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Corrigendum: Global climate impacts of forest bioenergy: what, when and how to measure?

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In table 1, the units in the last column '∆ Albedo' should be 'W m^{-2} kgC^{-1}' (not 'W kg^{-1} C^{-1}'). The corrected table and caption are shown below.

Table 1. Emissions per MJ of fuel combusted in the different energy systems and changes in surface albedo (instantaneous, at harvest) to be characterized with the metrics considered in this paper. Albedo values indicate the local radiative forcing (W m^{-2}) per unit of biomass harvested (in kg C). Abbreviations: Bio CO_2 = biogenic CO_2 emissions (from upstream carbon losses through conversion stages and combustion at plant); US = United States (east coast); PNW = Pacific Northwest; WI = Wisconsin; CA = Canada; NO = Norway; NO (fr) = Norway with collection of 75% of forest residues; NG = natural gas. A complete description of the case studies is available in [30].

Heat	CO_2 (g MJ_{fuel}^{-1})	Bio CO_2 (upstream) (g MJ_{fuel}^{-1})	Bio CO_2 (combustion) (g MJ_{fuel}^{-1})	CH_4 (mg MJ_{fuel}^{-1})	N_2O (mg MJ_{fuel}^{-1})	∆ Albedo (W m^{-2} kgC^{-1})
Willow, US	9.92	7.49	107	0.93	29.4	n.a.
Wood, PNW	16.5	12.3	96.0	26.3	2.44	−0.27
Wood, WI	27.7	13.1	97.6	36.9	2.44	−2.79
Wood, CA	8.96	13.1	101	6.52	3.21	−3.54
Wood, NO	4.94	12.3	95.9	29.4	15.5	−1.76
Wood, NO (fr)	4.94	12.3	95.9	29.4	15.5	−1.59
Fossils, NG	73.1	n.a.	n.a.	1.82	0.32	n.a.
Fossils, Oil	92.9	n.a.	n.a.	52.3	1.92	n.a.
Fossils, Coal	122	n.a.	n.a.	348	1.57	n.a.

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Global climate impacts of forest bioenergy: what, when and how to measure?

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Abstract

Environmental impact studies of forest bioenergy systems usually account for CO_2 emissions and removals and identify the so-called carbon debt of bioenergy through comparison with a reference system. This approach is based on a simple sum of fluxes and does not consider any direct physical impact or climate system response. Other recent applications go one step further and elaborate impulse response functions (IRFs) and subsequent metrics for biogenic CO_2 emissions that are compatible with the life-cycle assessment (LCA) methodology. However, a thorough discussion about the role of the different metrics in the interpretation of the climate impacts of forest bioenergy systems is still missing. In this work, we assess a single LCA dataset of selected bioenergy systems using different emission metrics based on cumulative CO_2 emissions, radiative forcing and global surface temperature. We consider both absolute and normalized metrics for single pulses and sustained emissions. The key challenges are the choice of end point (emissions, concentration, radiative forcing, change in temperature, etc), the type of measure (instantaneous or time-integrated) and the treatment of time. Bioenergy systems usually perform better than fossil counterparts if assessed with instantaneous metrics, including global surface temperature change, and in some cases can give a net global cooling effect in the short term. The analysis of sustained, or continuous emissions, also shows that impacts from bioenergy systems are generally reversible, while those from fossil fuels are permanent.

As shown in this study, the metric choice can have a large influence on the results. The dominant role traditionally assigned to cumulative metrics in LCA studies and climate impact accounting schemes should therefore be reconsidered, because such metrics can fail to capture important time dependences unique to the biomass system under analysis (to which instantaneous metrics are well suited).

