Methane mitigation achievement, including agriculture, is crucial to limiting dependence on uncertain carbon dioxide removal in national carbon budgeting equitably meeting Paris goals

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Abstract – Developed nations are likely to overshoot their "fair share" of a remaining global carbon budget (rGCB) equitably aligned with meeting the Paris Agreement (PA) temperature goal. PA-aligned pathways in integrated assessment modelling typically rely on large scale carbon dioxide removal (CDR), even though such reliance is highly uncertain and likely inequitable. Moreover, radical reductions in fossil fuel combustion (FFC) cut CO_2 emissions but result in a parallel reduction in cooling aerosols, severely reducing the available rGCB. Consequently, substantial land use change (LUC) CO_2 and agricultural non-CO_2 mitigation is now crucial to achieve global carbon budget outcomes aligned with meeting the stringent Paris temperature goal. However, most negative emissions literature undervalues or ignores the importance of early, sustained, and permanent methane (CH_4) in equitable mitigation limiting CDR dependence. Therefore, to meet a national PA "fair share" temperature goal, we use the recently developed GWP* CO_2 warming equivalence method in illustrative scenarios to assess trade-offs between: mitigation of CO_2 and N_2O; and temperature impact reduction (TIR), via CH_4 mitigation and limited CDR. Ireland provides an informative, developed nation case study due to: carbon budgeting law and policy; rising agricultural CH_4 and N_2O emissions; and net emissions of LUC CO_2, due to drained organic soils, ongoing peat extraction, and declining forestry CO_2 removals. Practically, Ireland's CDR potential may be only 200 $MtCO_2$. Based on the IPCC database scenario sets for *1.5C low overshoot* and *Lower 2C*, GWP* is used to benchmark a "prudent" multi-gas rGCB* of 640 $GtCO_2$we for CO_2+N_2O+CH_4 from 2015. Ireland's population-based share of this is a multi-gas national carbon quota (NCQ*) of 410 $MtCO_2$we, depleting from 2015 onward. Using a spreadsheet tool, illustrative scenarios are assessed for different CO_2+N_2O+CH_4 reduction pathways over time. Only radical scenarios, achieving net zero CO_2 before 2050 while permanently cutting CH_4 by 50%, limit overshoot and enable a return to the Paris-aligned national quota by 2050 without exceeding the practical CDR limit to 2100. Key findings include guidance on use of GWP* in mitigation analysis, the certainty-importance of early and deep CH_4 mitigation *in addition* to rapid CO_2 reduction to limit CDR reliance. Given mitigation delay, the need for immediate and deep CO_2 and CH_4 mitigation is confirmed, requiring regulatory limits on GHG-intensive agriculture and land use activities as well as radical reductions in fossil carbon combustion for energy and cement use.

1 Introduction

1.1 Prudence and equity consideration in meeting the Paris temperature goal

The Paris Agreement [1] Article 2 objective – linking limiting global warming to "well below 2ºC" and '*pursuing efforts to limit global average temperature to 1.5ºC above pre-industrial levels*' – can be considered as a single goal [2], referred to as '*the long-term temperature goal*' in Article 4. Also under Article 2, the UNFCCC Parties have agreed to achieve this goal through actions '*implemented to reflect equity and the principle of common but differentiated responsibilities and respective capabilities* [CBDR-RC]*, in the light of different national circumstances'*. Therefore, any assessment of "fair share" climate action by an individual Party requires a clearly defined CBDR-RC approach, applicable across all nations, setting out a justification for all quantitative and normative parameter choices being made toward meeting the temperature goal prudently and equitably [3], [4]. Even if met, as of 2022 existing Party commitments are collectively only sufficient to limit to just below 2ºC, falling well short of the PA goal unless additional action is achieved starting immediately [5]. The IPCC Sixth Assessment Report's three working group (AR6-WG) summaries for policymakers (SPMs) [6]–[8] set out the extreme urgency of climate action required to meet the more prudent 1.5ºC target with limited overshoot, even allowing for only a 50% probability of success. Achieving the PA temperature goal on a global CO_2-only basis can be quantified scientifically as a remaining global carbon budget (rGCB) from a stated base year. In the IPCC AR6-WGI SPM a central rGCB value of 500 $GtCO_2$ from the beginning of 2020 is given for a 50% probability of limiting further global temperature rise to 1.5ºC [6], assuming given stated uncertainties and defined non-CO_2 emission pathways, particularly for methane (CH_4) and nitrous oxide (N_2O). However, given "main case" median assumptions for non-CO_2 and other parameters [9] finds a 17% chance that the rGCB for 1.5ºC had already been exceeded by the start of 2020.

1.2 Equivalent temperature impact reduction (TIR) via CDR or CH4 mitigation

Non-CO_2 emissions have a substantial effect on the rGCB value and warming [10] such that IPCC illustrative CO_2 pathways limiting to 1.5ºC with low overshoot or to "well below 2ºC" rely on median total emission reductions by 2050 relative to 2020 of over 50% for CH_4 and ~20% for N_2O (Fig. SPM.5a in [8]). The warming-to-date due to long-lived climate forcers (LLCFs), primarily CO_2 but also N_2O, continues to increase while their combined annual net CO_2eq emissions are above net zero, whereas the total warming-to-date due to short-lived climate forcers (SLCFs), like CH_4, can decline in future if rates of SLCF annual emission are reduced substantially and permanently. Consequently, in mitigation scenarios, "temperature impact reduction" (TIR) can be achieved by CDR *or* by an equivalent reduction in annual CH_4 emissions rate [11]. Given the escalating difficulty of meeting the Paris goal [12], rapid CH_4 mitigation has increasing TIR value, and hence, echoing WGI, the AR6-WGIII SPM states:

> *'Deep GHG emissions reductions by 2030 and 2040, particularly reductions of methane emissions, lower peak warming, reduce the likelihood of overshooting warming limits and lead to less reliance on net negative CO_2 emissions that reverse warming in the latter half of the century.' [8]*

However, in contrast with this increased IPCC emphasis in AR6 on the importance of CH_4 mitigation, the draft full WGIII report's CDR assessment (Ch. 12.3) emphases reliance on TIR from development of CDR as an offset for residual GHGs on a GWP_{100} basis, without acknowledging the substantial TIR potential of immediate CH_4 mitigation to ease near-term mitigation or overshoot, and to limit long-term CDR reliance. Reflecting the Ch. 12.3 CDR emphasis on GWP_{100} assessment, the WGIII SPM states:

> *'The deployment of CDR to counterbalance hard-to-abate residual emissions is unavoidable if net zero CO_2 or GHG emissions are to be achieved. The scale and timing of deployment will depend on the trajectories of gross emission reductions in different sectors.' C.11 in [8]*

Globally, the importance of CH_4 mitigation for TIR is evident in IPCC illustrative modelling of CO_2 pathways aligned with the PA goal, which are reliant on deep reductions in CH_4 as well as on CDR, as is shown in: SR15 Figure SPM.3; AR6-WGI Figure.SPM.4 SSP1-[1.9 and 2.6] illustrative pathways; and in AR6-WGIII Figure SPM.5, most particularly in the deepest CH_4 reductions shown for the illustrative mitigation pathway IMP-SP from 2020, which focuses on shifting pathways toward global sustainable development, including significant dietary change away from animal food production and consumption. In the 1.5ºC IMP-SP scenario CDR reliance is minimal. In research examining alternative pathways to 1.5ºC with limited CDR requirement [13] includes a low non-CO_2 scenario with the following GHG cuts up to and sustained beyond 2050: for CH_4, '*ruminant enteric fermentation in ruminants 73%, sewage 95%, landfills 100%, animal waste/manure 100%*'; N_2O, '*emissions reductions are set at fertilizer use 80%, animal waste/manure 75%*'; and for fluorinated gases, 97%.

