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To cite this article: Antti-Ilari Partanen *et al* 2026 *Environ. Res. Lett.* **21** 164008

IOP Publishing Environ. Res. Lett. 21 (2026) 164008 https://doi.org/10.1088/1748-9326/ae9628

ENVIRONMENTAL RESEARCH
LETTERS

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OPEN ACCESS

RECEIVED
6 February 2026

REVISED
15 June 2026

ACCEPTED FOR PUBLICATION
6 August 2026

PUBLISHED
19 August 2026

LETTER

A new approach to determine national greenhouse gas budgets

Antti-Ilari Partanen[1,*], Tommi Ekholm[1], Jyri Seppälä[2], Sally Weaver[3], Taru Palosuo[4], Giacomo Grassi[5], Chris Smith[6], Kati Kulovesi[7], Hannele Laine[1,8] and Markku Ollikainen[9]

1 Finnish Meteorological Institute, Climate system research, Helsinki, Finland
2 Finnish Environment Institute, Helsinki, Finland
3 Ministry of environment, Helsinki, Finland
4 Natural Resources Institute Finland (Luke), Helsinki, Finland
5 European Commission, Joint Research Centre (JRC), Ispra, Italy
6 Energy, Climate and Environment Program, International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria
7 Center for Climate Change, Energy and Environmental Law at UEF Law School, University of Eastern Finland, Joensuu, Finland
8 Now at: ICOS ERIC, Helsinki, Finland
9 Department of Economics and Management, University of Helsinki, Helsinki, Finland
* Author to whom any correspondence should be addressed.

E-mail: antti-ilari.partanen@fmi.fi

Keywords: emission targets, 1.5° C temperature goal, LULUCF indirect effects, allowable warming contribution, simple climate model, CO_2-warming-equivalent, non-CO_2 greenhouse gases

Supplementary material for this article is available online

Abstract

We propose a new approach to determine national greenhouse gas (GHG) budgets that are collectively consistent with the 1.5° C goal of the Paris Agreement and compatible with the accounting method of national GHG inventories. Our approach is designed to bridge global mitigation assessments and national GHG inventory accounting, enabling fair and transparent Nationally Determined Contributions (NDCs) aligned with a given temperature goal. It is flexible, allowing the use of different equity principles and timeframes. GHG budgets are based on a fair share of the allowable warming contributions of GHG emissions. The approach translates the CO_2-warming-equivalent GHG budget to be compatible with national GHG inventories by applying adjustment terms for non-CO_2 GHG emissions and anthropogenic emissions from land use, land-use change, and the forestry (LULUCF) sector. The adjustment term for non-CO_2 GHGs equals the bias introduced to estimate CO_2-warming-equivalent emissions using Global Warming Potentials. The adjustment term for emissions in the LULUCF sector equals the projected indirect effects on managed lands due to climate change and CO_2 fertilization. These adjustments can be made either at the global or national level, leading to different national GHG budgets, depending on the country's mix of non-CO_2 GHG emissions and projected indirect effects. We demonstrate this by showing that Finland's GHG budget is much larger if the adjustments are made at the global level compared to the national level, resulting from high non-CO_2 GHG emissions and indirect effects. Nationally adjusted GHG budgets are consistent with countries' fair share of warming contributions, but GHG budgets with global-level adjustments are less sensitive to modeling uncertainty in indirect effects and scenario uncertainty of national non-CO_2 GHG emissions. Our approach helps improve the Global Stocktake of NDCs and assess the long-term climate strategies of the signatory countries of the Paris Agreement.

1. Introduction

Designing policies that keep global warming below the 1.5° C or 2° C temperature targets of the Paris Agreement requires quantification of the required reductions in greenhouse gas (GHG) emissions. While the Paris Agreement leaves discretion for its parties to define their Nationally Determined Contributions (NDCs) relative to global mitigation goals, the International Court of Justice recently affirmed that each party must make an adequate contribution to the 1.5° C temperature goal of the Paris Agreement (ICJ 2025, paras. 224 and 242). The UNFCCC requires signatory countries to submit their long-term climate strategies that reflect the requirement that net-zero GHG emissions are achieved at the global level around mid-century.

Assessing the adequacy of NDCs in the Global Stocktake and, especially, the alignment of national climate strategies with net-zero targets highlights the importance of science-based methodologies for quantifying a country's adequate contribution to achieving the collective goals of the Paris Agreement. In principle, a national adequate contribution consistent with limiting warming to a given temperature goal can be estimated, for example, by using an equity principle (van den Berg *et al* 2020) to allocate each country a share of the global remaining carbon budget (Gignac and Matthews 2015, Williges *et al* 2022), a share of GHG emissions from global mitigation pathways (Horup *et al* 2023) or a share of the allowable warming contribution (Li *et al* 2025). However, translating these global assessments to national GHG budgets that can be set and monitored using national GHG inventories is complicated by two challenges: accounting for non-CO_2 GHGs and anthropogenic net emissions from the land use, land-use change, and forestry (LULUCF) sector. We address these challenges and propose a new approach to derive national GHG budgets that are based on a fair share of allowable warming contributions from GHG emissions, are aligned with national GHG inventory accounting, and are collectively consistent with a given temperature goal.

The first challenge with non-CO_2 GHGs is that national GHG inventories aggregate all GHGs into CO_2-equivalents interchangeably with the Global Warming Potential using a 100 yr time horizon, whereas in global mitigation pathways, the warming contributions and lifetimes of each GHG are treated explicitly. The issue with using GWP is that the implied GWP-based CO_2-equivalent emissions do not match their actual projected warming impact (Pierrehumbert 2014). If the GHG emissions in a mitigation pathway consistent with the 1.5° C goal are aggregated using GWP100 and allocated to countries as GHG budgets (Horup *et al* 2023), the total warming contribution could differ if the mix and timing of non-CO_2 GHG emissions differ from the original global mitigation pathway (Fuglestvedt *et al* 2000). Separate targets for long- and short-lived GHGs have been proposed to make the warming effects of emission pathways more explicit (Allen *et al* 2022); however they could be more difficult to implement in climate policy than an overall GHG budget.

The second challenge related to anthropogenic net emissions from the LULUCF sector is that they are accounted for differently in global mitigation pathways and national GHG inventories. National GHG inventories follow the Intergovernmental Panel on Climate Change guidelines and use the 'managed-land proxy', where all carbon fluxes on managed land are considered anthropogenic (IPCC 2006, IPCC *et al* 2019). In contrast, many scientific assessments, such as the Global Carbon Project (GCP), define that the anthropogenic LULUCF sector's net CO_2 emissions include only fluxes directly caused by human interventions, such as land-use change, forest harvests and subsequent regrowth (Friedlingstein *et al* 2025). GCP and global mitigation pathways, in general, consider indirect effects, such as CO_2 fertilization and climate change on both managed and unmanaged lands, as natural. This difference in definitions is the main reason behind the large discrepancy in the estimates of LULUCF sector's net CO_2 emissions globally, with the GCP estimate ~7 Gt CO_2 yr^{-1} higher in 2010–2020 than the sum of the national GHG inventories (Grassi *et al* 2023, 2025). If mitigation goals are calculated using the GCP definition, but progress is tracked using national GHG inventories, this discrepancy in definitions leads to an underestimation of the mitigation challenge (Grassi *et al* 2021, Gidden *et al* 2023, Allen *et al* 2025).