Keywords: life-cycle assessment (LCA), bioenergy, emission metrics

S Online supplementary data available from stacks.iop.org/ERL/8/014049/mmedia

1. Introduction

1.1. Background

Life-cycle assessment (LCA) studies, emission accounting schemes, and climate policy regulations need to compare emissions of different greenhouse gases (GHGs) using simplified metrics. A range of metrics able to aggregate the climate impact of different forcings in common units are currently available. The Global Warming Potential (GWP) introduced by the IPCC in 1990 [1] is by far the most recognized and applied emission metric, given its predominant use in emission reporting under the UNFCCC [2], Kyoto Protocol [3], LCA studies [4] and policies [5, 6]. Regarding GWP, the radiative forcing from a pulse emission at time zero is integrated until an arbitrary time horizon (TH) and divided by the result of an equivalent integration for CO_2. One of the main reasons for the selection of a TH is that a pulse emission of CO_2 has a very long response that does not decay to zero, so that the computation of a normalized metric requires some arbitrary cut-off. GWPs are frequently studied, discussed and criticized in climate science [7–12]. One main criticism to GWP is that it is built on a concept, radiative forcing, which is less clear than temperature change in terms of climate impact, so that it is perceived to be inappropriate in certain contexts [13]. However, recent studies show that cumulative CO_2 emissions can be an effective constraint on peak temperature [14–16], suggesting that future temperature-based targets can be met by setting a limit to cumulative CO_2 emissions. Further criticism to the GWP concerns the treatment of short-lived GHGs [9, 17]. The Global Temperature change Potential (GTP) has been proposed as an alternative to GWP [18], and is the ratio between the temperature response at a certain time from a pulse emission and the temperature response for a reference gas, usually CO_2. While GWP is an integrative measure that considers the total radiative forcing contribution over the selected TH, the GTP is an instantaneous metric that considers the instantaneous impact at the specific time. Following from GTP, the Integrated Global Temperature change Potential (IGTP) is the integrated temperature response from a certain gas divided by the integrated temperature response from the reference gas (CO_2) [18–20]. In addition, the Sustained Global Temperature change Potential (SGTP) has been proposed as the temperature response at a certain TH of a sustained (i.e., continuous) emission of the gas at a constant rate divided by the temperature response following sustained emissions of CO_2 [18]. The TEMP is also a metric applied to sustained emissions but based on the integrated temperature response [21, 22]. Several papers investigated the analytical and conceptual relationships between emission metrics [9, 13, 18–20, 23, 24]. GWP and IGTP are shown to be similar in magnitude [19, 25] and tend to be asymptotically equal when the time horizon approaches infinity [20, 26]. A close similarity has been shown between SGTP and GWP [18], with SGTP being basically identical to IGTP when linearity in the temperature response is assumed [20]. Others have also assessed metrics where both economics and physical considerations are taken into account [10, 27, 28].

1.2. Aim and scope of the study

Connections between metric-oriented studies and LCA applications are limited, in particular in the context of bioenergy, and more specifically in the context of forest bioenergy, where systems are usually assessed through accounting of cumulative CO_2 fluxes. This type of analysis does not consider any direct climate response. Further, it reveals serious shortcomings when climate agents other than GHGs (e.g., changes in surface albedo, aerosols) need to be assessed with common units. Recent research developments moved further into the climate system and elaborated impulse response functions (IRF) and GWPs for CO_2 emissions from biomass combustion considering the additional carbon sink ensured by re-growing vegetation in addition to surface albedo dynamics, thereby integrating these complex mechanisms into conventional LCA and subsequent applications [29, 30]. However, a thorough analysis of the different climate metrics in the bioenergy context is still missing, and the time is ripe for LCA practitioners to take advantage of this growing literature on emission metrics to investigate the additional outcomes that can be gathered when options other than cumulative CO_2 emissions and GWPs are used to compare the effects of various forcings on climate. In this paper, we focus on structural uncertainties of the metrics [11], i.e., the implications of using different types of metrics (GWP, GTP, etc) for a given application, including an analysis of key aspects and choices like the selection of a TH and end point, and the consideration of a pulse emission versus a sustained emission. The issues related to scientific uncertainties, i.e., the range of values that can be computed for any given metric due to uncertainties and variations of parameters in the climate system (e.g., radiative efficiency, climate sensitivity, climate efficacy, etc), are not included in this work. