mathijssen *et al* (2022).

In addition to numerical simulation, we showed analytically that, with a set of assumptions likely to be valid for many natural mire systems and consistent with the data availability in practice, the current RF due to the development and functioning of a mire can be expressed to a close approximation by its total C storage and recent net fluxes of $\mathrm{CO_2}$ and $\mathrm{CH_4}$; see supplement I for a full mathematical derivation. The specific CAR trajectory before about 1000 years ago has no significant effect on the current RF. Furthermore, this RF does not depend on the more recent CAR changes if these changes are modest. In the case of constant CAR in recent years, we can express the atmospheric perturbation to $\mathrm{CO_2}$ mass simply as:

$$\Delta m_{\mathrm{CO2}} \approx -\alpha_0 S_{\mathrm{C}} + \beta F_{\mathrm{CO2}} \tag{5}$$

where S_{C} is the present areal mass density (kg m^{-2}) or the total mass (kg) of accumulated C, or C storage, in the ecosystem, and $\beta = \sum_{i=1}^{3} \alpha_i \tau_i \approx 99.9$ yr. Here, the βF_{CO2} term represents the transient contribution of C fluxes related to CAR during the last $\sim$1000 yr; this term is generally small compared to the storage term (supplement I).

In contrast to $\mathrm{CO_2}$, the RF due to the $\mathrm{CH_4}$ emission of a mire is independent of the total $\mathrm{CH_4}$ balance since peat initiation and only depends on the flux during the past few decades (figure 1). This is due to the short chemical lifetime of $\mathrm{CH_4}$ in the atmosphere, which prevents a long-term or an accumulative concentration perturbation, as is the case with $\mathrm{CO_2}$. The same applies to $\mathrm{N_2O}$. Assuming constant $\mathrm{CH_4}$ and $\mathrm{N_2O}$ flux for a period of multiple times their respective lifetimes, we obtain a steady-state atmospheric perturbation:

$$\Delta m_\chi = \tau_\chi F_\chi,\ \chi = CH_4, N_2O. \tag{6}$$

As long as peat accumulation has initiated at least 1000 years ago, the present-day RF is insensitive to the initiation date (figure 1). Even though the peat age does not directly affect the current RF, some data or assumptions on the age distribution of the peat layers are needed, as large recent changes in CAR

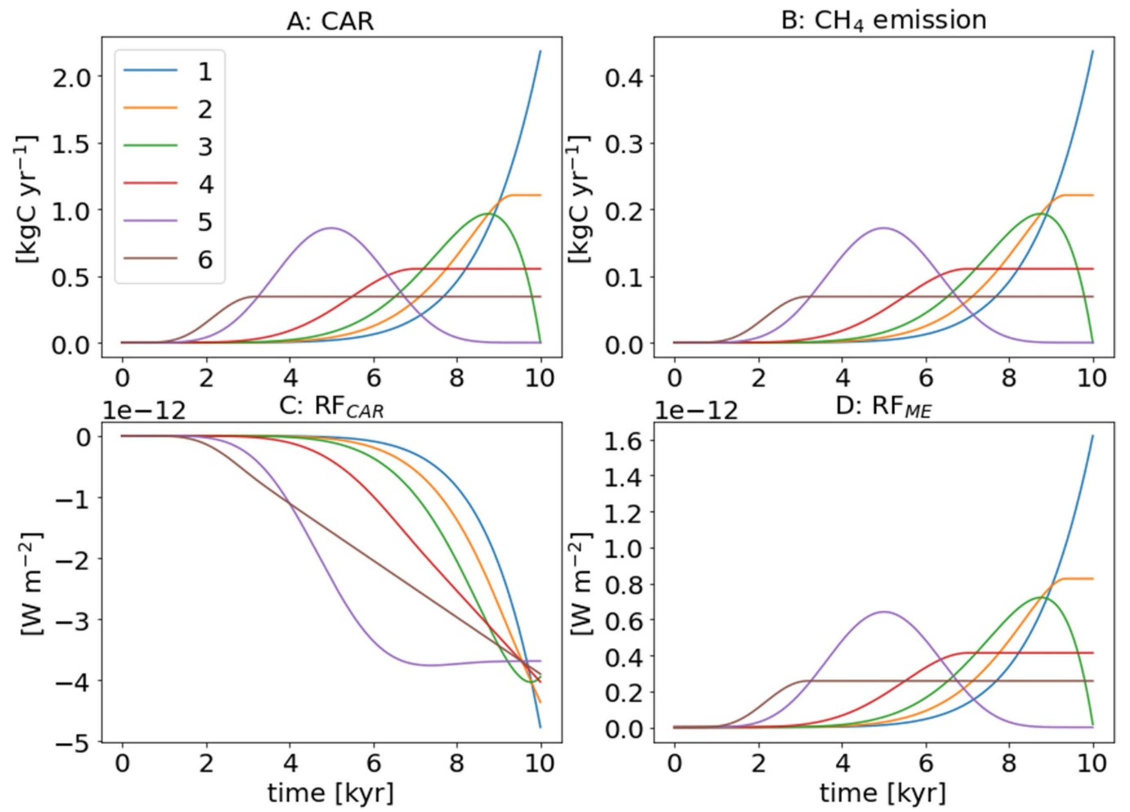

Figure 1. Radiative forcing created by C accumulation (mostly CO_2 exchange) and methane emission of a mire ecosystem. A: A selection of hypothetical CAR trajectories with the same total accumulated carbon over 10 000 years. B: CH_4 emission rates per assuming methane emission is 20% of CAR. C: RF caused by CAR. D: RF caused by CH_4 emission. Constant radiative efficiencies (Table SI.1) and perturbation time scales (table SI.2) were assumed.

can have a considerable transient effect on RF. These changes cannot be reduced to the total C storage but would need to be treated separately. Mostly, however, the differences in the current RF resulting from even recent CAR variations are relatively minor for any mire with a deep peat layer (supplement I).

3. Accumulated carbon and methane emission (ACME) approach for RF

Based on the rationale developed above, we conclude that the current climate impact of a mire ecosystem, expressed in terms of RF, can be justifiably approximated with data on the total C storage of the ecosystem and its CH_4 emission during the past 40 years. Thus, we propose a new climate metric, ACME, which relates the C storage and CH_4 fluxes to the current RF via simple coefficients akin to GWP and SGWP (equation (7), table 1). Also, N_2O emission and recent C exchange (the βF_{CO2} term in equation (5) can be included in ACME.

The RF of an ecosystem, according to the ACME approach, is defined as

$$\mathrm{RF_{ACME}} = -\mathrm{RFC_S} \times S_C + \mathrm{RFC_{CH4}} \times F_{CH4} + \mathrm{RFC_{CO2}} \times F_{CO2} + \mathrm{RFC_{N2O}} \times F_{N2O} \quad (7)$$

Table 1. Radiative forcing coefficients (RFC) for conversion of the densities of ecosystem C storage and CH_4, CO_2 and N_2O fluxes to ACME radiative forcing.

	RFC
C storage	1.39×10^{-15} W m^{-2}/(kg C m^{-2})
CH_4 flux	2.27×10^{-12} W m^{-2}/(kg CH_4 m^{-2} yr^{-1})
Net CO_2 flux	1.74×10^{-13} W m^{-2}/(kg CO_2 m^{-2} yr^{-1})
N_2O flux	3.90×10^{-11} W m^{-2}/(kg N_2O m^{-2} yr^{-1})

where $\mathrm{RFC_S}$ and RFC_χ are the RF coefficients of C storage and GHG fluxes, respectively (table 1). In most cases, it is sufficient to evaluate the two first terms in the right-hand side of equation (7), i.e., the terms that refer to the C storage and CH_4 emission. The two last terms can be added into the calculation if there are data on recent CO_2 and N_2O fluxes. It is important to note that here F_{CO2} corresponds to the net change in the atmospheric CO_2 mass and thus equals CAR, i.e., the balance formed by the atmosphere–ecosystem fluxes of CO_2 and CH_4 and lateral C flow assuming that the C associated with CH_4 and lateral flow is oxidized to CO_2 and rapidly returned to the atmosphere.

The ACME approach can be used to estimate the climatic effect of a mire system with a minimal set of measurement data. The data needed for ACME include at least one peat core from the mire surface to the mineral soil for determination of the C storage density, and the annual CH_4 emission, for example measured by an eddy covariance (EC) system or a number of flux chambers (Bansal *et al* 2023). Additionally, estimates of annual net C and N_2O fluxes can be introduced to elaborate the RF_{ACME} calculation. The flux data should represent the last 40, 1000 and 300 years for CH_4, CO_2 and N_2O, respectively.

4. Discussion

The appropriate method for quantification and commensuration of climatic effects of different GHGs crucially depends on the question to be addressed. The traditional GWP approach (Shine *et al* 1990), in which the mass of a non-CO_2 GHG is simply converted to a unit of CO_2-eq, is suitable for answering the question on the relative climatic effects of different GHGs released in a pulse-like manner. Typically, anthropogenic emissions, where the baseline is 'no emission', can be counted into this category. GWP can also be used for commensuration of short-duration changes in sustained GHG emissions, such as those due to temporary drought in wetland ecosystems (e.g. Rinne *et al* 2020). In this particular case, the net flux expressed as CO_2-eq must be calculated from the difference between the GHG exchange during the drought and a reference period. The SGWP approach, on the other hand, is suitable for commensuration of step-like change in sustained GHG emissions, such as those due to a land use change (Deshmukh *et al* 2023). In this case, the CO_2-eq flux must be calculated from the difference in GHG exchange before and after the land use change.

Neither the GWP nor the SGWP approach relate the climatic effect to any specific time but average the effect over the given time horizon. For example, the climatic effect of a change in GHG exchange of a mire due to a drought year, as analyzed by the GWP approach, may indicate warming during the commonly used 100 year time horizon. However, this masks the actual RF dynamics with an initial cooling effect during the first decades after the drought and a warming effect thereafter (Rinne *et al* 2020). The GWP coefficients also ignore the dependency of radiative efficiency on atmospheric GHG concentrations.

The ACME approach presented here has been designed to answer the question of what the current climatic forcing of an existing mire ecosystem is, compared to the situation that there was no ecosystem with significant C storage or CH_4 emission at the site, such as a tundra-like ecosystem. If the mire has developed replacing an earlier forest ecosystem on mineral soil, we should consider the difference in the C storage and CH_4 emission between these ecosystems. The C storage densities of boreal forest ecosystems on mineral soils (ca. 10 kg m^{-2}; Kauppi *et al* 1997, Ilvesniemi and Liu 2001, Liski *et al* 2006) are typically very small compared to the C storage densities of many boreal mires (100–200 kg m^{-2}, See Table SIII.1). Furthermore, the CH_4 emission from such forest ecosystems is close to zero (Matson *et al* 2009, Gillespie *et al* 2024). Thus, even in this case, the ACME approach can provide a reasonable first approximation of the current climatic effect of the mire ecosystem.

We need to acknowledge some practical challenges in using the ACME metric. First, the CH_4 emission should be estimated for the past 30–40 years, while the longest measurement data series cover 10–20 years in length (e.g. Delwiche *et al* 2021). Thus, we need to extrapolate these data back in time, making assumptions on the temporal representativeness of our data. This is an even more salient point for N_2O, which has a much longer atmospheric lifetime and typically shorter flux time series. Second, the available observations, both peat cores for C storage and flux chamber or EC measurements for CH_4 emission, may not be spatially representative of the whole mire complex. This can be especially important in mires with a significant lateral expansion in recent times. Also, deriving CAR from peat core-based C accumulation may result in overestimation of the recent CAR (Young *et al* 2019).

The lateral expansion of mire ecosystems may complicate the derivation of CAR (e.g. Mathijssen *et al* 2022) and thus also the current RF of the whole mire. However, we can apply the ACME metric as a simpler 'bucket view' that includes only the vertical peat growth, with the GHG exchange and C storage expressed per unit area, as indicated in table 1. A more comprehensive 'whole mire view', which in principle is equally applicable with equation (7), would include considerations of the lateral peat expansion and requires the C balance of the total mire area as input.

Commonly, GHG exchange measurements are conducted within the central area of a mire system, with peat depth and C storage also reported for this area. This is the case especially for EC measurements due to their requirement of large horizontally homogenous surface around the measurement tower. Thus, EC measurements may not represent the full mire area ignoring the spatial flux variability especially in the vicinity of the mire's edges. In the same vein, the C storage reported with EC measurements usually only represents the flux footprint. We can visualize this limited focus as a bucket of peat in the middle of peatland; this bucket represents a specific area (square meter, hectare, etc.) within the flux footprint and has a height of the average peat depth within this area. In this bucket, GHG exchange and C storage are laterally uniform, only the vertical growth of peat is considered. Thus, the accumulated C storage