While progress has been made in incorporating non-CO_2 GHGs into emission targets, significant challenges remain in defining scientifically robust targets that are compatible with national GHG inventories and practical policy implementation. One widely used approach to guide mitigation efforts is the concept of the remaining carbon budget, which provides an upper limit on cumulative CO_2 emissions (Zickfeld *et al* 2009, Rogelj *et al* 2016, Lamboll *et al* 2023). It takes into account non-CO_2 GHGs (Rogelj and Lamboll 2024) but does not provide explicit limits on their emissions. To include also non-CO_2 GHGs, the European Scientific Advisory Board on Climate Change (ESABCC 2023) formulated a GHG budget for the European Union based on cost-effective scenarios that did not explicitly consider any equity principle or total warming contribution implied by the GHG budget.

Rather than relying on cost-effective approaches, Li *et al* (2025) presented a method for sharing the mitigation burden based on allowable CO_2-equivalent warming contributions between 1850 and 2050. This method can accurately incorporate the non-CO_2 warming contributions by calculating the CO_2-warming-equivalent emissions by dividing the non-CO_2 warming contribution by the Transient Climate Response to Cumulative CO_2 Emissions (TCRE), a near-linear relationship between cumulative CO_2 emissions and CO_2-induced warming (Allen *et al* 2009, Matthews *et al* 2009). While their approach enables the setting and monitoring of science-based national emission targets, our approach goes one step further by translating non-CO_2 GHG emissions to be directly compatible with national GHG inventories.

To address the challenge related to anthropogenic net emissions from the LULUCF sector, estimates of indirect effects on managed lands can be used to adjust mitigation targets either at the global (Grassi et al 2021, Gidden et al 2023, Weber et al 2026) or national level (van Soest et al 2021, ESABCC 2023), thereby improving compatibility with national GHG inventories. None of these studies have examined how the choice of whether to adjust GHG budgets before or after allocating them to individual countries affects the resulting national GHG budgets. Yet, such an analysis is needed to ensure the coherent application of adjustments and avoid compromising the global temperature target.

In this study, we present a novel approach to derive national GHG budgets that are compatible with national GHG inventories with respect to emissions in the LULUCF sector and emissions of non-CO_2 GHGs but are also consistent with science-based targets for emission reductions. We use Finland as an example to demonstrate how the national GHG budget can substantially differ depending on whether the adjustments for non-CO_2 GHGs and indirect effects are done at the global or national level. Finland presents an interesting case study as one of the few countries to adopt a science-informed GHG-neutrality target for 2035 (officially referred to as 'carbon neutrality' despite including all GHGs) based on a fair-share analysis conducted by the Finnish Climate Change Panel (Ollikainen et al 2019).

2. Methods

2.1. Global CO_2-warming-equivalent GHG budget

We first calculated the global CO_2-warming-equivalent GHG budget for 2020–2050, consistent with limiting global warming below 1.5° C (the method could also be applied to for example 2° C temperature target). We chose 2050 as the target year because limiting warming to close to 1.5° C with limited or no overshoot requires net-zero CO_2 emissions around 2050 (IPCC 2022). A fixed time range, as opposed to the more general approach of limiting peak warming, is necessary because the choice of target year affects the conversion of non-CO_2 GHG emissions to CO_2-warming-equivalent contributions. To avoid further warming after the target year, net anthropogenic warming contributions after the target year should also be zero or negative, in addition to keeping below the CO_2-warming-equivalent GHG budget for 2020–2050. This does not prevent individual countries from having positive warming contributions after the target year if they are collectively offset by other countries. Instead of relying on approximate metrics such as GWP, the warming contribution of non-CO_2 GHGs was explicitly calculated and converted to CO_2-warming-equivalent using TCRE. Our method for calculating the GHG budget is based on assessing individual warming contributions, similar to what has been done in quantifying the remaining carbon budgets (Lamboll et al 2023).

Figure 1 presents a schematic of our calculation of the global CO_2-warming-equivalent GHG budget. Warming from 1850–1900 to a given temperature threshold T (solid horizontal blue line) can be expressed as the sum of individual warming contributions (vertical arrows):

$$T = \delta T_{\mathrm{hist}} + \delta T_{CO_2\mathrm{recent}} + \delta T_{\mathrm{GHGfuture}} + \delta T_{\mathrm{other}} + \delta T_{\mathrm{nonCO_2GHGhist}} \quad (1)$$

where δT_{hist} is historical warming from 1850 to 1900 until a recent reference period (2010–2019), $\delta T_{CO_2\mathrm{recent}}$ is warming from recent CO_2 emissions from 2015 to 2019 not accounted for in δT_{hist}, $\delta T_{\mathrm{GHGfuture}}$ is the allowable warming contribution of future GHG emissions in our target period of 2020–2050, $\delta T_{\mathrm{other}}$ is the warming contribution from sources other than GHG emissions (mainly aerosols, but including e.g. changes in albedo due to land-use change) and $\delta T_{\mathrm{nonCO_2GHGhist}}$ is the change (from 2010 to 2019 to 2050) in the warming contribution of historical non-CO_2 GHG emissions emitted before 2020. In this approach, the non-CO_2 warming contribution used in the remaining carbon budget calculations, for example, Lamboll et al (2023), was split into $\delta T_{\mathrm{nonCO_2GHGfuture}}$, $\delta T_{\mathrm{nonCO_2GHGhist}}$, and $\delta T_{\mathrm{other}}$, where $\delta T_{\mathrm{nonCO_2GHGfuture}}$ is the warming contribution of future non-CO_2 GHGs and was combined with the future CO_2 warming contribution to obtain $\delta T_{\mathrm{GHGfuture}}$.

Reorganizing equation (1) and converting the warming contributions to CO_2-warming-equivalent emissions by dividing by TCRE gives the global GHG budget:

$$B_{\mathrm{gl,GHG}} = \frac{T - \delta T_{\mathrm{hist}} - \delta T_{\mathrm{other}} - \delta T_{\mathrm{nonCO_2GHGhist}}}{\mathrm{TCRE}} - E_{\mathrm{recent}}. \quad (2)$$

As our aim was to demonstrate the derivation of a GHG budget only until 2050, we did not include zero-emission commitment (temperature increase after net-zero CO_2 emissions, ZEC) or Earth system feedbacks (ESFs) not covered by TCRE as warming contributions. We made this choice for both simplicity and because evidence suggests that the ZEC may be zero or negative at the 1.5 °C cumulative emissions budget level (MacDougall et al 2020, Lee et al 2021, Sanderson et al 2025, Pelz et al 2025), and the ESFs are poorly quantified in the current models (Matthews et al 2021).

2.2. Adjustments to align with national GHG inventories

To align the CO_2-warming-equivalent global GHG budget presented in equation (2) with the national GHG inventories, we introduced two adjustment terms that account for the indirect effects in the LULUCF sector and the bias introduced by using

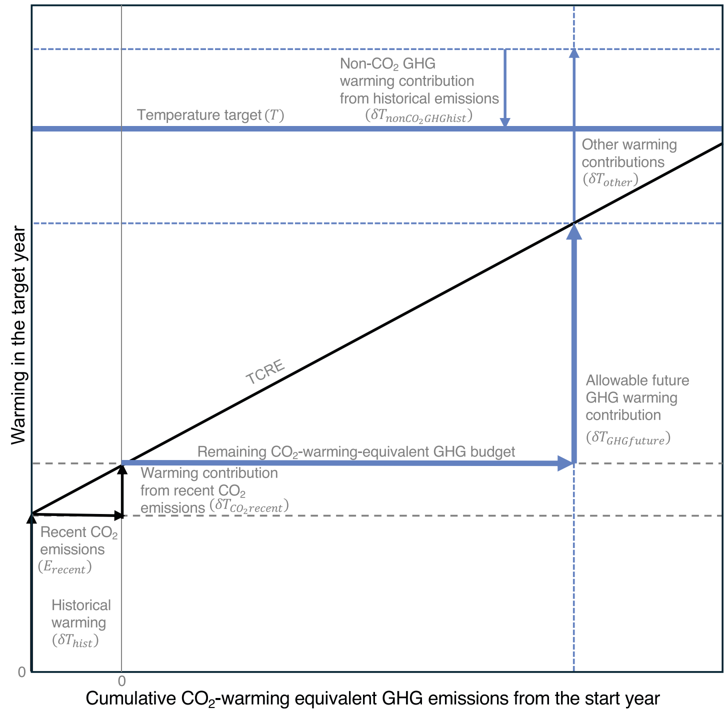

Figure 1. Schematic of deriving the allowable warming contribution of future GHG emissions and related CO_2-warming-equivalent GHG budget for a chosen temperature target, T, and target year. The vertical arrows represent the different warming contributions that sum up to the target temperature increase from the pre-industrial climate (thick blue line in the top part of the figure). The CO_2-warming-equivalent GHG budget (including both CO_2 and non-CO_2 GHGs) is calculated by dividing the allowable future GHG warming contribution by the transient climate response to cumulative CO_2 emissions (TCRE).

GWP100 to aggregate non-CO_2 GHGs. The adjustment term A_{LULUCF} (in equations (4) and (5)) covers the cumulative indirect effects in 2020–2050 in the managed land. Both projected adjustments depend on the global GHG emission scenario, and the LULUCF adjustment also depends on potential changes in managed land extent but not on direct CO_2 emissions from the LULUCF sector (Grassi *et al* 2021). The adjustment term for non-CO_2 GHGs can be calculated as the difference between the cumulative CO_2-equivalent emissions aggregated with GWP100 $(E_{\mathrm{GWPnonCO_2GHG}})$ and the explicit warming contribution of those emissions by 2050 $(\delta T_{\mathrm{nonCO_2GHGfuture}})$ converted to CO_2-warming-equivalent using the TCRE:

$$A_{\mathrm{nonCO_2GHG}} = E_{\mathrm{GWPnonCO_2GHG}} - \frac{\delta T_{\mathrm{nonCO_2GHGfuture}}}{\mathrm{TCRE}}. \quad (3)$$

Adding these adjustment terms to the global GHG budget yields a budget compatible with the accounting of national GHG inventories (with a given non-CO_2 emission scenario and projected indirect effects on managed land):

$$B_{\mathrm{gl,GHG,\,NGHGI}} = \frac{T - \delta T_{\mathrm{hist}} - \delta T_{\mathrm{other}} - \delta T_{\mathrm{nonCO_2GHGhist}}}{\mathrm{TCRE}} - E_{\mathrm{recent}} + A_{\mathrm{LULUCF}} + A_{\mathrm{nonCO_2GHG}}. \quad (4)$$

Figure 2 shows three ways of allocating a national GHG budget from the CO_2-warming-equivalent GHG budget, assuming a fair share f of the global GHG budget based on an equity principle (van den Berg *et al* 2020). First, a fair share of the global GHG budget can be used directly with no adjustments (figure 2(a)). This method ignores inconsistencies in the accounting of national GHG inventories and is used as a reference. Second, adjustments can be made at the global level, and the national GHG budget is simply the fair share of the globally adjusted budget (figure 2(b)). Thus, the adjustment terms for indirect effects and non-CO_2 GHG emissions for each country represent the share f of the global adjustment terms instead of country-specific conditions. Third, the adjustment terms are calculated and applied at the national level after partitioning the global GHG budget (figure 2(c)):

$$B_{\mathrm{nat,GHG,NGHGI}} = f\left(\frac{T - \delta T_{\mathrm{hist}} - \delta T_{\mathrm{other}} - \delta T_{\mathrm{nonCO_2GHGhist}}}{\mathrm{TCRE}} - E_{\mathrm{recent}}\right) + A_{\mathrm{LULUCF,nat}} + A_{\mathrm{nonCO_2GHG,\,nat}}, \quad (5)$$

where $A_{\mathrm{indirect,nat}}$ is the cumulative indirect effects in the managed land of a given country and $A_{\mathrm{nonCO_2GHG,\,nat}}$ is the cumulative national non-CO_2 GHG emissions minus their warming impact converted to CO_2-warming-equivalent using TCRE. National adjustments would make the national GHG budget correspond better to the fair share of