1.3 Questioning "hard-to-abate" assertions in sectoral CDR policy reliance

The AR6-WGIII IMP-SP and literature pathways assessing radical GHG reductions through combined regulatory action and demand reduction indicate they are at least possible and therefore achievable with directed policy. This directly challenges the AR6-WGIII assertion that sectors such as aviation, heavy industry, and animal agriculture can be simplistically characterised as "hard-to-abate". Furthermore, the Paris goal importance of agricultural non-CO_2 forcing changes and land use change (LUC) CO_2 removals are made apparent in the scenario finding described by Mengis and Matthews in [14] which

> *'indicates clearly that focussing only on fossil fuel emissions reductions, without also mitigating LUC-related CO_2 emissions and non-CO_2 GHG from LUC and agriculture, would likely result in an impossibly small remaining fossil fuel carbon budget for the 1.5 °C target' [14]*

This understanding, which can be extended to Party-level carbon budgeting under the good faith and fair share principles underpinning national PA commitments [3], shows that it is misleading, and may result in mitigation deterrence [15], [16], to assume simplistically that agriculture or aviation or other emissions are necessarily "hard-to-abate". However politically difficult it may be to abate such high GHG sectors, they may *need* to be abated to meet a Party's fair share target given the PA's '*binding obligations of conduct coupled with a good faith expectation of results*' [17] in delivering sufficient climate action and in the context of relevant legal principles for national fair share effort [3], [18]. (The UK FIRES Absolute Zero report [19] indicates highly restrictive pathways on aviation and animal agriculture emissions are required due to insufficient technical mitigation.) Therefore, the phrases “hard-to-abate” or “hard-to-transition” can be misleading as they *incorrectly* imply: (1) quantitatively, that individual GH gases or sector-total GHGs can be meaningfully equated on a GWP_{100} basis to assess warming impact; and (2) normatively, that existing GHG intensive activities continue unchecked if only costly technical measures are assessed to address them. The latter issue is especially apparent in the IPCC evaluation of mitigation for agriculture in AR6-WGIII, for which Table 7.3 in [20] indicates that only estimates of technical mitigation measures have been assessed and “no data” is available for IAMs for demand-side measures. This means that the large residual agricultural CH_4 seen by 2050 in IAMs occurs because mitigation of ruminant and manure CH_4 is found to be *technically* costly, and yet policy and regulatory options that may be less *societally* costly than non-agriculture mitigation or CDR have not been assessed.

In this article, using coarse-grained assessment for a developed nation, we evaluate this “hard-to-abate” framing at the individual Party level by presenting alternative scenarios meeting the same PA-consistent fair share GHG quota by 2100. The methodology enables scenarios to show by-gas and aggregate pathways to examine trade-offs between LLCF gross emissions and TIR (from differing combinations of CH_4 mitigation CDR), within a context of limited assessed national CDR potential. Crucially, we assess the temperature impact of scenarios, using the GWP* method in coarse-grained modelling, rather than depending only on GWP_{100} equivalence, which does not show the substantial near- and medium term TIR mitigation opportunity available through reducing a Party’s annual CH_4 emissions rate. The results indicate that agricultural sector emissions can only be sufficiently abated by substantially reducing ruminant-derived food production.

1.4 Assessing CDR and CH_4 in PA mitigation using temperature impact modelling

Suggested CDR methods aiming to limit net emissions or to achieve a period of net negative emissions, globally or at Party level, include ‘*anthropogenic activities that remove* CO_2 *from the atmosphere and store it durably in geological, terrestrial, or ocean reservoirs, or in products*’ as described in AR6-WGIII section 12.3 [20] and as shown in the CDR taxonomy in its Cross-Chapter Box 8, Figure 1. Serious concerns are expressed in this section regarding reliance on CDR at scale, including the risk that they may not be achieved at the scale required, citing [34], [35], and that any assumption of CDR at large scale may deter more immediate or certain mitigation of GHGs. This AR6-WGIII section notes that in globally limiting to a temperature goal or to achieve global TIR after overshoot, different nations could follow different pathways that add up to these outcomes. The discussion in this CDR-focused WGIII section advocates

> *achieving net zero GHG implies gross CO_2 removals to counterbalance residual emissions of both CO_2 and non-CO_2 gases, applying GWP_{100} as the metric for reporting CO_2-equivalent emissions, as required for emissions reporting under the Rulebook of the Paris Agreement [20]*

However, this quote references a Ch. 2 discussion in *Cross-Chapter Box 2 GHG emission metrics* that notes that rapidly cutting emissions of short-lived climate forcers (SLCFs) including CH_4 have greater climate benefits than if weighted by GWP_{100}, so it does not make sense to counterbalance declining CH_4 with CDR simplistically on a GWP_{100} basis. Even if GWP_{100} reporting is required for PA Rulebook reporting, *temperature impact* modelling of by-gas societal and sectoral pathways in line with equitably meeting the accepted *temperature* target can still be used informatively to show corresponding GWP_{100} trajectories to assess policy options or regulatory action.

As confirmed by [14] and summarised in AR6-WGIII (Box TS.2 in, [8]) the TIR effect of sustained CH_4 reductions has been shown to be equivalent to CDR in terms of a one-off CDR, as can be estimated by use of the GWP* [36]–[38] or CGTP (Combined Global Temperature Change Potential) [39] approaches to determine changes in cumulative CO_2 warming equivalent (CO_2we) from a given start year. These methods have commonly been described as GHG equivalence step-pulse "metrics" but it is more accurate to describe them as coarse-grained '*micro climate models (MCMs)*' [40] useful in assessing temperature impact on the basis of readily available or projected time series of by-gas mass emissions (or equivalent CO_2eq data). It is important to understand annual GWP* or CGTP values are not directly comparable with the annual GWP_{100} CO_2eq values, so they are not directly useful to assess current action on mass emissions (for which GWP_{100} is a useful linear proxy) or as a metric for UNFCCC inventory reporting [40] and simplistic use of these method could result in inequitable outcomes [41] unless a PA CBDR-RC context is clearly defined. In this article this is achieved by first assessing a global multi-gas rGCB* from 2015 as a common basis for burden sharing so that all nations have an identical per capita share from a benchmark 2015 base year.

1.5 Ireland: a case study of CH_4 and CDR reliance in meeting the Paris goal

Ireland provides an informative case study of the effects and importance of including non-CO_2 emissions in climate mitigation assessment relative to the PA goal because it has an unusual emissions profile of high CH_4 and N_2O per capita. 93% of each of these GHGs is related to agriculture, primarily from farm production of milk from dairy cows and meat from livestock. Moreover, Ireland's climate governance is also notable in having amended its climate Act in 2021 to institute a programme of 5-year carbon budgeting on a cumulative CO_2eq basis that is required to be 'consistent with' PA Articles 2 and 4(1).

Following passing of the amended Act, national budgets of 295 MtCO_2eq and 200 MtCO_2eq for 2021–2025 and 2026–2030, as well as a provisional 2031–2035 budget, were first recommended by the independent Climate Change Advisory Council (CCAC) in a Technical Report in October 2021 [42] (hereafter denoted as *CCAC-TR*). Subsequently, in April 2022 the first two society-wide 5-year carbon budgets were confirmed by the Irish parliament, the Oireachtas, and then, by the end of June 2022, the government is to propose constituent legally binding *sectoral ceilings* – for power generation, industry, transport, buildings, agriculture and waste. In its assessment of carbon budgets the CCAC defined five *core scenarios* – on a simplified basis of "Agriculture", as a proxy name for non-CO_2 mitigation by 2030, and corresponding "Energy" (CO_2) mitigation levels – calculated to meet the approximately the same overall 10-year CO_2eq budget up to 2030 and for 2020–2050. The CCAC-TR scenarios were based on Agriculture mitigation by 2030 of 19%, 26%, 33%, 40%, and 51% , resulting in corresponding scenario Energy CO_2 reductions of 69%, 65%, 61%, 57%, and 51%, respectively. CH_4 and N_2O are assumed to be reduced by the same stated scenario "Agriculture" rate up to 2030. Net CO_2 emissions reach net zero in CO_2eq terms by 2050 at latest. Notably, using a form of GWP*, the CCAC-TR Figure 4-3 indicates that it is the differences in CH_4 mitigation that result in a much larger variation in estimated temperature impact across scenarios than N_2O or CO_2 mitigation differences.

To inform Ireland's current national policy discussion in advance of agreeing sectoral ceilings, this article focuses on and contrasts "Agriculture" scenarios that reduce CH_4 and N_2O by 10%, 22% and 30%, by 2030, as well as an additional deeper non-CO_2 mitigation scenario to align action with meeting the PA goal by 2050. As Ireland's climate Act requires that the carbon budgeting programme is consistent with the temperature goal, as described under the Methods (2.1), we assess a multi-gas 1.5ºC rGCB* for [CO_2+N_2O+CH_4] that is then allocated on an equal per capita and population CBDR-RC basis to give a "minimally equitable", multi-gas national carbon budget (NCQ*). Informed by current policy discussion and using a spreadsheet tool, coarse-grained scenarios are then applied according to a consistent scenario definition method, to define and assess pathways that meet the temperature target NCQ* quota level by 2100 at latest but ideally by 2050.

Although global pathways minimising 1.5ºC overshoot have been intensively examined using climate models [5], [20], developed nation overshoot scenarios have not, therefore the methodology applied in this article contributes an informative methodology for analysis of national mitigation choices that is readily applicable to other Parties. Such analysis informs understanding of crucial fair share mitigation issues for developed Parties that has not been widely understood. This includes differentiating reaching an *overshoot net zero* (ONZ) – corresponding to a level of "no further warming" but at peak carbon debt [43] – from achieving *quota net zero* (QNZ), stabilising at the target NCQ* level after cancelling any carbon debt. This distinction is important because recent grey literature climate policy briefings often confusingly and misleadingly suggest that a "no further warming" ONZ for a Party is an appropriate climate action goal when, logically it is only reaching an equitable QNZ without any overshoot carbon debt that can be assessed as being consistent with Paris Article 2 and the subordinate Article 4(1). Given that the PA and UNFCCC are predicated on action by national or regional Parties, such claims are even more misleading when incorrectly asserted as a meaningful goal for an individual sector or corporate entity.

In the context of equitable 1.5ºC carbon budgeting whereby urgently required rapid fossil fuel CO_2 reduction is becoming insufficient to avoid PA target overshoot, this article contributes to climate mitigation literature by clarifying important trade-offs between: TIR achieved more certainly and more quickly through agricultural and fossil CH_4 mitigation; and, TIR achieved less certainly and more slowly by CDR such as BECCS that may not deliver at scale [44], or through land-based soil [45] for or forestry CDR that are inherently of limited mitigation value [46] due to uncertainty, impermanence, saturation and additionality issues [47]–[50].

2 Methods

2.1 Assessing multi-gas remaining global GHG budget and a derived Party "fair share"

In the research for this article the GWP* method is used as described in Ch. 7 of [51], and in greater detail in [52], to assess the remaining global GHG budget, denoted rGCB*, in cumulative CO_2we on a combined [CO_2+N_2O+CH_4] multi-gas basis from 2015. Assessed rGCB* values from 2015 are based on the IAM *1.5C low overshoot* and *Lower 2C* scenario-set sampling of possible climate model temperature outcomes. Respectively, corresponding to the PA goal, using the 50th percentile *1.5C low overshoot* results for 1.5ºC gives an rGCB* of 640 $GtCO_2$we; and using the 10th percentile Lower 2C results for "well below 2ºC" gives an rGCB* of 1030 $GtCO_2$we. Acknowledging the inherent grandfathering and inequity in any "fair shares" approach [4], as set out in [43] we argue that 2015, the year of the global political commitment to the PA, is the latest possible start date for an analysis of Paris consistency and that a prudence level of a 50% chance of 1.5ºC is a reasoned basis for a "minimally equitable" PA fair sharing among Parties. This benchmark level results in a *maximum* remaining emissions quota for developed Parties with high per capita emissions because choosing an earlier year or using more stringent criteria would result in a *relatively* smaller remaining budget. (Given the rationale in [43], choosing a later year would require referenced and normative justification. For example, although the CCAC-TR "Paris Test" used the base year stated in IPCC AR6, no such basis for CBDR-RC fair sharing is ever advocated by IPCC reports so a recent year cannot be simply used as a base year without additional referenced justification.)

As it is simply defined and is aligned with principles of international environmental law [3] – unlike inertia, least cost or convergence – we then use equal per capita sharing of the 1.5ºC 50th percentile rGCB* from 2015 on a national population basis (defined as the 2015 equal per capita rGCB* share multiplied by 2015 national population) to define a national fair share GHG quota (NCQ*). This is then the PA-consistent target corresponding to their temperature impact share of the remaining warming up to 1.5ºC without overshoot with a 50% likelihood. In this approach therefore, all UNFCCC Parties are allocated a cumulative NCQ* CO_2we total for [CO_2+N_2O+CH_4] on the same equal per capita global basis at the start of 2015. For each Party this is adjusted by the annual emissions from then onward based on cumulative CO_2we emissions calculated using GWP*. For Ireland the NCQ* values derived from the 2015 rGCB* values are 410 $MtCO_2$we for 1.5ºC and 660 $MtCO_2$we for "well below 2ºC". As noted, using this minimally equitable approach simply benchmarks comparative action on a multi-gas basis from 2015, its use does not imply that high emitting nations can avoid identifying additional actions – to partially defray prior historic responsibility or accepting their greater relative capacity for mitigation action – in order to to mitigate unfair biases in climate action against poorer nations [53]. Clearly, explicitly defining the parameters for a national "Paris Test" of society-wide carbon budgeting is therefore important to assess national or regional Party scenarios relative to alignment with the Article 2 temperature goal and equitable implementation. As countries to date have made only limited statements regarding equity [54] and more will be required for the PA Global Stocktake [55], the CCAC-TR makes a credit-worthy initial attempt at a Paris Test analysis of its carbon budgeting, but it requires improvement as key normative and quantitative parameters are not made sufficiently explicit to provide required clarity.

2.2 Defining policy relevant national scenarios consistent with the Paris goal

This section sets out the basis of four illustrative scenarios used here to examine the effect of different proportions of non-CO_2 and CO_2 mitigation within Ireland's carbon budgeting programme. The aim of this coarse-grained scenario assessment is to assess the aggregate temperature impact effect (represented by cumulative CO_2we from 2015) of alternative by-gas combinations defined by on four options for CH_4 mitigation by 2030. The proposed national programme sets out to limit total cumulative inventory emissions to 495 MtCO_2eq for the period 2021–2030 (comprising 295 MtCO_2eq for 2021–2025 and 200 MtCO_2eq for 2026–2030). Land use emissions under an illustrative CCAC-TR scenario are constrained to 37 MtCO_2eq (see Table 3-3 in [42] p. 42), but this will certainly be exceeded, so a total of 45 MtCO_2eq is allowed in this study for LUC emissions for this 2021–2030. This leaves a rounded cumulative total of 450 MtCO_2eq for all other sectors as a round figure scenario constraint for this period.

Up to June 2022, policy documents and political discussion in Ireland have focused on: a 10% reduction in CH_4 emissions by 2030 relative to 2018, as stated in the Food Vision 2030 agri-food policy [56]; and a 22–30% reduction in agricultural emissions by 2030 in the 2021 Climate Action Plan ([57] p. 10), though this rate range does not appear to apply to both CH_4 and N_2O equally as the announced measures appear to focus on N_2O. Given the proposed sectoral 2030 mitigation targets for the agricultural sector include reductions of 10%, 22% and 30% these targets are used here to define three scenarios that can inform policy. A fourth scenario, based on examination of what would be required to meet the GHG-QNZ level by 2050, targets a 43% reduction in CH_4 and N_2O by 2030. In each scenario from 2031 onwards, CH_4 emissions decrease at a rate of about 0.3% yr^{-1}, to stabilise its GWP* annual warming contribution thereafter, and N_2O emissions are also set to follow this same reduction rate from 2031. In Ireland, 93% of both CH_4 and N_2O are from agriculture therefore in this study non-CO_2 mitigation primarily requires corresponding agricultural policy to be aligned with achieving the non-CO_2 pathway.

An extended spreadsheet tool [58] previously developed for the analysis presented in [51] is used to define annual emissions pathways, excluding LUC, for 2015–2100 by-gas and in aggregate, using CO_2we via GWP*, but also showing both CO_2eq via GWP_{100} for comparison. The tool sums cumulative emissions from the start of 2015, primarily to show the scenario warming impact by-gas and in aggregate using cumulative CO_2we. Recorded emissions are used for 2015–2020 or else, if not available, 2020 emissions echo 2019. Piecewise linear pathways are defined through chosen years – 2030, 2050 and 2100 – based on the by-gas percentage reductions achieved by each chosen year relative to 2020 emissions. The 2030 non-CO_2 target level is set first and the 2050 and 2100 CH_4 targets are set to ensure a stable CH_4 warming impact by 2050 given the 20-year lag-time inherent in GWP* partially reflecting the real lag time from CH_4 emission pulse to warming impact. For N_2O, the 2030, 2050 and 2100 targets echo those for CH_4. The net-CO_2 value is then adjusted to ensure 2021–2030 emissions total 450 MtCO_2eq.

Scenarios are named based on the initial "**N**" of **N**on-CO_2 and the initial "**C**" of net-CO_2 combined with the by-gas percentage reduction for each. The **N** values are 10%, 22%, 30% and 43%, and the **C** values are the corresponding CO_2 reduction by 2030 meeting the 450 MtCO_2eq cumulative target. For example, the **N10.C76** scenario defines a 10% reduction in both of the non-CO_2 gases, CH_4 and N_2O, by 2030 relative to 2020 and a corresponding 76% reduction in CO_2 emissions by 2030 to meet the target 10-year CO_2eq total.

As residual N_2O emissions due to fertilisation in agriculture will need to be balanced by CDR in the long-term, in each scenario the negative annual net-CO_2 level is adjusted to balance the N_2O emissions value in 2100. The final step in scenario definition is to adjust the 2050 net-CO_2 to a negative value sufficient to ensure that aggregate cumulative CO_2we returns to the GHG-QNZ level (after initial GHG-ONZ overshoot) by 2100 at latest. Note that, provided the average negative value for net-CO_2 is maintained over the duration of net negative values, the same total cumulative negative net-CO_2 value could be achieved in a scenario with a less negative 2050 net-CO_2 value (and hence a later peak cumulative net-CO_2 value).

2.3 Annual and cumulative charts: *overshoot net zero* versus *quota net zero*

Figure 1 provides a key to reading the 2015–2100 scenario results that are shown as stacked annual and corresponding cumulative emissions from 2015, with solid by-gas pathways shown separately for net-CO_2, N_2O, net-CO_2+N_2O (combining the warming effect of the long-lived climate pollutants), and CH_4. The primary focus is on the society-wide warming outcome over time, shown by the solid red line denoting aggregate [CO_2+N_2O+CH_4] GHGs in both charts compared to the horizontal dotted magenta line in the cumulative chart, denoting the national CO_2we quota (NCQ*) level estimated for the chosen Paris goal based on the central value of TCRE given in IPCC AR6-WGI. Dashed lines show CO_2eq pathways for CH_4 and for aggregate [CO_2+N_2O+CH_4]. The annual GWP_{100} CH_4 line usefully shows the relative change in rate of annual CH_4 emissions by mass over time, but the cumulative CH_4 and aggregate dashed lines are only shown to illustrate the failure of GWP_{100} to reflect the temperature impact of changes in CH_4 and aggregate GHGs including CH_4.

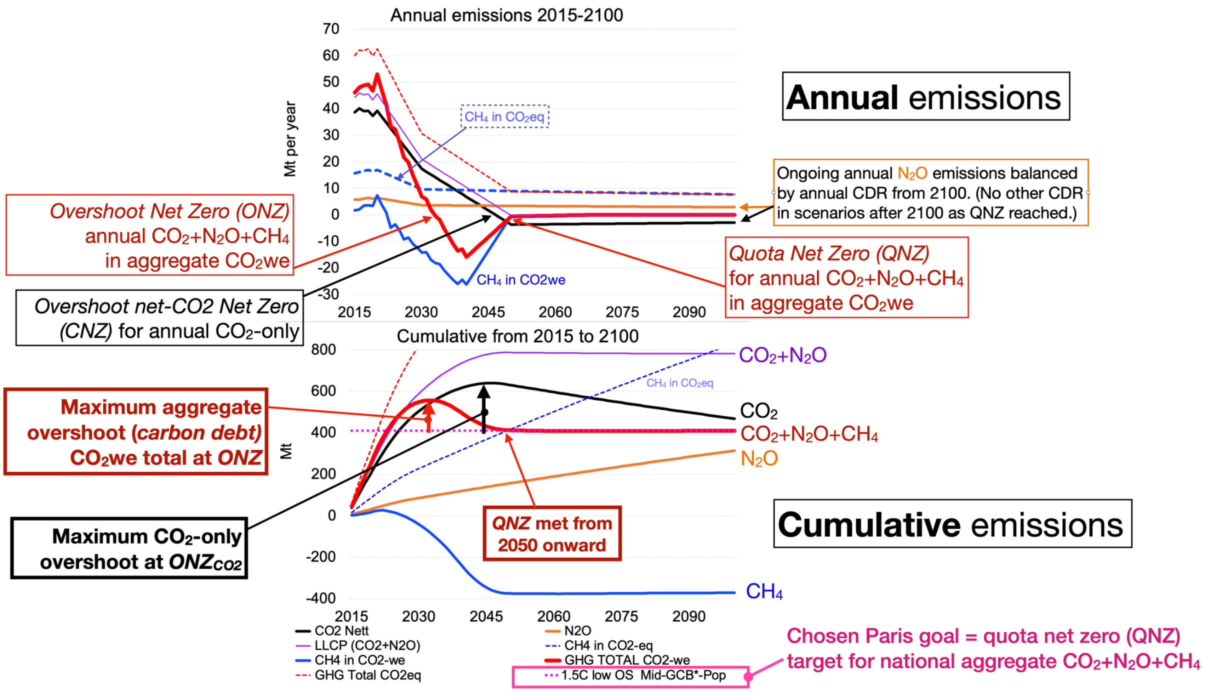

Figure 1. Annotation to assist reading Figure 2 scenario results. *Showing stacked 2015–2100 annual and cumulative emissions charts, particularly to identify differing net zero definitions. N43.C56 is the scenario example shown here. Solid lines show GWP* CO_2we and dashed lines show GWP_{100} CO_2eq.*

The figure's annotations for aggregate [CO_2+N_2O+CH_4] GHGs emphasise the difference between the *overshoot net zero* (ONZ) at peak carbon debt and the later achievement of the stabilisation at *quota net zero* (QNZ) after a period of net negative CO_2we warming reduction sufficient to cancel the peak carbon debt (at the maximum overshoot when the ONZ is attained) to reach the QNZ by 2100 at latest. In the scenario shown in **Figure 1** (**N43.C56** in the results), the QNZ is reached by 2050 and sustained thereafter. Ideally, scenarios would not overshoot the QNZ level at all, but it is now too late for Ireland to avoid overshoot within this minimally equitable approach. Hence, scenarios for Ireland can aim to limit maximum overshoot, which occurs in the ONZ year and to return, thereafter, to the QNZ as soon as possible via sustained cuts in CH_4 yr^{-1} and negative net-CO_2 within outlined limits.

3 Results:

3.1 Comparing illustrative policy-relevant Paris-consistent national scenarios

As per the scenario definition basis given in Section 2, **Figure 2** presents and compares results for the four illustrative 2015–2100 society-wide scenarios for Ireland – **N10.C76**, **N22.C69**, **N30.C64**, and **N43.C56** – defined on the basis of substantial 2020–2030 non-CO_2 reduction with non-CO_2 (N) cuts of 10–43% by 2030. As constructed, all four scenarios require extremely rapid reduction in annual net CO_2 emissions to CO_2-only net zero (CNZ) by 2040 at latest (for **N43.C56**), and lesser non-CO_2 reductions have an earlier CNZ. Net-CO_2 annual emissions remain negative after CNZ in all four scenarios, more deeply negative for lesser non-CO_2 reduction, and, by scenario definition, end in 2100 with annual negative CO_2 emissions balancing N_2O emissions from then onward.

In the annual emissions charts in **Figure 2**a, the 2020–2030 major reduction in the flow of non-CO_2 emissions, followed by a 0.3% yr^{-1} decrease, is shown in the annual GWP_{100} CO_2eq line charts, as a dashed blue line for CH_4, and a solid orange line for N_2O. Both CH_4 and N_2O gross annual emissions remain positive to 2100: relative to 2020, the 10–43% non-CO_2 cut by 2030, becomes a 17–47% reduction spread by 2050, and a 29–54% reduction spread by 2100. However, as seen by using GWP* CH_4 mitigation in the defining 2022–2030 period results in a lagged warming reduction that goes into negative annual CO_2we values for all scenarios, with more negative outcomes for deeper sustained reductions in annual CH_4, that also begin earlier. The initial rise in CH_4 CO_2we from 2015 reflects prior increases in CH_4 emissions over the previous decade due to expansion of ruminant agriculture, and this rise in CO_2we is only reversed after reflecting the delayed warming response to CH_4 flow changes that is at least partially incorporated in GWP* usage. After ONZ, the lagged CH_4 warming reduction effect of 2020–2030 CH_4 mitigation shown as negative annual CO_2we values continues until 2050, after which CH_4 CO_2we emissions are zero due to the 0.3% yr^{-1} decline in CH_4 CO_2eq, directly reflecting the change in CH_4 mass emissions.

In **Figure 2**b, stacked below and aligned with the annual emission charts, are corresponding line charts for 2015–2100 cumulative CO_2we emissions, by-gas and in aggregate, reflecting their warming contribution in the scenarios. (The dashed cumulative GWP_{100} CO_2eq lines for CH_4 and aggregate are presented only to show that they do not reflect warming outcomes involving CH_4 mitigation). Zero for cumulative emissions is set at the beginning of 2015 – the “minimally

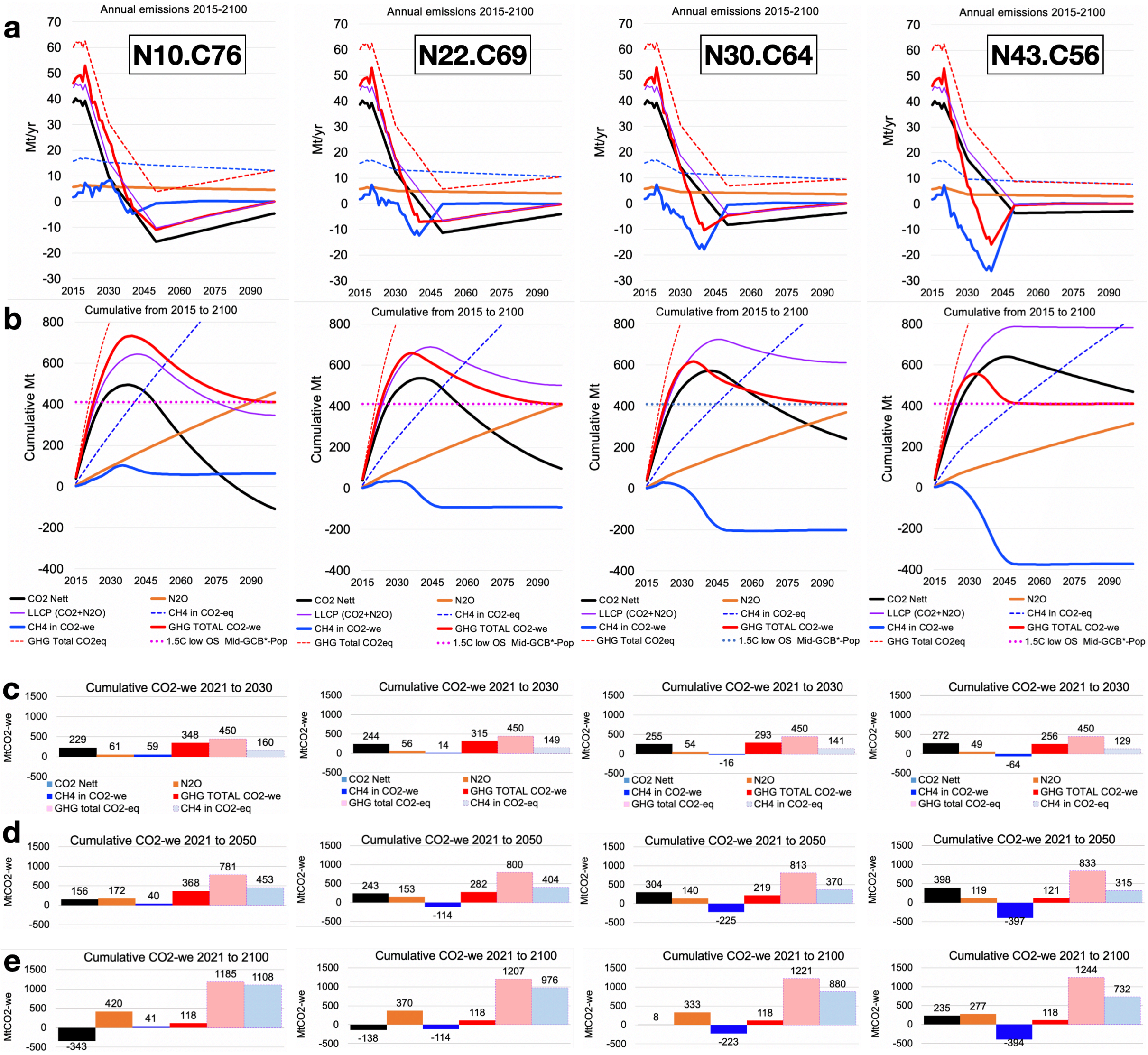

Figure 2. Results for four illustrative 2015–2100 scenarios for Ireland consistent with 1.5ºC 50%. Scenarios reach a national CO_2we quota for CO_2+N_2O+CH_4 by 2100 at latest. CH_4 annual emissions mitigation relative to 2020 increases from left to right: 10%, 22%, 30%, and 43%. The horizontal dotted line in the cumulative charts shows the 1.5ºC 50% NCQ quota target level. All emissions values in Mt with vertical axes matched to enable direct comparison. For all scenarios: the total GWP_{100} cumulative budget for 2021–2030 is 450 $MtCO_2$eq; in 2100 annual CDR equal to annual N_2O; and 2050 net CO_2 adjusted to ensure net zero at quota level is reached by 2100 at latest. Only **N43.C56** reaches QNZ by 2050.*
(a) Annual emission pathways: solid lines for net CO_2 (black), N_2O in CO_2eq (orange), CH_4 in CO_2we (blue), and aggregate GHGs (red); dashed lines show CH_4 in CO_2eq (blue) and aggregate CO_2eq (red).
(b) Cumulative emissions from 2015 corresponding to the annual emissions pathways, including long-lived climate pollutants summing CO_2+N_2O (purple solid line).
Below (b) are bar charts of cumulative CO_2we by-gas and in aggregate, including pale bars at right for each scenario showing aggregate CO_2eq (pink) and CH_4 (pale blue), for: (c) 2021–2030; (d) 2021–2050; and (e) 2021–2100.

equitable” baseline year for this study while acknowledging the serious equity concerns previously discussed. All scenarios are consistent with aligning with a long-term goal of a 50% chance of limiting to 1.5ºC by stabilising, by 2100 at latest, with the estimated population-based national QNZ level of cumulative 410 $MtCO_2$we from 2015 for CO_2+N_2O+CH_4. This level is shown as a horizontal dotted line that is reached by aggregate emissions by 2050 in **N43.C56** and only by 2100 in the other three scenarios. All four scenarios go into overshoot of this QNZ level by 2023, after which *carbon debt* accumulates up to a peak at maximum overshoot corresponding to ONZ ("no further warming") in the annual charts. Peak carbon debt is highest for N10.C76 and overshoot is most strongly limited by the warming reduction effect of increased CH_4 mitigation up to N43.C56.

