Reply to Comment on: 'Unintentional unfairness when applying new greenhouse gas emissions metrics at country level'

Joeri Rogelj[1,2], Carl-Friedrich Schleussner[3,4]

[1] Grantham Institute, Imperial College London, London, UK

[2] International Institute for Applied Systems Analysis, Laxenburg, Austria

[3] Climate Analytics, Berlin, Germany

[4] IRITHESys, Humboldt University, Berlin, Germany

In reaction to a recent study with the title 'Unintentional unfairness when applying new greenhouse gas emissions metrics at country level', Cain *et al.* submitted a comment to which we here respond. The study referred to by the comment presents a critique of some of the ethical implications of applying a GWP*-like metric at the country level. Henceforth, the original study (Rogelj and Schleussner, 2019) is referred to as RS19. The comment by Cain *et al.* is referred to as CCmt.[i]

Some of the points made by CCmt might contribute to a constructive debate on the application of greenhouse gas metrics in climate policy. Moreover, a broader debate of the ethical implications of greenhouse gas metrics for inter- and intragenerational justice continues to be timely. Unfortunately, most of the discussion provided in CCmt doesn't address the point made by the criticized RS19 study, and seems to start from a misunderstanding of RS19 or from context unrelated to it. We are grateful for this opportunity to clarify these aspects.

Key points of RS19

To contextualize this rebuttal, we first reiterate what RS19 is – and is not – about. RS19 provides a scientific critique of the potential ethical implications of applying GWP*-like metrics at the country level. RS19 therewith highlights an ethical blind spot in the current greenhouse gas metrics literature.

RS19 establishes that applying GWP*-like metrics at any but the global level raises ethical questions of how historic and on-going methane emissions in an atmosphere common to all are nationally accounted for in a fair and equitable manner (see Box 1). RS19 provides a discussion and potential solutions to address this issue.

BOX 1: Illustration of grandfathering of historical methane contributions when applying GWP*-like metrics

The equity issues that are identified in RS19 can best be clarified by means of an example. Imagine three farmers A, B, C who can be called Abraham, Bethany, and Chris – and can be used as analogues for three illustrative countries. Abraham is 21 years old and has ten cows. His father was a farmer and so was his grandfather. Abraham lives a happy and fulfilled life with his ten cows, and does not want to increase their number. Bethany is also 21 years old and comes from a poorer family that historically was not able to afford cattle. However, through a bank credit she was able to also buy ten cows. Also Bethany is happy with her ten cows, and intends to keep her herd constant at that level. Finally, there is Chris, who is also 21 years old and comes from an established farming family. His father and grandfather had a herd of 20 cows passed down over generations. Chris, however, has decided to downsize and now also keeps a herd of just ten cows. Also Chris is happy. Abraham, Bethany, and Chris thus have exactly the same number of cows, with the only difference between them the number of cows their fathers owned. Following equation (1) in CCmt from (Lynch et al., 2020) this would nevertheless result in very different GWP*-based CO_2-equivalent emissions for each of them over their adult farming lives (here assumed to be from about 21 to 70 years, and assuming that 10 cows emit about 1 tonne of methane per year):

– ***Abraham***, keeping his cows at the level of his father and grandfathers, is assigned 140 and 350 tCO_2*-equivalent methane emissions over the first 20 and 50 years, respectively.
– ***Bethany***, who was able to buy 10 cows despite her parents not owning any, is assigned 2240 and 2450 tCO_2*-equivalent methane emissions during the first 20 and 50 years, respectively.
– ***Chris***, who kept half of the 20 cows of his father, is assigned negative 1960 and negative 1750 tCO_2*-equivalent methane emissions during the first 20 and 50 years, respectively.
– ***Globally*** (in this case, simply all three farmers together), methane emissions would be estimated at 420 and 1050 tCO_2*-equivalent during the first 20 and 50 years, respectively. The latter global CO_2*-equivalent emissions reflect the equivalent global warming impact of the on-going global methane emissions.
– Meanwhile, the dung produced by each farmer's herd was also responsible for several additional tonnes (in CO_2-equivalence) of long-lived N_2O emissions which are more similar to CO_2 in their climatic effect and are accounted for identically under GWP and GWP*.

Despite Abraham, Bethany, and Chris having kept exactly the same number of cows for 50 years, their assigned CO_2-equivalent emissions under the grandfathering application of a GWP* metric vary both in sign and magnitude with the only reason for this variation being the number of cows their fathers owned. This example does not provide a solution yet, but clearly illustrates the potential fairness and equity issues as they are presented in RS19 and which surround the application of a GWP*-based metric for policy at any but the global scale.

RS19 explores solutions by looking at the implications of different considerations of equity including redistributing (historic) emissions allowances per capita. These approaches would provide a level playing field for Abraham, Bethany, and Chris. For example, using one of the approaches discussed in RS19, each farmer would be assigned the same share of global CO_2*-equivalent emissions instead of one that depends on the emissions of their fathers. While redistributing national emissions, this approach still accurately captures the global warming implications of short-lived greenhouse gases at the global level expressed in GWP*.

END BOX 1

RS19 does not discuss equity considerations in relation to (historic) CO_2 emissions, and neither does it provide a comprehensive assessment of all ethical implications of treating different greenhouse gases (GHGs) with a common metric. However, the well-established equity context of (historic) CO_2 emissions provides a useful starting point to illustrate the core issues addressed in RS19. For CO_2, a long-lived greenhouse gas, cumulative emissions are linked approximately linearly to global average temperature increase. Considerations of equity and fairness generally lead to the conclusion that actors with higher historical cumulative emissions have contributed more to current warming and therefore have a larger responsibility to reduce their emissions in the future, for example, see McKinnon (2015), Vanderheiden (2008), or Robiou du Pont *et al.* (2016) and Kartha *et al.* (2018). The linear relationship between cumulative CO_2 and global temperature increase allows one to align ethical considerations based on historical emissions and historical warming.

For a short-lived greenhouse gas, like methane, this is different. Here, annual emissions over time determine largely the resulting warming effect, and changes in their emissions rate cause this warming contribution to increase or decrease. A metric like GWP*, focuses on capturing these changes in warming when aggregating different time series of GHGs into CO_2-equivalent emissions, not on the total warming per se. This focus results in a different relation between CO_2-equivalent emissions and warming that raises new questions of equity and fairness. These issues were for the first time highlighted in RS19.

It highlights ethical issues that arise from moving away from an emissions centred metric like GWP-100 – where every unit of emissions of a certain greenhouse gas (GHG) is treated equally and independent of the emitter or timing of emissions – to metrics like GWP* – which focus on additional warming and where the treatment of a unit of emissions depends on the emitter and their emission history. As a consequence, the concept of environmental pollution thus changes when moving towards GWP*. Under an emissions centred metric such as GWP-100 every GHG emission constitutes an act of environmental pollution. Warming centred metrics like GWP*, on the other hand, only capture the additional pollution outcome. RS19 clarifies that a switch between metrics is thus not just a question of physics but represents a change to the normative framework.

Specifically, RS19 outlines how application of the GWP* metric, which focusses on warming differentials, can strongly benefit actors with high historic methane emissions in ways an emissions-focused perspective (represented by GWP-100, or by the direct reporting of individual gases) would not. This potential benefit for high historic methane emitters contrasts with considerations of equity and fairness (Dooley et al., 2021; Kartha et al., 2018), and constitutes what is typically referred to as 'grandfathering' in the equity debate. When considering to use a GWP*-like metric, one first needs to address the equity and fairness issues related to the right of an emitter to occupy their current share of global atmospheric warming, which is caused by their past and present emissions of short-lived greenhouse gases. Only thereafter, a GWP*-like metric can be applied to give credit to changes in countries' warming contribution due to changes in on-going and future emissions of short-lived greenhouse gases. The standard application of GWP* starting from today disregards the question of historic responsibilities and is referred to in RS19 as the 'grandfathering' GWP*.

The issues highlighted in RS19 are most effectively illustrated by CCmt, with an altered version of the example available in Box 1. CCmt's adaptation describes three different methane sources A, B and C. For each of the sources, CCmt describes how future CO_2-equivalent emissions of methane estimated with GWP* and their warming contributions differ as a function of the sources' respective historical emissions (as does our example in Box 1). The CCmt example, however, remains silent on the ethical implications of the different starting points of the various sources, highlighting the ethical blind spot that RS19 described. By not acknowledging this ethical question, CCmt's example implicitly suggests that it is OK, by default, to grandfather historical levels of methane warming into assessments of future mitigation contributions. Conceptually, a historical high emitter is thus rewarded for its past pollution by receiving, either literally or figuratively speaking, credit for continuing to pollute at a lower level than before. Overlooking ethical aspects of countries' emissions while focussing on their warming impact alone, as is the case in CCmt, neglects the point that besides aiming to hold warming well below 2°C and 1.5°C, international climate policy as set out under the Paris Agreement *"will be implemented to reflect equity and the principle of common but differentiated responsibilities and respective capabilities, in the light of different national circumstances"* (UNFCCC, 2015).