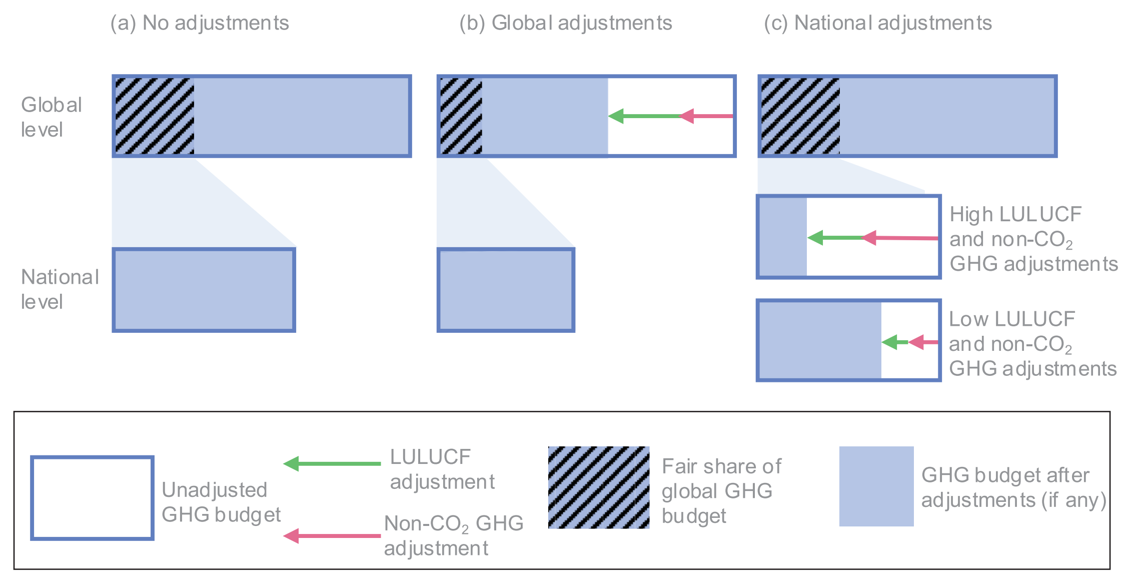

Figure 2. Schematic demonstration of allocating the global GHG budget (1st row) to the national level (2nd row) and adjusting it to be compatible with national GHG inventories. The same unadjusted global CO_2-warming-equivalent GHG budget and its relative share were used in all methods. In (a), no adjustments are made at the global or national level, and the national GHG budget is simply the fair share of the global GHG budget, ignoring any biases introduced by using GWP100 to aggregate non-CO_2 GHG emissions or including indirect effects on the land carbon sinks on managed lands as anthropogenic. In (b), the global GHG budget is adjusted to be compatible with national GHG inventories at the global level before allocating them to individual countries. In (c), the global GHG budget is first allocated to countries and then adjusted based on national-level indirect effects by the bias of using GWP to aggregate the non-CO_2 GHG emissions compared to the explicit modeling of the CO_2-warming-equivalent non-CO_2 GHG emissions. For illustrative purposes, the national adjustments are shown for both high LULUCF and non-CO_2 GHG adjustments, demonstrating that national adjustments can lead to either lower or higher national GHG budgets, depending on the national indirect effects and the magnitude, mix, and timing of non-CO_2 GHG emissions.

the allowable future GHG warming contribution. Figure 2 also demonstrates that the national GHG budget with national adjustments can be lower or higher than the budget with global adjustments, depending on the national non-CO_2 GHG scenario and the indirect effects.

For the global-level adjustment, if an equity principle is applied consistently to derive the fair shares f_i, they sum up to 1, and summing up the national GHG budgets yields the global GHG budget. We did not consider emissions from international shipping or aviation (bunker fuels), which led to overestimating the national GHG budgets. They could be incorporated into global adjustments by decreasing global GHG budget by projected bunker fuel emissions (Weber *et al* 2026) or potentially also to national adjustments if bunker fuel emissions are attributed to individual countries (Selin *et al* 2021).

The national-level adjustment terms for the indirect effects sum up to the global adjustment term. To account for potential non-linearities in summing the national non-CO_2 GHG warming contributions, we used downscaled projections of SSP scenarios (Gütschow *et al* 2021) to calculate the national non-CO_2 GHG warming contribution for 116 countries and the rest of the world. We then scaled the national warming contributions so that their sum matched the global non-CO_2 GHG warming contribution. With this normalization, also the national non-CO_2 adjustments sum to the global total. The detailed methodology and sensitivity to the number of countries are presented in Text S1.

2.3. Data and methodology for a demonstration case

To demonstrate the calculation of the fair national GHG budget, adjusted for the indirect effect in the LULUCF sector and for the warming contribution of non-CO_2 GHGs, we present a case study of Finland, which has historically had a notable LULUCF sink according to the national GHG inventory.

We estimated the indirect effects in the LULUCF sector at the global and national levels using data collected by Grassi *et al* (2021), Grassi *et al* (2023). Grassi *et al* (2021) applied IMAGE/LPJmL to estimate future indirect effects in the SSP2-1.9 scenario by running the model with and without climate change. Because these data were from a single model, which does not provide uncertainty quantification and can be more biased than the multi-model mean, we adjusted the time series of indirect effects with a constant so that the mean indirect effect in 2010–2020 matched the multi-model mean from the study by Grassi *et al* (2023). We also assumed a normal distribution for the uncertainty in annual indirect effects with a standard deviation of the mean over 1990–2020 in the multi-model ensemble by Grassi *et al* (2023).

To calculate the non-CO_2 adjustment terms, we used one global and one country-level scenario for Finland. The global scenario SSP1-1.9 (Meinshausen *et al* 2020), harmonized with historical emissions (Gidden *et al* 2018, Smith 2026), is a low-emission scenario roughly consistent with the 1.5° C target of the Paris Agreement and reaching net-zero CO_2 emissions in 2059. Because the aim of our study was to demonstrate a novel principle for deriving national GHG budgets, we did not consider scenario uncertainty or align the global scenario with the premise of keeping global warming below 1.5° C.

To assess the sensitivity of the results to the choice of the global scenario, we also used the indirect effects from SSP2-2.6 and emissions from SSP1-2.6 (see text S2 for details).

For Finland, we used the WAM-CN scenario (figure S1) that was designed to be compatible with Finland's GHG-neutrality goal for 2035: zero net GHG emissions using the emission accounting of national GHG inventories. The scenario was a combination of scenarios for the LULUCF sector (Maanavilja *et al* 2021) and fossil fuels, agriculture, and waste sectors (Lehtilä *et al* 2021). We used data from Finland's national GHG inventory (Statistics Finland 2026) for 2020–2024 and scenario data from 2025 onwards. In this scenario, methane, nitrous oxide, and F-gas emissions are reduced by 27%, 18%, and 94%, respectively, from 2020 to 2050.

To simulate the warming impact of these scenarios, we used the simple climate model FaIR 2.2.4 (Leach *et al* 2021) with a calibration version of 1.6.0 (Smith *et al* 2024, Smith 2026). Using the global and Finnish emission scenarios, we designed a set of FaIR experiments (table 1) to calculate the non-CO_2 adjustment terms needed for the GHG budget in equation (4). The terms were evaluated as differences in surface temperature change from 2010 to 2019 to 2050 between the two runs, as described in table 2.

Table 1. List of experiments using the FaIR model.

Experiment	Description
SSP1-1.9	Historical and SSP1-1.9 scenario (1750–2050).
Non-CO_2-GHG-stop	As SSP1-1.9, but non-CO_2 GHG emissions set to their pre-industrial (1750) anthropogenic levels from 2020 onwards.
No-non-GHG	As SSP1-1.9, but without solar and volcanic forcing and with aerosol-precursor emissions set to pre-industrial anthropogenic levels.
No-non-CO_2-GHG	As SSP1-1.9, but non-CO_2 GHG emissions were set to pre-industrial anthropogenic levels.
CO_2-only	As SSP1-1.9, but all species except CO_2 set to pre-industrial anthropogenic levels.
Non-CO_2-GHG-stop-Fin	As SSP1-1.9, but non-CO_2 GHG emissions from Finland were subtracted from emissions for 2020 to 2050.

Table 2. Calculation of terms for GHG budgets from the FaIR experiments.

Warming contributions	Calculated as difference in surface temperature change from 2010–2019–2050 between runs
$\delta T_{\mathrm{other}}$	SSP1-1.9 and no-non-GHG
$\delta T_{\mathrm{nonCO_2GHGhist}}$	Non-CO_2-GHG-stop and no-non-CO_2-GHG
$\delta T_{\mathrm{nonCO_2GHGfuture}}$	SSP1-1.9 and non-CO_2-GHG-stop
$\delta T_{\mathrm{FinlandnonCO_2GHGfuture}}$	SSP1-1.9 and non-CO_2-GHG-stop-fin
$\delta T_{\mathrm{nonCO_2}}$	SSP1-1.9 and CO_2-only

2.4. Probabilistic assessment of GHG budgets

We calculated the best and probabilistic estimates of the GHG budgets by running FaIR in a probabilistic configuration with 841 ensemble members (Smith *et al* 2024). For the best estimates, we used the mean values of the TCRE, indirect effects (global and national levels), and all terms calculated from the FaIR simulations (table S3).

For the probabilistic assessment, we sampled the indirect effects and TCRE from the fitted normal distributions. The non-CO_2 warming contributions were sampled by randomly selecting one of the 841 ensemble members and evaluating all non-CO_2 warming contributions for the given ensemble member while retaining any covariance between these terms. In total, we sampled 1000 000 realizations of the GHG budgets.

For the baseline fair share of the global GHG budget for Finland, we used the value of 0.235‰, which was used by the Finnish Climate Change Panel to derive the national GHG budget for Finland (Ollikainen *et al* 2019). It is based on the ability-to-pay principle (the ratio of national to global purchasing power-adjusted gross domestic product). To test the sensitivity of the results to the choice of guiding equity principle, we also calculated the GHG budgets using the historical warming contribution since 1990 and per-capita sharing of GHG budgets (Text S3). As the focus of this study is to demonstrate the adjustment of GHG budgets to be compatible with national GHG inventories, we did not evaluate budgets based on other equity principles (Mattoo and Subramanian 2012, van den Berg *et al* 2020, Dooley *et al* 2021, Pelz *et al* 2025).

3. Results

3.1. Adjustment terms

Figure 3 shows the cumulative non-CO_2 GHG emissions globally and in Finland in using GWP100-based and in CO_2-warming-equivalent aggregation. The CO_2-equivalent emissions calculated with GWP100 were only approximately half of the amount quantified through explicit modeling of the warming contribution in 2050. This was expected as GWP100 integrates forcing following emission over a 100 yr time window, much of which falls outside the 2020–2050 time window. This leads GWP100 to increasingly underestimate methane's warming contribution for later years. The best estimates for this adjustment term were −544 Gt CO_2 with a 95% uncertainty range of (−3370, −71) at the global level and −0.436 (−2.90, −0.0272) Gt CO_2 for Finland.

Figure 4 shows the time series of the cumulative indirect effects on managed land at the global level and for Finland for 2020–2050. The LULUCF adjustments for the global level and for Finland correspond to the cumulative indirect effects in 2050 (black arrows in figure 4). The cumulative indirect effects were −151 Gt CO_2 ($\sigma = 55$ Gt CO_2) at the global level and −0.438 Gt CO_2 ($\sigma = 0.532$ Gt CO_2) in Finland. Figure S2 shows the annual indirect effects for the period of 1990–2020 and for SSP2-1.9 based on the original non-adjusted data from Grassi *et al* (2021) for 2020 to 2050 and data adjusted so that the mean indirect effects in 2010–2020 matched the mean of the multi-model data by Grassi *et al* (2023).

Table 3. Best estimates and 95% uncertainty ranges for the GHG budgets for 2020–2050 and adjustment terms at the global and national (Finland) levels. All terms are expressed as Gt CO_2-eq.

	No adjustments	Global adjustments	National adjustments
Global level			
Global GHG budget	936 (285, 4650)	936 (285, 4650)	936 (285, 4650)
Non-CO_2 GHG adjustment at global level		−544 (−3370, −71)	
LULUCF adjustment at global level		−151 (−260, 43)	
Global GHG budget to be shared	936 (285, 4650)	240 (−703, 1730)	936 (285, 4650)
National level			
Finland's fair share of global GHG budget	0.220 (0.067, 1.09)	0.0565 (−0.165, 0.406)	0.220 (0.067, 1.09)
Non-CO_2 GHG adjustment at national level			−0.436 (−2.900, −0.027)
LULUCF adjustment at national level			−0.438 (−1.480, 0.602)
Finland's adjusted GHG budget	0.220 (0.067, 1.09)	0.0565 (−0.165, 0.406)	−0.654 (−2.570, 0.522)

3.2. Global and national GHG budgets

Table 3 shows the calculation of the national GHG budgets for 2020–2050, starting from the global level and then adjusting them either at the global level (before national-level allocation) or at the national level based on the national non-CO_2 GHG scenario and indirect effects to adjust the GHG budget for compatibility with the national GHG inventories. The no-adjustments case is provided for reference and to demonstrate how a simplistic interpretation of GHG budgets without considering the differences in accounting for LULUCF emissions and non-CO_2 GHGs can underestimate mitigation challenges.

The global GHG budget without adjustments was 936 (285, 4650) Gt CO_2-eq, which decreased to 240 (−703, 1730) Gt CO_2-eq after adjustments for non-CO_2 GHGs and the LULUCF sector. Using the ability-to-pay equity measure, Finland would have 0.235‰ of the global GHG budget, leading to a national budget of 0.220 (0.067, 1.09) Gt CO_2-eq without adjustments and 0.0565 (−0.165, 0.406) Gt CO_2-eq with global-level adjustments. With national-level adjustments, the national budget was −0.654 (−2.570, 0.522) Gt CO_2-eq, requiring significant net-negative cumulative GHG emissions to remain within the budget.

Finland's share of global adjustment terms for indirect effects and non-CO_2 GHGs was −0.03 Gt CO_2-eq and −0.128 Gt CO_2-eq, respectively. These adjustments were greater in magnitude when calculated at the national level (−0.438 Gt CO_2-eq for indirect effects and −0.436 Gt CO_2-eq for non-CO_2 GHGs). This means that the indirect effects on managed land in Finland are relatively much stronger than at global average (or specifically, the share *f* of global total), because Finland has a large forest cover relative to its emissions. The national-level non-CO_2 GHG adjustment was larger in magnitude than the share of the global adjustment term because the national non-CO_2 GHG warming contribution was also larger than the share of non-CO_2 GHG warming contribution in the global SSP1-1.9 scenario (figure S3).

The CO_2-warming-equivalent GHG budget and adjustment terms were sensitive to the choice of the global background scenario. With SSP1-2.6 for warming contributions and SSP2-2.6 for indirect effects, global GHG budgets with and without adjustments were larger than in our baseline results. The national non-CO_2 and LULUCF adjustments were stronger in the sensitivity study, leading to a lower national GHG budget despite a larger global

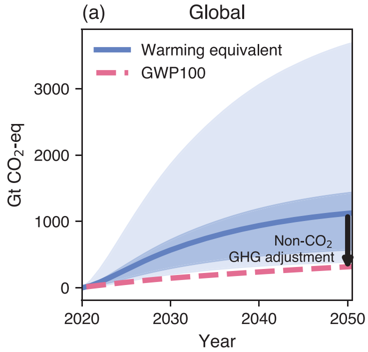

Figure 3. Time evolution of cumulative CO_2-equivalent non-CO_2 GHG emissions using either warming equivalent through explicit modeling and converting the warming contribution to CO_2-equivalent using TCRE or GWP100-based conversions for different GHGs. (a) Global level emissions based on SSP1-1.9 and (b) National level emissions in Finland based on the WAM-CN scenario. The black arrows show the adjustments needed to bring the GHG budget into compatibility with the national GHG inventories and GWP100-based accounting of non-CO_2 GHGs. The shadings show 95% and 66% uncertainty ranges estimates based on warming equivalency.

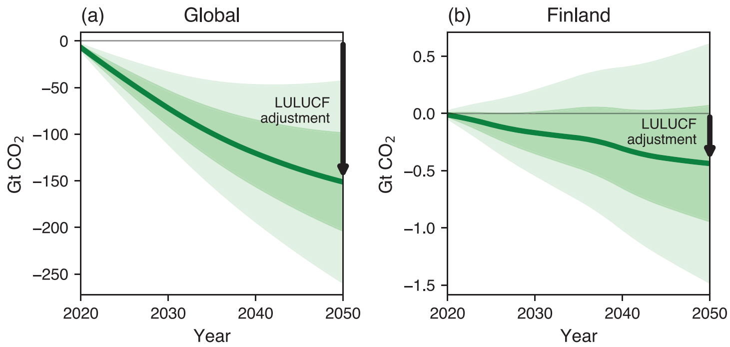

Figure 4. Cumulative Indirect effects on land sinks on managed lands between 2020 and 2050 globally (a) and in Finland (b). The figure shows data for SSP2-1.9 from Grassi et al (2021), which were adjusted so that the mean over 2010–2020 match the multi-model mean from Grassi et al (2023). The shadings show 95% and 66% uncertainty ranges of the indirect effects. The black arrows denote the best estimates for the LULUCF adjustments, which were based on the cumulative indirect effects for the years 2020–2050.

GHG budget. Details are provided in text S2 and table S2.

3.3. Considering per-capita share of GHG budget and historical warming contribution

To complement the analysis based on the ability-to-pay equity principle to calculate the share of the global GHG budget from 2020, we calculated Finland's national GHG budgets by allocating the global GHG budget per capita and optionally considering the historical warming contribution of emissions from 1990 to 2019.

Table 4 shows a comparison of results with either ability-to-pay or per-capita share (0.7 ‰, about three times the ability-to-pay share) and with or without considering the historical warming contribution. For both adjustment levels and equity principles, the earlier start year was associated with a lower GHG budget for 2020–2050. In 1990–2019, Finland's total GHG emissions were 1.24 Gt CO_2-eq (using GWP100), which is larger than any of the calculated GHG budgets for 1990–2050. Thus, considering the historical warming contribution consistently led to negative GHG budgets for 2020–2050.

For GHG budgets with global-level adjustments and 2020 as the start year, the ratio of per-capita and ability-to-pay GHG budgets was, by design, equal to the ratio of these shares. This was also true for the 1990–2050 GHG budgets, but when the historical warming contribution was considered, the ability-to-pay GHG budget for 2020–2050 was about ten times as negative as the per-capita GHG budget. With national-level adjustments and considering the historical warming contribution, the absolute difference between the ability-to-pay and per-capita GHG budgets was the largest at 1.17 Gt CO_2-eq. Thus, the choice of equity principle had the largest effect when historical responsibility was considered, with the absolute difference in national GHG budgets between equity principles being comparable to the effect of applying national-level adjustments over the same period (−1.70 Gt CO_2-eq).

When the historical warming contribution was considered, the adjustment terms were also

Table 4. Best estimates and 95% uncertainty ranges for the national GHG budgets for Finland with different starting years (1990 or 2020), with either ability-to-pay or per-capita share of the global GHG budget and with global or national non-CO_2 GHG and LULUCF adjustments. All GHG budgets are given in Gt CO_2-eq using the accounting of the national GHG inventories. For each GHG budget with a start year of 1990, GHG emissions from 1990 to 2019 depleted it by 1.24 Gt CO_2-eq. GHG budgets for 1990–2050 were evaluated only when the start year was 1990.

Equity principle	Adjustment level	Start year	National GHG budget for 1990–2050	National GHG budget for 2020–2050
Ability-to-pay	Global	2020		0.057 (−0.165, 0.406)
		1990	0.389 (0.179, 1.430)	−0.855 (−1.070, 0.183)
	National	2020		−0.654 (−2.570, 0.522)
		1990	−1.110 (−4.150, 1.140)	−2.350 (−5.390, −0.107)
Per-capita	Global	2020		0.169 (−0.493, 1.210)
		1990	1.160 (0.533, 4.260)	−0.083 (−0.712, 3.010)
	National	2020		−0.218 (−1.570, 1.130)
		1990	0.066 (−2.190, 2.980)	−1.180 (−3.440, 1.740)

applied for the 1990–2019 period. For Finland, the additional non-CO_2 GHG and LULUCF adjustments over this period were larger than the corresponding increase in the CO_2-warming-equivalent GHG budget for an earlier start year. This led to an unintuitive result that with national-level adjustments and ability-to-pay share, the GHG budget was larger (less negative) in 2020 than in 1990.

3.4. Terms in the global GHG budget calculation

The simulated global background scenario (SSP1-1.9) reached a temperature of 1.71 (1.21, 2.42) °C in 2050 (figure S4). Thus, there was a considerable overshoot of the 1.5° C goal, which was the global context assumed in the GHG budget calculations.

Figure S5 shows the time evolution of the terms needed in the GHG budget calculations and the probability density distributions of their changes from 2010 to 2019 to 2050. The warming contribution of historical (before 2020) non-CO_2 GHGs emissions decreased by 0.28 (0.17, 0.41)° C (figure S5(b)). The warming contribution of other (mainly aerosol) forcing decreased in magnitude, contributing to a mean additional warming of 0.19 (−0.00, 0.48° C from 2010 to 2019 levels (figure S5d). The warming contribution of non-CO_2 GHGs emitted globally since 2020 in SSP1-1.9 was 0.39 (0.26, 0.57)° C (figure S5(f)). The probability density distribution of change from 2010 to 2019 to 2050 of the sum of the warming contributions from other forcings, future non-CO_2 GHG emissions and historical non-CO_2 GHG emissions, matched quite closely with the total non-CO_2 warming contribution change (figure S6(b)), but the time evolution was somewhat different (figure S6(a)), mainly because of the non-linearities of the methane lifetime.

4. Discussion

4.1. Comparison to previous approaches

Our approach for deriving national GHG budgets offers several advantages over the existing methods. By including non-CO_2 GHGs, it is more applicable to guide or assess climate policy than the CO_2-only approach of sharing the global remaining carbon budget. Although several recent methods consider non-CO_2 GHGs (Li *et al* 2025) or indirect effects in the LULUCF sector (Gidden *et al* 2023, Weber *et al* 2026), none provide a GHG budget constrained by a fair share of the GHG warming contribution of future emissions that is compatible with national GHG inventories.

Concerning non-CO_2 GHGs, our calculation of the national allowable warming contribution is similar to the method proposed by Li *et al* (2025), which is based on fair shares of warming contributions. However, they did not isolate the decreasing warming contribution of historical emissions and did not convert the fair share of warming contribution to GHG budgets that are consistent with the accounting of national GHG inventories.

Another method for deriving CO_2-warming-equivalent GHG budgets (Mastropierro *et al* 2025) is GWP* (Collins *et al* 2020, Lynch *et al* 2020). It is a modified version of GWP that considers both the current atmospheric concentration and recent (e.g. past 20 yr) changes in non-CO_2 GHG emissions and can accurately capture the warming impact of different emission trajectories. However, Meinshausen and Nicholls (2022) argued that GWP* functions more as a simple model than a climate-policy metric, because it produces high variability in aggregated emission time series and can even reverse the sign of the marginal warming effect of a single year's emissions.

Similar to our global-level adjustment, Weber et al (2026) made an adjustment to global remaining carbon budgets based on indirect effects. Finally, the scientific analysis by the European Scientific Advisory Board on Climate Change (ESABCC 2023) took into account the indirect effects similarly to our national-level adjustment. While their use of either cost-effective GHG pathways or a combination of equity-based carbon budgets with cost-effective non-CO_2 GHG pathways ensures that global targets are met if consistently applied to all countries, they did not provide equity-based GHG budgets as we do here. Our approach can be interpreted as a combination of adjustment for indirect effects (Weber et al 2026) and calculation of CO_2-warming-equivalent emissions (Li et al 2025) that are translated to be compatible with national GHG inventories.

4.2. Applicability to guide climate policy

Our approach could support the assessment of national long-term climate strategies under the UNFCCC and the Global Stocktake of NDCs in relation to global temperature goals and a fair distribution of responsibilities. For example, countries could compare their NDCs to GHG budgets calculated using our method to assess their fairness, similar to how Weber et al (2026) analyzed national remaining carbon budgets.

Making the assumptions on indirect effects and non-CO_2 GHGs explicit, while expressing the final GHG budget consistent with the national GHG inventories, can help pragmatically bridge the scientific and policy communities. An overall GHG budget based on GWP100 could be easier to integrate into national climate change mitigation goals than separate targets for long- and short-lived GHGs. Additionally, it could make the substitution between GHGs easier, although the GHG budget would need to be readjusted if the mix of GHGs differed from the assumed projection. This makes our GHG budget mathematically equivalent to specifying a remaining carbon budget plus the assumed non-CO_2 GHG scenario but expressed as a single GWP100-aggregated number used in national GHG inventories and targets.

Our method is compatible with different equity principles and can include historical warming contributions to fairly share the allowable warming contribution and GHG budgets. An international agreement on the equity principle would also be useful for the wider use of the approach presented here, similar to any other method for allocating responsibilities. The International Court of Justice clarified the criteria relevant for defining an adequate contribution to the 1.5 °C global temperature goal. They include historical and cumulative GHG emissions, as well as a country's level of development and national circumstances (ICJ 2025, para 247).

The choice of whether to adjust the GHG budget at the global or national level would involve similar challenges to choosing the guiding equity principle for sharing the global budget. If consistently applied across all countries, both global and national-level adjustments to GHG budgets would allow limiting global warming under a specified limit with a chosen probability. Thus, from a scientific perspective, both options are equally valid for limiting global warming.

However, if the allowable warming contribution of countries is accepted as the starting point, the national-level adjustment reflects it better. When the adjustment is done at the global level, the adjustments for individual countries reflect their fair share of global adjustments needed for compatibility with national GHG inventories.

For countries such as Finland, with high negative indirect effects relative to their total GHG emissions, global-level adjustment would be very beneficial, as indirect effects could be accounted for in mitigation efforts. However, when global warming intensifies soil respiration and land carbon sinks weaken with decreasing emissions, indirect effects could turn positive for some regions, such as Africa and the Middle East (Grassi et al 2021), and using global-level adjustment would mean that some countries would be responsible for the indirectly increased emissions in the LULUCF sector.

Similarly, if the global target year is 2050, global-level adjustments for non-CO_2 GHGs would allow countries with relatively high methane emissions to have GHG budgets that exceed their share of allowable warming contributions, and this exceedance would be collectively offset by lower GHG budgets for other countries.

In addition to choices concerning equity principles, time frames, and selecting between national- or global-level adjustments, there is a challenge that the adjustment terms for non-CO_2 GHGs and indirect effects in the LULUCF sector depend on emission scenarios and climate change. The non-CO_2 GHG adjustment depends on either the assumed global or national non-CO_2 GHG scenario, and the LULUCF adjustment term depends on climate change and the CO_2 concentration trajectory.

To address the challenge of these dependencies, especially for national-level adjustments, countries should define both an overall economy-wide GHG mitigation budget and projections for each individual GHG. This would require an iterative approach, as the overall GHG budget both limits and depends on the emissions of non-CO_2 GHGs. In addition to separate targets or projections for methane and nitrous oxide, it is important to examine whether a shift from GWP100 to GWP_{20}-based aggregation could improve the consistency of actual policy with climate modeling and CO_2-warming-equivalent GHG budgets.

In the future, the GHG budgets would need to be revised to account for past emissions, revised projections of the indirect effects and emissions of non-CO_2 GHGs or aerosols, and improved understanding of the climate system. This could, for example, be tied to the 5-yearly Global Stocktake of the Paris Agreement, while acknowledging that too frequent updates could decrease the credibility and legitimacy of climate policies (Dolphin *et al* 2023).

4.3. Technical limitations of the study

In addition to applying the method to a larger set of countries, there are some key points on how the analysis presented here could be extended in future studies.