The depth of CH_4 mitigation is also seen to be critical in determining the cumulative amount of net negative net-CO_2 required to cancel the carbon debt completely to return to an annual QNZ Paris Test quota level. In **N43.C56** the CH_4 mitigation is sufficient to entirely cancel the overshoot carbon debt by 2050 and net-CDR is only needed to balance N_2O emissions. By contrast the other three scenarios require additional net-CDR to compensate for shallower mitigation in annual CH_4 emissions rate in cancelling a larger carbon debt as well as balancing somewhat higher N_2O emissions. For **N43.C56**, CDR (net negative net-CO_2) is required at an average sequestration rate of -2.6 $MtCO_2$ yr^{-1} over 67 years, whereas **N10.C76** requires an average of -10 $MtCO_2$ yr^{-1} over 60 years.

The bottom of Figure 2, shows bar charts of cumulative CO2we by-gas and for aggregate GHGs over (c) 2021–2030 (d) 2021–2050 and (e) 2021–2100, respectively, including pale bars at right for each scenario showing cumulative CO2eq for aggregate GHGs (pink) and CH4 (pale blue). The CO2we values reveal the substantially smaller warming impact from CH4 and the dependent aggregate GHG than is indicated by GWP_{100}.

For the four illustrative scenarios, **Table 1** sets out the ONZ year of maximum target overshoot, with the peak carbon debt in $MtCO_2we$ reached at that time, the timing of CO_2 net zero (CNZ); and the year when the QNZ is reached by cumulative aggregate CO_2we for CO_2+N_2O+CH_4. Only the **N43.C56** scenario reaches the QNZ by 2050, the other three meet it in 2100. As shown in **Table 1**, with increasing depth of non-CO_2 mitigation, from N10.C76 through to **N43.C56** the scenarios show reduced maximum carbon debt relative to the QNZ cumulative threshold, while the ONZ year occurs sooner and the CNZ year later.

Table 1. Timing of scenario net zero years and with maximum overshoot carbon in $MtCO_2we$.

Net zero timing and C-debt by Scenario	**N10.C76**	**N22.C69**	**N20.C64**	**N43.C56**
Overshoot Net Zero (ONZ) occurs in	2040	2037	2036	2033
Max carbon debt at ONZ ($MtCO_2we$)	***322***	***249***	***206***	***146***
Net-CO_2 Net Zero (CNZ) occurs in	2038	2041	2043	2047
Quota Net Zero (QNZ) occurs in	2100	2100	2100	2050

Figure 3 presents stacked bar comparison of the scenario cumulative net-CO_2we values by-gas for 2021–2050 and 2021–2100, with cumulative positive net-CO_2 values up to ONZ (grey bars) presented separately from cumulative negative net-CO_2 (net CDR) values after ONZ. In **Figure 3**a, the maximum cumulative net CDR is -105 $MtCO_2we$ because, even with radical and extreme CO_2 mitigation it takes time for net CO_2 to reduce to CNZ. In contrast, CH_4 mitigation, primarily through reduction in ruminant agriculture, achieves -394 $MtCO_2we$ by 2050. **Figure 3**b shows the required amounts of net-CO_2we needed for each scenario. For all scenarios the total 2021–2100 cumulative CO_2we for the sum of net-CDR and CH_4 is ~560 $MtCO_2we$ revealing the important warming impact trade-off between CH_4 mitigation and net-CDR requirement. Shallower CH_4 reduction results in a requirement for greater net CDR due to

substantially greater overshoot, increasing the peak carbon debt at ONZ, and somewhat higher cumulative N_2O emissions due to the scenario definition of identical by-mass mitigation rates for CH_4 and N_2O.

Given a practical maximum CDR of cumulative -200 $MtCO_2$ by 2100, as assessed in [59], only **N43.C56**, the scenario with the largest non-CO_2 reduction, achieves a net-CDR level lower than this threshold at -172 $MtCO_2$. Minimising CDR to within the practical limit is primarily enabled by of the large methane mitigation warming reduction of -394 $MtCO_2$we. The N10.C76 scenario requires -604 $MtCO_2$, far greater than the practical CDR threshold; the **N22.C69** and **N30.C64** scenarios also fail to meet this threshold.

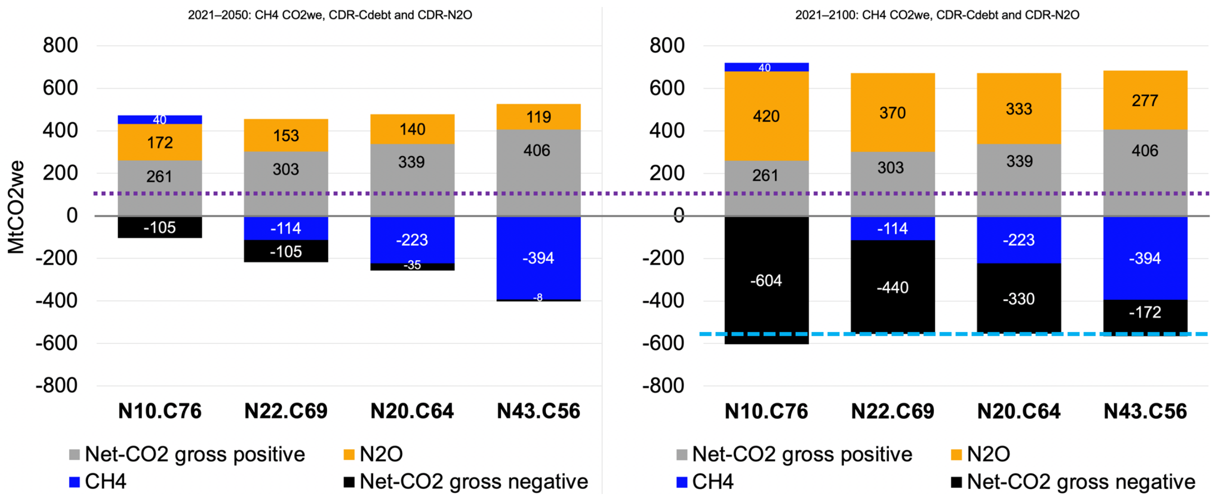

Figure 3. Scenario by-gas CO_2-we values for (a) 2021–2050 and (b) 2021–2100. The level dotted line at 118 $MtCO_2$we indicates the CO_2we national quota of $CO_2+N_2O+CH_4$ remaining from 2021 onward, based on depletion of the 2015 remaining quota over 2015–2021. In (b), the level, light blue dashed line indicates the net warming reduction due to the sum of CH_4 emission rate change and net-CDR.

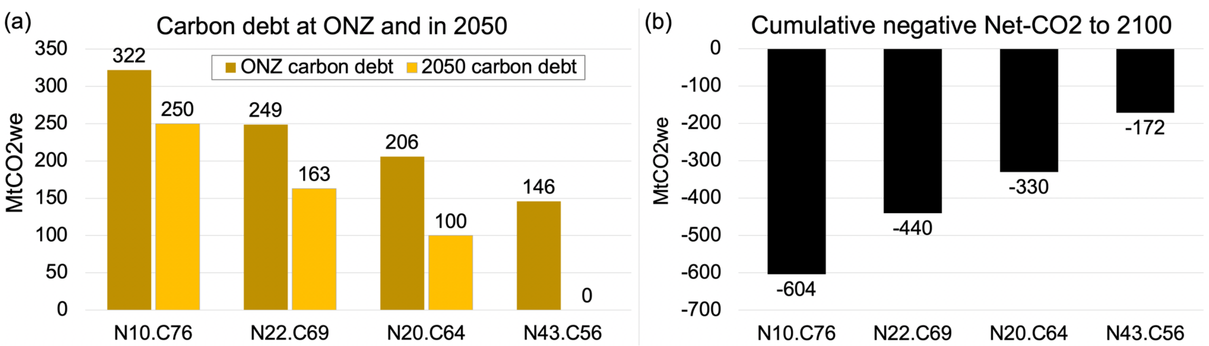

Figure 4. Scenario carbon debt and net negative emissions. (a) Carbon debt at overshoot net zero (ONZ) and in 2050, (b) Cumulative negative net-CO_2 (CDR requirement) up to 2100.

Notably, although the annual CO_2eq flow of both N_2O and CH_4 are reduced by the same rate in each scenario, primarily up to 2030 at each scenario's given non-CO_2 rate, and only very slowly thereafter, the scenarios' temperature impact range for N_2O is 420 to 277 $MtCO_2$we, a spread of 143 $MtCO_2$we, yet the range for CH_4 is +40 to -394 $MtCO_2$we, a spread of 430 $MtCO_2$we. This illustrates the large CH_4 TIR opportunity available that can significantly limit near-term warming in addition to mitigating CO_2 and N_2O. Importantly, in agricultural mitigation assessment relative to a temperature goal, CH_4 and N_2O are not simply exchangeable on a CO_2eq basis. Therefore, CH_4 mitigation is a priority in effective climate action if substantial overshoot or breaching of potential CDR limits is possible. In the scenarios, as shown in **Figure 4**a the national overshoot carbon debt can by substantial at ONZ and in 2050, and, as in **Figure 4**b, only the **N43.C56** scenario constrains the CDR requirement within Ireland's assessed practical limit of 200 MtCO_2 to 2100 suggested in [59]. Substituting CO_2 or N_2O for apparently equivalent CO_2eq reductions in CH_4 via GWP_{100} will result in greater scenario warming, as the cumulative CO_2we outcomes reveal via use of GWP*.

4 Discussion

4.1 CH_4 mitigation in limiting overshoot and CDR reliance

The stark reality of what is now necessary for good faith PA-aligned mitigation by a high-emitting developed Party is plainly conveyed by all four indicative national scenarios in this coarse-grained modelling. Under equal per capita sharing of the defined global warming budget (rGCB*), Ireland's aggregate carbon quota (NCQ*) for CO_2+N_2O+CH_4 was 410 MtCO_2we in 2015, but as of the start of 2021 less than 120 MtCO_2we remained after quota depletion by 2015–2020 emissions. Furthermore, this does not allow for further reductions in the basis for the quota that need acknowledgment, including the issue that IAM's overestimate 1.5ºC global carbon budgets by about 20% [60], or that the national share of global warming due to international aviation and shipping [30] is not accounted for, even though Ireland's frequent-flying citizens and its airlines could be deemed inequitably responsible [61], [62]. Even without these considerations, overshoot of Ireland's 2015-basis NCQ* quota is imminent, occurring in 2023 in all four scenarios. On this basis, radical reductions in all GHGs are urgently required, especially CO_2 and CH_4, starting immediately, at rates well beyond what is generally considered feasible in the national energy and agricultural economics-based modelling of society-wide transition that have hitherto informed climate advisory reporting and emissions projections [63]. If deep reductions in agricultural GHGs are not achieved energy decarbonisation costs are 'extraordinarily challenging' in recent notionally "least cost" energy modelling [64]. Any further delay in meeting the very deep mitigation now required to align national climate action with 'pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels will only increase overshoot peak carbon debt at ONZ and the amount of net warming reduction then required to return to the quota level QNZ via some combination of net CDR and CH_4 reduction. As shown in the scenario results, only deep and early cuts in annual CH_4 emissions, implying substantial mandated reductions in ruminant agriculture, can achieve sufficient warming reduction to effectively limit overshoot by the 2050 date noted in the climate action plans of many Parties and limit CDR within an assessed practical storage limit. Instead, by taking advantage of the ending of the EU milk quota, Ireland's 60% expansion in milk intake from 2010 to 2020 (an outlier in the EU) and a coupled rise in CH_4 emissions, has been driven by agri-food industry strategy endorsed by governments as policy [65], despite the evident conflict with declared climate and environmental policy [66].

For all Parties, substantially reducing the annual CH_4 emissions rate can effectively be considered a negative emission technology, equivalent to net CDR by achieving a warming reduction equivalent to a one-off removal of CO_2 as estimated by CO_2we via use of the GWP* method. Methane emission factors for agriculture and energy are established in UNFCCC inventory reporting and are directly related to activity levels of animal farming, fossil fuel combustion and waste handling. By contrast, CDR technology at the scale needed to achieve PA-aligned mitigation at global or high-emitting Party *without* the CH_4 mitigation seen in IPCC global scenarios, or national-level scenarios as presented here, does not yet exist at the scale required, and must be deemed highly uncertain thereby incurring higher cost and moral hazard given the risk of non-achievement.

4.2 Implications for Ireland's carbon budgeting and sectoral ceilings.

Relative to other UNFCCC Parties, Ireland, like New Zealand, has high CH_4 emissions due to ruminant agriculture, so these nations have a particularly large agricultural CH_4 mitigation opportunity in limiting overshoot and returning to QNZ at the NCQ* level. Achieving the Paris-consistent **N43.C56** scenario would require immediate policy action to limit agricultural milk and livestock (meat) production. This is politically difficult, but without deep CH_4 reduction, as well as reducing fossil fuel combustion for power, industry, buildings and transport (with high costings in recent least cost energy modelling) , it is rapidly becoming impossible to meet the long-term goal. Ireland's CCAC in 2021 operating under time pressure to provide for 2021–2030 carbon budgets under the amended climate Act, presented five alternative "core scenarios" in its CCAC-TR [42] confirming that cutting CH_4 has the largest warming impact compared to cutting CO_2 and N_2O. Contrary to our results, though similarly based on an 1.5ºC rGCB* equal per capita sharing approach, the advisory report appears to overestimate the rGCB*, indicates that no core scenario overshoot of warming quota would occur, and suggests that a 19% reduction in non-CO_2 by 2030 could achieve a "Paris Test" quota threshold by 2050. However, the report appears to overestimate the rGCB* for their core scenario basis of [CO_2+N_2O+CH_4] uses a GWP* time averaging parameter **Δ**t of 1 year rather than the 20 years advised in GWP* literature [37], and the IPCC AR6 2020 reference as a base year, which is arguably less than minimally equitable for fair share assessment [43]. Our scenario results, also in the context of equal per capita sharing of a 1.5ºC 50% rGCB*, but assessed on the basis of a literature-justified base year of 2015 and standard GWP* analysis using literature-recommended parameters, indicate that the CCAC-TR requires reassessment. Toward future improvement of the CCAC's Paris Test, a separate paper in preparation will address these scientific and normative issues.

The results show that overshoot of Ireland's NCQ* limit is imminent and only scenarios with the deepest CH_4 reduction of more than 40% by 2030 can limit overshoot carbon debt and reduce tacit reliance on substantial and highly uncertain net-CDR achievement in excess of balancing ongoing N_2O and within the 200 $MtCO_2$ CDR limit. The 10% CH4 reduction in the Food Vision 2030 policy [56], and the range of 22–30% in agricultural non-CO_2 CO_2eq emissions by 2030 reduction put forward in Ireland's 2021 Climate Action Plan [57], fall well short of the scenario 43% reduction in annual CH_4 emissions found in our modelling as required to achieve effective society-wide mitigation to meet a 2050 quota target, while limiting overshoot and restricting reliance on CDR to repay carbon debt. Concerningly, the proposed agricultural mitigation options in the Climate Action Plan emphases N_2O reduction to achieve the CO_2eq reduction; and the asserted "with additional measures" CH_4 mitigation by 2030 does not appear to be physically achievable, especially given policy that continues to support growth in ruminant-based agricultural production. The possibility of Paris-consistent climate action in Ireland is rapidly being lost due to such policy incoherence.

4.3 Implications for high emitting Parties

The coarse-grained scenario analysis presented for Ireland is indicative for many high emitting Parties: aligning equitable action with the PA-goal requires radical reductions in fossil fuel use, far faster than is generally being considered in advisory documents and research, and effective regulatory efforts to directly abate so-called “hard-to-abate” sectors are also now required. For such Parties, even radical net-CO_2 reduction will not be enough to avoid near-term overshoot of fair share GHG quotas CH_4 mitigation to limit overshoot and reliance on CDR to cut carbon debt. A preliminary analysis for the EU, on the same 1.5ºC scenario basis as here for Ireland, indicates a later 2032 overshoot ONZ year, but similarly the aggregate pathway relies on CH_4 reduction to limit carbon debt and achieve an earlier return to QNZ at the quota level to limit CDR reliance. In further research, more accurate Paris Test analysis for the EU or other Parties needs all climate action policy to show the by-gas scenario emission pathways for all key GHGs from all sectors under proposed scenario alternatives. Although Ireland’s governance system continues to struggle to achieve meaningful climate action, assessing the level of committed action has been greatly assisted by the legal requirements under Ireland’s amended Climate Act for near-term carbon budgeting, with cumulative limits on the 2021–2030 CO_2eq totals, legally binding subordinate sectoral budgets, and a need to show that these near-term budgets are consistent with meeting the Paris Agreement goal equitably. Other Parties could benefit from examining Ireland’s carbon budgeting outline and progress. As shown in this study, the use of GWP* methodology enables comparative assessment of the warming impact of aggregate scenario emissions including CH_4 through calculation of cumulative CO_2we and production of alternative scenarios achieving a fair share of the remaining global GHG warming budget (cumulative CO_2we) from a global common base year.

As the now-abandoned EU milk quota showed, it is possible to apply supply-side limits on nutrient input and animal agriculture output that limit or cut CH_4 emissions from enteric fermentation and GHGs from animal excretion, while still providing the same or greater food production [21]–[24]; and that removing this restriction can result in emissions and warming impact increasing rapidly as has occurred in Ireland [25]. Compared to plant-based diets, food production by animal agriculture is relatively nutrient and land inefficient [26], [27], [22] and reductions in ruminant production and derived food consumption, in particularly in developed Parties, would contribute to meeting the Paris goal through methane mitigation, with environmental and social co-benefits [28], [29]. Similarly, beyond the uncertain effect of proposed technical measures, future aviation and shipping emissions [30] could be directly limited by policy and regulatory instruments to reduce frequent flying [31] or to cut consumption of shipped products through demand management [32]. It should also be noted that the tertiary or ‘service’ sector cannot be considered as inherently low carbon [33]. Therefore, it is highly questionable to categorise agriculture and LUC, or aviation and shipping, or finance and services, in ways that exclude or partially exclude them from global or Party carbon budgeting in relevant advice to decisionmakers. Assessment needs to show the different temperature impacts of different by-gas and aggregate GHG pathways for scenario options across all sectors relative to a quantified and normative Paris temperature goal definition in a CBDR-RC context. The coarse-grained modelling presented here enables such a Party-level assessment.

4.4 Asserting CDR reliance for so-called "hard-to-abate" sectors is hard to justify

AR6-WGIII Ch. 12.3 states:

> *Within ambitious mitigation strategies at global or national levels, CDR cannot serve as a substitute for deep emissions reductions but can fulfil multiple complementary roles: (1) further reduce net CO_2 or GHG emission [67] levels in the near-term; (2) counterbalance residual emissions from 'hard-to-transition' sectors , such as CO_2 from industrial activities and long-distance transport (e.g., aviation, shipping), or methane and nitrous oxide from agriculture, in order to help reach net zero CO_2 or GHG emissions in the mid-term; (3) achieve and sustain net-negative CO_2 or GHG emissions in the long-term, by deploying CDR at levels exceeding annual residual gross CO_2 or GHG emissions*

As this article's results show at a Party level, this characterisation is potentially misleading because GWP_{100} does not reflect the limiting of aggregate temperature impact by rapid CH_4 mitigation. Instead as is noted in AR6-WGIII Ch. 2, using simple climate models, or new approaches like GWP* or CGTP that approximate such models, can show temperature impact of multi-gas mitigation scenarios. The quoted characterisation above reflects a common but problematic presentation common in CDR literature and reviews [68]–[73], including Ch. 12 and other AR6-WGIII chapters (apart from Ch. 2 and 3), whereby GHG analyses based on the GWP_{100} CO_2eq equivalence metric are used to categorise the GHG emissions of particular sectors as "hard-to-abate", thereby potentially misleadingly suggesting that CDR can substantively offset these sector emissions in the near-term and their residual emissions entirely in the long-term. Such CDR-focused reviews fail to make it sufficiently clear that substantial and sustained immediate reductions in CH_4 from all sources, including agriculture, would result in a significant and more certain near-term TIR than from CDR. Mitigation deterrence through appeals to technical fixes is an ongoing issue in climate policy as described by [67]. In short, it does not make sense to "counterbalance" *any* ongoing CH_4 emissions on a GWP_{100} basis with CDR, as doing so is too liable to cause decisionmakers to overlook the greater near-term TIR effectiveness and certainty of CH_4 mitigation and thereby deter near-term CH_4 mitigation effort. As in our methodology, Paris consistency for a Party can be examined by evaluating the aggregate temperature impact over time of alternative society-wide options relative to meeting a quota net zero (QNZ) level corresponding to an estimated fair share temperature impact from a common base year based on defined normative and quantitative basis. A Party achieving "no further warming" ONZ while in overshoot of a minimally equitable PA carbon budget cannot be said to be consistent with PA Article 2.

5 Conclusion

For developing or poorer nations with low per capita emissions, reducing their livestock and other CH_4 emissions is not important within the fair sharing GHG budget framework presented here because they are likely not at risk of near-term GHG quota overshoot, even with substantial increases in near-term fossil fuel use. However, for developed nations with high ongoing emissions, overshoot is already imminent in this fair share context. Therefore, *in addition to* radical CO_2 emissions reduction, substantial CH_4 mitigation can limit peak carbon debt at overshoot net zero (ONZ) and hasten cancelation of this debt to return to quota net zero (QNZ) within a mitigation timeframe centred on 2050. Any policy reliance on CDR to balance a very limited level of long-term residual emissions will need to be assessed with care on the basis of equity as '*[a]ny further delay in concerted anticipatory global action on adaptation and mitigation will miss a brief and rapidly closing window of opportunity to secure a liveable and sustainable future for all.*' [7]. Consequently, the simplistic assertion in much CDR literature that whole sectors, notably intensive ruminant agriculture, are "hard-to-abate is hard to justify in the CBDR-RC context required by the Paris Agreement and too readily enables mitigation deterrence among developed Party decisionmakers and regulation of such sectors. As our results demonstrate, urgent fossil and agricultural CH_4 emissions mitigation over the next decade to enable temperature impact reduction is important to reduce reliance on costly and uncertain CDR, so it deserves much greater focus in national mitigation policy assessments. The coarse-grained methodology presented is easily applicable to any nation or regional UNFCCC Party, enabling rapid comparison of society-wide, aggregate pathway, carbon budget options to align Party-level action with meeting the PA temperature goal equitably.

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