RS19 outlines real-world consequences of the application of GWP* and outlines how developed countries, some of which have per capita methane emissions that are about an order of magnitude higher than most developing countries, would clearly benefit from the grandfathering perspective that is implied by a direct application of GWP* relative to the recent past (see Figure 1 in RS19).

Having identified the issue, RS19 proposes a set of possible solutions. It highlights various concepts of equity, such as burden sharing vs resource sharing (Rao, 2011), to establish equitable reference levels for countries' methane emissions and quantifies five different variants of GWP* metrics that reflect these concepts in different ways. Several of these variants keep *global* GWP* emissions at exactly the same level as would be the case under the original GWP* formulation, but redistribute (historic and other) reference emissions on a per capita basis to the level of individual countries, therewith exploring various possible interpretations of equity. Furthermore, RS19 also discusses how GWP* emissions in a given year can vary by an order of magnitude because of methodological choices, highlighting challenges for avoiding loopholes in international emissions trading if GWP* metrics are applied by countries. Despite giving examples, RS19 neither indicates a specific approach to be ethically superior nor does RS19 define what is or isn't fair in the context of a specific country.

Observations and reflections

CCmt's first section titled 'Overview' unfortunately fails to acknowledge or address the fairness perspectives presented in RS19. CCmt instead repeats the already well-established discussion of how GWP* provides a closer link between cumulative CO_2-equivalent emissions and global mean temperature increase, compared to CO_2-equivalent emissions estimated with a common GWP-100 metric. This aspect has been extensively described in the scientific literature by the same authors (Allen et al., 2018; Cain et al., 2019a; Lynch et al., 2020), is not disputed, and is explicitly acknowledged and repeated in RS19.

CCmt further presents aspects related to comparing different greenhouse gases, such as CO_2 and methane, which are fairness aspects different from those that were critiqued in RS19. These aspects of CCmt's criticism on RS19 hence do not address the initial critique but instead simply mention other only vaguely related issues. This approach in our view rather distracts than contributes to a constructive exchange. The existence of equity issues when comparing different greenhouse gases in different metrics does not negate the grandfathering or other distributive justice issues that arise as part of on-going emissions of short-lived climate forcers between countries. The latter can occur when a GWP*-like metric is applied to individual countries without considering the fairness and equity of their historical levels of short-lived emissions. Unfortunately, CCmt chose not to engage with this question of distributional justice that is central to RS19. Meanwhile, a group of the world's biggest diary producers seems happy to consider the grandfathering GWP* perspective and explicitly dismisses other fairness perspectives that would increase their companies' responsibility for reducing methane emissions (Cady, 2020).

CCmt's overview section contains several statements that require clarification or correction.

GWP* metric version – CCmt writes that it appears that RS19 applied the equation provided by Allen *et al.* in 2018 (Allen et al., 2018) and not the expanded version published by Lynch *et al.* in 2020 (Lynch et al., 2020). We'd like to clarify that there should be no doubts on this matter to the attentive reader. RS19 explicitly states that it is *"following Allen et al. (2018)"* and it reproduces the equation that is used. Furthermore, RS19 was published in the year preceding the publication of Lynch *et al.* (2020), which provides a compelling reason for why the equation from Lynch *et al.* (2020) was not yet applied. Missing from the observations by CCmt, however, is an acknowledgment that RS19's ethical critique of GWP* remains valid, also if more recent expressions to estimate CO_2-equivalent emissions with GWP* (Cain et al., 2019a; Lynch et al., 2020) would be applied. In a constructive and valuable contribution to the debate, CCmt does, however, highlight that RS19's critique is also more widely applicable beyond GWP*, to metrics with similar characteristics such as the Combined Global Temperature Potential (Collins et al., 2020).

Greenhouse gas metrics in UNFCCC – CCmt correctly notes that the GWP-100 metric has been agreed as the default greenhouse gas metric for the reporting of aggregated national emissions and removals, and this is hence the only metric for which internally consistent information will be made available across all countries under the United Nations Framework Convention on Climate Change's (UNFCCC) Paris Agreement (UNFCCC, 2018). Countries can also choose to apply other metrics to aggregate emissions, as part of supplemental information or in the context of their national targets. Hence the important warning in RS19 that applying default GWP* metrics to national emission targets by countries with historically high methane emissions would lead to grandfathering and unfairness issues.

CCmt incorrectly claims that because *"calculating the current rate of CO_2-warming-equivalent (CO_2-we) emissions using GWP* (E*) involves differencing two rates of GWP100-based CO_2-e emissions"* it is hence *"entirely compatible with the UNFCCC decision to report emissions using GWP100"*. This is a misrepresentation of the UNFCCC decision in question (UNFCCC, 2018). In this 2018 decision, the UNFCCC decided that *"each Party shall report estimates of emissions and removals for all categories, gases and carbon pools considered in the [greenhouse gas] inventory […] on a gas-by-gas basis in units of mass at the most disaggregated level"* (UNFCCC, 2018). All gases are thus reported separately without using a greenhouse gas metric. However, when considering all greenhouse gas emissions together it specifies that *"each Party shall use the [GWP-100] values from the IPCC Fifth Assessment Report, or 100-year time-horizon GWP values from a subsequent IPCC assessment report […] to report aggregate emissions and removals of GHGs, expressed in CO_2 eq"* (UNFCCC, 2018). In the context of UNFCCC decisions, it has been established for over a decade that aggregating greenhouse gas emissions with GWP-100 means that each individual gas is multiplied by its respective GWP-100 value and all contributions subsequently summated. To argue – as CCmt and other papers by the same authors (Lynch et al., 2020) do – that a very different metric would be *"entirely compatible"* with the Paris Agreement because it is based on a manipulation of GWP-100 values can therefore not be taken seriously in light of the long-established legal context of the UNFCCC and the interpretation of international treaties (Gardiner, 2015).

We agree with CCmt that the ambiguity in the temperature outcome of emissions levels and targets can be avoided by treating each greenhouse gas separately. Fortunately, historical and current greenhouse gas emissions are reported by countries for each greenhouse gas individually for the past two decades already. As indicated above, this separate treatment is also the established standard for greenhouse gas reporting under the Paris Agreement. Scientifically, this represents the best and most transparent approach, which is also being discussed as part of the transparency guidelines for how projections of greenhouse gas emission and removals should be communicated for pledged Nationally Determined Contributions (NDCs) by countries, for example, see UNFCCC (2020).

CO_2 versus short-lived forcer mitigation – A second misrepresentation by CCmt is their suggestion that the equity perspectives for short-lived climate forcer mitigation across countries presented in RS19 would imply a value judgement not *"to implement active CO_2 removal"*. As clarified above, RS19 does not deal with equity considerations in relation to CO_2 and thus neither implies that CO_2 should not be reduced, nor that it should not be reduced beyond zero. Without any doubt, considerations of equity are important to inform fair levels of CO_2 removal between countries, and we have contributed to recent literature that pioneers fairness approaches in this context (Fyson et al., 2020).

RS19 highlights that perceived negative contributions under a grandfathering GWP* metric could be used by countries to offset or not implement further CO_2 emission reductions. This understanding is shared by RS19 and CCmt, as members of the CCmt author team have earlier written that *"[A] decline [of 24%] in methane emissions [by 2050] would actually generate enough cooling to compensate for the warming generated by all the non-methane greenhouse gases emitted by New Zealand as they approach net zero. […] [The reductions in New Zealand's agricultural methane emissions] would offset the warming impact of all the other emissions. New Zealand could declare itself climate neutral almost immediately, well before 2050, and only because farmers were reducing their methane emissions. That's a free pass to all the other sectors, courtesy of New Zealand's farmers"* (Cain, 2019). There is thus a clear and acknowledged risk that negative GWP* contributions that result from reductions of short-lived climate forcer emissions are considered to compensate or as a *"free pass"* for CO_2 emissions in other sectors – a point for which RS19 highlights that it would favour historic high emitters of methane (or other short-lived greenhouse gases) when the grandfathering GWP* metric is applied.

The above quote also provides the precise context in which Cain (2019) earlier referred to the cooling effect of methane reductions. RS19 indicated that such a statement would amount to a misunderstanding or misrepresentation. To be sure, the physics of what occurs in this case are undisputed but the RS19 critique comments on the ethical position of the statement. When the effects of lowering methane emissions from a high baseline are described exclusively as cooling, historically accrued annual methane emissions are considered a *fait accompli* relative to which deviations are expressed irrespective of the ethical consequences of that choice. Equally unethical is the use of the term climate neutrality in this context, which implies grandfathering and is fundamentally skewed towards benefitting historical high emitters of methane. Because methane warming is largely the effect of on-going emissions, an equally valid, emissions-focussed perspective is to describe this evolution merely as 'less warming' from on-going methane emissions. Physically the same, but ethically different. The difference in views result from different ethical choices about historical responsibility and time horizon. In context of RS19, which discusses these ethical challenges, failure to communicate the existence and implications of this choice was considered an inaccurate representation of the full picture of ethical implications. We thus consider the initial critique by RS19 to remain valid both at the national and the global level.

Grandfathering of emissions versus warming – A third misrepresentation by CCmt is what they refer to as a *"fundamentally flawed assumption"* in making no clear distinction between grandfathering of emissions and grandfathering of warming. CCmt only seems to argue in terms of ethical principles that are linked to historical warming contributions and between various greenhouse gases, disregarding the points raised in RS19. RS19 highlights equity issues that are linked to distributive justice as part of on-going emissions of short-lived climate forcers between countries. These equity issues are additional to historical warming considerations from long-lived greenhouse gases. What is described as a fundamentally flawed assumption is thus based on a misrepresentation of RS19.

CCmt highlights that it is not evident to them if different ethical standards should be applied to methane and CO_2. Although not part of the discussion in RS19, considerations of the treatment of ongoing emissions from short lived non-CO_2 gases such as methane and long-lived gases such as CO_2 exist. It is intuitive to understand that different equity implications can be identified for warming caused by multi-decade-old emissions of long-lived greenhouse gases (emitted by a cohort of the global population at a time when climate science was less robustly established or widely understood and no clear low-carbon alternatives were available) compared to on-going warming of short-lived climate forcers of which the effects and impacts are currently well established and that could be reduced today with available technologies. No different ethical standards have hence to be applied for different ethical implications to emerge. Reflecting on distributive versus corrective approaches to climate justice can further contribute to this discussion of the treatment of various greenhouse gases, as has been done earlier for CO_2 (McKinnon, 2015).

Fairness consequences of specific GWP* use – CCmt state that the unintentional unfairness consequences from GWP* are not a characteristic of the metric in itself, but of the policy framework in which it is embedded. This is indeed correct. As RS19 describes: the equity and unfairness consequences that could result from using GWP* occur specifically when GWP* is applied to the country level without taking into account historical contributions of short-lived climate forcers like methane. RS19 clarifies this point and states that *"Applied at the global level they provide clear scientific merit with a more direct link between the representation of CO_2-equivalent emissions and their warming impact. However, when applied at a national level they all suffer from the same implicit grandfathering bias, […]"*. Without evidence or examples in support of CCmt's implicit claim that specific policy frameworks would exist in which the application of GWP* metrics at the country level would not result in unintended fairness consequences, the original statement by RS19 remains a valid and correct reflection of limitations of GWP* metrics. We agree with CCmt that many alternative ways of using GWP*-like metrics exist which may offer a way to address this issue – a first, but very likely not last, example of such alternative ways is described in RS19.

CCmt write that *"there is nothing inherently unfair or inconsistent in the use of a metric that more accurately reflects impact on [global mean surface temperature] to inform decisions".* This is only partially true: it is the specific use of a metric that determines whether it will be considered unfair or inconsistent within a policy context. Indeed, RS19 highlights that applying GWP* to compare methane mitigation contributions between countries without taking into account their historically grandfathered starting position is deeply unfair. CCmt in addition writes that *"the use of a metric that reflects the impact of all gases on [global mean surface temperature] makes it easier to include methane in discussions of historical responsibility, not the reverse".* We agree, and RS19 provides a way of applying GWP* concepts while dealing with these fairness aspects. This perspective can be further expanded with the additional inclusion of fairness considerations that discuss contributions between various greenhouse gases. Unfortunately, such an expanded, integrative perspective was not provided by CCmt.