First, a larger set of global and national non-CO_2 GHG emission scenarios could be considered. Ideally, an iterative approach should be used to calculate the GHG budget and a compatible national non-CO_2 GHG emission pathway, as they depend on each other. Second, multi-model and multi-scenario projections of future indirect effects are needed to better quantify the involved uncertainties. We used a multi-model ensemble to estimate the uncertainty in indirect effects, but the future trend was based on a single model and considered only forested areas. Third, the sensitivities and implications of the choice of timeframe should also be explored. Fourth, the implications of a wider range of equity principles should be explored systematically (Li *et al* 2025, Weber *et al* 2026). Fifth, the effect of target year could be assessed. From a national point of view, assuming a later target year would decrease the warming contribution of methane emitted in the near future. The effect on the global GHG budget would depend on the additional warming contribution from aerosol emissions and decreasing warming contribution of historical non-CO_2 GHG emissions. Sixth, adding an adjustment for bunker fuels would be better for consistency (Weber *et al* 2026).

4.4. Implications to Finland's goal of achieving net-zero GHG emissions by 2035

Finland has enshrined in its Climate Change Act of 2022 a binding GHG-neutrality goal, defined as net-zero GHG emissions by 2035 as reported in the national GHG inventory. The goal is based on a national GHG budget of 0.079 Gt CO_2-eq calculated using the ability-to-pay principle to allocate to Finland a fair share of the global remaining carbon budget associated with limiting global warming below 1.5° C with 66% probability (Ollikainen *et al* 2019, Arasto *et al* 2021).

Although not intended as a full-depth analysis of Finland's GHG-neutrality goal, our study provides some relevant implications. Neither indirect effects nor explicit warming contribution of non-CO_2 GHGs were adequately considered in the calculations behind Finland's goal. Furthermore, we use the same ability-to-pay share as Arasto *et al* (2021) and Ollikainen *et al* (2019). Therefore, our GHG budget with no adjustments is conceptually similar to calculations behind Finland's national target.

Our best estimate of Finland's 2020–2050 GHG budget of −0.654 Gt CO_2-eq with national adjustments is substantially lower than the GHG budget which the national GHG-neutrality goal is based on. Thus, our results imply that reaching GHG neutrality in 2035, according to the national GHG inventory, is unlikely to be compatible with Finland's fair allowable warming contribution with the ability-to-pay equity principle behind Finland's current target. Our best estimate for the GHG budget with global adjustments (0.0565 Gt CO_2-eq) is close to the GHG budget behind Finland's national target, indicating that Finland's GHG-neutrality goal would be fairly consistent with a fair share of the GHG budget with global adjustments. The difference between national- and global-level adjustments highlights that applying global-level adjustments to the GHG budget would lead Finland to vastly exceed its fair share of warming contribution.

Considering also the per-capita equity principle and historical warming contribution offers some additional insights. With adjustments, only GHG budget calculated with per-capita principle and global adjustments without considering historical responsibility was larger (best estimate of 0.169 Gt CO_2-eq) than the GHG budget behind Finland's national target. When historical responsibility for emissions from 1990 to 2019 was considered, the resulting GHG budget was negative for both equity principles and at both adjustment levels (table 4). These GHG budgets would mean that Finland's GHG emissions for 2020–2050 would need to be net negative for Finland to stay within the budgets.

5. Conclusions

We provide a novel framework to derive national GHG budgets based on allowable warming contributions that are compatible with both scientific assessments of required emission reductions and national GHG inventories used to track the progress of mitigation efforts. Our illustrative calculation for Finland shows that there can be significant differences in national GHG budgets depending on whether adjustments for indirect effects and non-CO_2 GHG warming contributions are made at the global or national level. Our methods can be easily applied to other countries if national non-CO_2 GHG pathways and projections of indirect effects are available. Our method can be applied by individual countries to assess the compatibility of their NDCs with fair and adequate contributions to climate change mitigation without requiring international agreement on the application of the adjustments, equity principles or GHG budget timeframes. Agreeing on common practices internationally would facilitate coordinating NDCs to collectively meet the global temperature targets.

Acknowledgments

This article was supported by the Strategic Research Council of the Research Council of Finland under project 2035Legitimacy (Grant No. 335559), Research Council of Finland for the ACCC Flagship (Decision No. 359342), and the Finnish Climate Change Panel. We also thank Antti Lehtilä, Sofia Vikfors and Tarja Tuomainen for providing the data for the national non-CO_2 GHG emission scenario and Timo Vesala for providing comments on an earlier draft of the manuscript. Claude (Sonnet 4.6, Opus 4.6–4.8) was used to assist in refactoring, revising, and debugging the analysis scripts. Claude, Microsoft 365 Copilot (GPT-5), and Paperpal were used to suggest edits and review text to enhance the readability of the manuscript.

Data availability statement

The data and code that support the findings of this study are openly available at the following URL/DOI: https://doi.org/10.57707/fmi-b2share.9hxst-jfe98.

Supplementary Material available at: https://doi.org/10.1088/1748-9326/ae9628/data1.

Author contributions

Antti-Ilari Partanen 0000-0002-0883-8161
Conceptualization (lead), Data curation (lead), Formal analysis (lead), Funding acquisition (supporting), Investigation (lead), Methodology (lead), Project administration (supporting), Resources (equal), Software (lead), Validation (lead), Visualization (lead), Writing – original draft (lead), Writing – review & editing (lead)

Tommi Ekholm 0000-0002-9124-6289
Conceptualization (supporting), Investigation (supporting), Methodology (supporting), Visualization (supporting), Writing – original draft (supporting), Writing – review & editing (supporting)

Jyri Seppälä 0000-0002-0261-9590
Conceptualization (supporting), Funding acquisition (supporting), Investigation (supporting), Methodology (supporting), Writing – review & editing (supporting)

Sally Weaver
Conceptualization (supporting), Investigation (supporting), Methodology (supporting), Validation (supporting)

Taru Palosuo 0000-0003-4322-3450
Conceptualization (supporting), Investigation (supporting), Methodology (supporting), Writing – review & editing (supporting)

Giacomo Grassi 0000-0003-0650-0391
Data curation (supporting), Investigation (supporting), Writing – review & editing (supporting)

Chris Smith 0000-0003-0599-4633
Formal analysis (supporting), Methodology (supporting), Writing – review & editing (supporting)

Kati Kulovesi 0000-0003-2700-2834
Funding acquisition (supporting), Writing – review & editing (supporting)

Hannele Laine 0000-0001-6264-0706
Conceptualization (supporting), Funding acquisition (supporting), Investigation (supporting), Methodology (supporting), Writing – review & editing (supporting)

Markku Ollikainen 0000-0003-3333-4683
Conceptualization (supporting), Investigation (supporting), Methodology (supporting), Writing – original draft (supporting), Writing – review & editing (supporting)

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