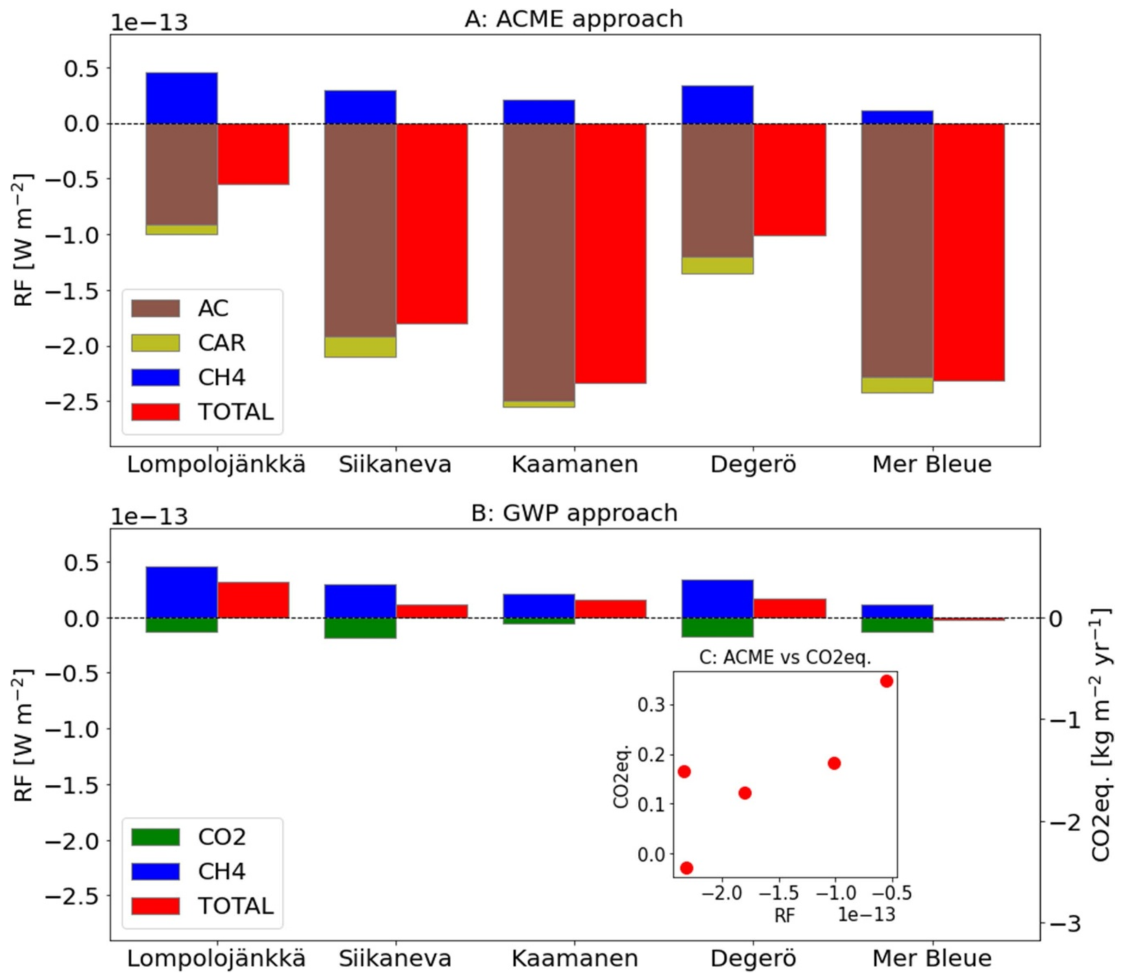

Figure 2. Radiative forcing of five northern mires, per m^2 of mire, calculated with the ACME (A) and GWP approaches (B). The ACME-based RF is calculated by equation (7) using data on accumulated C (AC), current C accumulation rate (CAR) and CH_4 flux (CH4) densities. The CAR is calculated as a difference between CO_2-C uptake, and the sum of CH_4-C emission and lateral C flux. The RF corresponding to the 100-year GWP is calculated using data on the current CO_2 flux (CO2) and CH_4 flux (CH4) densities as detailed in supplement III. The insert C shows the relationship between the ACME-based RF and the GWP-based CO_2-eq flux (Pearson's correlation $r = 0.81$, two tailed $p = 0.097$). The data used in calculation are presented in table SIII.1.

density can be obtained from even a single peat core extending from surface to the mineral soil below the peat layer.

The lateral growth of mire ecosystems can be an important determinant of their recent CAR and thus of their transient climatic effect. The variations of total CAR of mires depend strongly on the topography of the underlying soil, determining the lateral growth rate (Juselius-Rajamäki *et al* 2023). In some mires, lateral growth has increased the total CAR approximately linearly while in others the total CAR has accelerated over time (Mathijssen *et al* 2022). A higher (constant) CAR in recent times can be incorporated into the F_{CO2} term of equation (7), which in principle can be extended by assuming a mathematically feasible lateral growth trajectory; a solution for linear growth of CAR is provided in supplement I.

With the caveats discussed above, we can use the ACME approach to estimate the climatic effect of mires both for individual ecosystems and as aggregated regionally. For an illustrative example, we used the EC measurement data from five northern mires (supplement III Yu *et al* 2002, Roulet *et al* 2007, Nilsson *et al* 2008, Juutinen *et al* 2013, Aurela *et al* 2015, 2002, Larsson *et al* 2016, Rinne *et al* 2018, Heiskanen *et al* 2023, Piilo *et al* 2020, Mathijssen *et al* 2022) to calculate their climatic effect using the ACME approach (figure 2). For comparison, we also show the GHG fluxes expressed as CO_2-eq and the RFs corresponding to this GWP-based conversion. The ACME approach results in negative, i.e. cooling, RF for all the mires, as the effect of long-term C accumulation outweighs the warming effect of the present-day CH_4 emission. In contrast, the GWP approach leads to positive RF, i.e. a warming effect, at almost all sites; this illogicality results from the omission of the RF of sustained C sequestration from the atmosphere. The SGWP approach would suggest an even stronger warming effect as the SGWP coefficient of CH_4 is higher than the GWP of CH_4

(Neubauer and Megonigal 2019). Furthermore, there is no statistically significant correlation between the GWP-based results and those of the ACME approach (figure 2). It is noteworthy how the (S)GWP-based results differ in a qualitative manner from those of the ACME approach.

To demonstrate the robustness of the ACME approach, we calculated RF dynamically using the explicit RF model for Mer Bleue, for which there is high-time-resolution CAR data available from the past 1000 years. The details of the computation are presented in supplement III. Despite the relatively large changes in CAR within the last 500 years at Mer Bleue, the RF resulting from the ACME coefficients (-2.31×10^{-13} W m^{-2}) was very close to that obtained from the full impulse-response model (-2.35×10^{-13} W m^{-2}), which lends confidence to the ACME approach (figure SIII.1).

Furthermore, adopting the estimate of 250–400 Pg C for the C storage in mires north of 45 °N (Turunen *et al* 2002) and the estimate of 31–38 Tg CH_4 yr^{-1} for CH_4 emission from these ecosystems (Peltola *et al* 2019), we obtain an estimate of—0.49 to—0.26 W m^{-2} for the current RF due to the GHG dynamics of these mires. This is very similar to the range of −0.56 to −0.22 W m^{-2} estimated by Frolking and Roulet (2007) for the RF caused by the northern mires. The similarity between the RF estimates arises from the similarities in the methods employed. However, while the modeling of Frolking and Roulet (2007) employed the CAR and methane trajectories over the Holocene, the ACME approach requires only data on the total accumulated carbon and recent methane emission. Both approaches suggest that the formation of northern mires during the Holocene has created a considerable cooling effect compared to a situation without their GHG exchange.

As already discussed above, other metrics are more suitable for commensuration of the changes in GHG exchange caused by recent or planned land use changes. Especially useful approaches for this would be the explicit modeling of RF, and GWP*- or SGWP-based calculations. Finally, it should be noted that preservation of mires and other wetland ecosystems, their restoration, or construction of new wetlands may serve other purposes than climate change mitigation, such as biodiversity protection, flood risk and eutrophication mitigation and recreative purposes. Thus, the cost-benefit analysis of these actions cannot be based solely on their climatic effects.

5. Concluding remarks

We propose here a new ACME metric to estimate the current climatic effect of mire ecosystems, based on their accumulated carbon storage and recent methane emission rate. The metric is suitable for natural mires with a large carbon storage established more than 1000 years ago and requires only peat core data on accumulated carbon and measurements on annual methane emissions. The ACME metric indicates a considerable contemporary cooling effect by the northern mires formed during the Holocene, both for a selection of individual mires and globally. For estimation of the current climatic effect of mire systems, it would be beneficial that research reports, data publications and data repositories on carbon accumulation and GHG exchange of ecosystems, such as the FLUXNET products and ICOS Carbon Portal (Delwiche *et al* 2021, Heiskanen *et al* 2022), would include also the total carbon storage densities from the peat cores collected.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

This research has been partly supported by the ‘GHG Fluxes and Earth System Feedbacks’ (GreenFeedBack) project (No. 101056921), and ‘Upgrading knowledge and solutions to fast-track wetland restoration across Europe’(WetHorizon) project (No. 101056848) from the European Union’s Horizon Europe Framework Programme for Research and Innovation; by the ‘Peatland restoration for GHG emission reduction and carbon sequestration in the Baltic Sea region’ (EU LIFE+ LIFE21-CCM-LV-LIFE PeatCarbon, No. 101074396) funded by the European Union; and by European Commission Just Transition Fund, through Council of Oulu Region (2021/900302/09).

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