Sensitivity of GWP*-based metrics to parameter choices – Finally, CCmt write in their comment that the choice of time interval ΔT used to determine rates of change for GWP*-like emission metrics does not *"strongly alter results".* This statement holds only in the highly idealized case considered by CCmt in which climate targets are expressed purely in terms of cumulative warming-equivalent emissions and under the stylized assumption that annual emissions change smoothly over time. Reality contrasts strongly with these simplifying assumptions.

As part of their NDCs (https://www4.unfccc.int/sites/ndcstaging/), countries are submitting targets for *annual emissions* at *five-yearly intervals* instead of the cumulative emissions targets assumed by CCmt. Furthermore, real-world methane emissions do not necessarily change smoothly over time, as illustrated by data in historical national emission inventories (Crippa, M. et al., 2019). These real-world emission features make estimated GWP* emissions in a given year sensitive to the choice of time interval ΔT. Annual GWP* emission values in a given year are thus sensitive to time intervals that can potentially be arbitrary picked to set and describe 'nationally determined' targets for a specific year and can hence vary strongly from country to country and NDC to NDC. The ad-hoc application of GWP* metrics at the country level thus opens a potential door to undermining emission accounting integrity and comparability across countries and over time.

For the eGWP* metrics introduced in RS19, changes in the time interval ΔT further affect the reference levels that are used to estimate per capita fair shares of global short-lived methane emissions (defined in Equation 3 in RS19). These shares are not just informed by individual countries' historic emissions, but also by emissions of other countries and population dynamics (see the orange line in RS19 Fig. 2b to see China's 'per capita equitable emissions' changing over time).

The 'zero reference' case in RS19 is indeed an extreme case that can be used to approximate the warming resulting from historical methane emissions in the first timestep of an emissions series analysis. The choice of time interval ΔT has the strongest influence here because the reference point is invariably zero. Whether ΔT is chosen to be 1 or 20 years,

$\Delta E(t)$ always equals $E(t)$. If countries choose to continue with a different eGWP* metric and different time interval ΔT thereafter, this would lead to inconsistencies. Robust guidance is required but would be difficult to enforce as countries can pick and choose their preferred 'nationally determined' approach. In the past, countries have shown to be unhelpfully creative in defining nationally determined targets for their land use, land-use change, and forestry (LULUCF) sectors (Fyson and Jeffery, 2019).

In RS19 Figure 3, and throughout the manuscript, a standard time interval of $\Delta T = 20$ years was applied to estimate emissions under varying metrics for the year 2015. The figure correctly shows how CO_2-equivalent methane emissions in the year 2015 can vary depending on the type of GWP*-based metric that is used, following equations cited in the manuscript. This suggestion by CCmt that an error in the rate of change contribution in the GWP* equation was made in RS19 is thus unsubstantiated and invalid.

Policy context for greenhouse gas metrics

In this last section, we have a closer look at the international policy context in which greenhouse gas metrics are used, and which CCmt comments on in several instances.

CCmt writes that *"metrics were introduced to inform and evaluate policy options, not to dictate policy outcomes"*. This is only part of the story.

Although initially devised to inform and evaluate policy, decisions and established practice mean that the use of GWP-100 has become part of the policy context and the interpretation of UNFCCC policy decisions, including the Paris Agreement. The metric therefore does not dictate the policy outcome, but the decisions of countries to apply a given metric does. For example, under the Paris Agreement, countries have decided to use GWP-100 as the standard metric to aggregate emissions and removals (UNFCCC, 2018). This has clear and measurable implications for the policy outcome of the Paris Agreement's 'net-zero' goal that is described in its Article 4 (Fuglestvedt et al., 2018; Rogelj et al., 2021): global warming will peak and subsequently start to decline. When considering alternative metrics, also policy targets that refer to emissions reductions have to be adequately converted for their original meaning or ambition not to be changed.

CCmt further writes that statements by RS19 would suggest that *"the policy context is immutable, but it is not"*. This is only partially correct.

First, the past policy context is indeed immutable. In particular, the Vienna Convention on the Law of Treaties states that *"a treaty shall be interpreted in good faith and in accordance with the ordinary meaning to be given to the terms of the treaty in their context"* (Gardiner, 2015). The context in which the Paris Agreement was negotiated and adopted is situated in the past and does not change. The suggestion by CCmt that countries cannot have given meaning to parts of the Paris Agreement based the standard GWP-100 metric is baseless, given that GWP-100 was the established approach to report aggregate emissions under the UNFCCC in 2015 and had already been used to this end for more than a decade in similar contexts. The historical policy context in which the Paris Agreement was adopted is thus undeniably one in which GWP-100 is the standard metric to assess aggregated emissions and removals of greenhouse gas emissions.

Second, the current and future context of policy *can* change. However, UNFCCC policy in itself only changes through new policy decisions adopted by all Parties to the Agreement, not by scientists redefining past decisions through new, alternative methods.

These important reservations are not appreciated by CCmt. CCmt discusses the use of novel metrics in a climate policy context including under the Paris Agreement. CCmt claims that *"there is no inconsistency between warming-equivalent emissions and the Paris architecture, and since all metrics are based on a linearization, to allow the responses to different emissions to be added up, there is also no reason to restrict their application to global emissions".* However, this discussion misses out on the fact that the mitigation action architecture of the Paris Agreement encompasses more than just a temperature goal. Analysis elsewhere has shown that GWP* cannot be considered directly consistent with the Paris Agreement (Schleussner et al., 2019). In fact, the latter study shows that a plain application of GWP* to net zero greenhouse gas targets as a proxy for the Paris Agreement's Article 4 could undermine the integrity of the mitigation architecture of the Agreement, with extreme cases even failing to ensure that warming would be halted during this century.

Applying novel metrics to a pre-defined policy context is thus problematic if no appropriate measures are taken to ensure internal consistency with the earlier use of metrics in that context. Switching to GWP* without adjusting the targets that rely on the policy context in which the Paris Agreement was adopted changes the agreement's ambition and is thus not merely a technical or scientific clarification, but a masked change in policy ambition. This outcome can be avoided, but only by diligently considering how the ambition and outcome of the Paris Agreement goals are affected by this change.

Finally, using the GWP* metric to compare various greenhouse gases provides an improved equivalence between cumulative CO_2-equivalent emissions and their global temperature rise implications. However, the challenge for its robust application in the current climate policy context lies in the fact that targets are not expressed in terms of cumulative CO_2-equivalent emissions. They are expressed as single-year milestones instead. This is true both for NDCs and long-term low-carbon strategies that include many net-zero targets. For such single-year targets, GWP*-weighted CO_2-equivalent emissions provide a weak metric because small single-year fluctuations in methane emissions have a very strong impact on the amount of net WGP*-weighted emissions in a given year.

To conclude our reflections on policy context, we want to highlight how requirements of an accounting metric differ between policy and physics. The climate policy context includes distributional questions between countries and sectors, and over time; it also includes market mechanisms. As we have outlined above, accounting based on GWP* is both time as well as (historical) context dependent. This dependence renders its direct application in a real-world policy context problematic. A crucial requirement for a functioning metric in policy or market mechanisms would be that a tonne of emissions of a certain greenhouse gas is accounted the same, independent from who emits it or when it is emitted. Being based on the long-term warming effect of an isolated emission pulse, GWP-100 provides this. To be sure, we acknowledge the limitations of the standard GWP-100 metric that are by now well understood. However, this context might provide an explanation for its prevalence in climate policy despite its shortcomings in representing the direct warming effect of short-lived greenhouse gases. GWP* provides a physical-science improvement to the metric, but its use for policy still requires important further work. As RS19 illustrates, it would be overhasty to conclude that because something is deemed to be the better choice from a physical science perspective, it is also automatically the better choice from an ethical or policy perspective.

Conclusion

In conclusion, we welcome CCmt's thoughts on this issue but have only to a limited degree been able to engage constructively because many statements misrepresent the original position of RS19, or speak to other issues. Nevertheless, this exchange highlights the difficulties to accurately communicate the wider implications of using GWP* because of different choices that are built into the metric and which are easily underappreciated or misunderstood by users. This exchange furthermore also provides a good illustration of persistent interdisciplinary gaps in understanding as well as implicit and disciplinary biases that have to be addressed when translating insights from physics-oriented modelling exercises to policy and society. We conclude that this topic would benefit strongly from contributions by interdisciplinary, science-policy and climate ethics scholars.

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[i] The first version of the comment, published online as a pre-print (Cain et al., 2019b) misrepresented RS19 and statements throughout the comment included contradictions. A reply to this first version of the comment is documented in the associated pre-print archive (Rogelj and Schleussner, 2021), and was shared bilaterally. This reply responds to the revised version of CCmt.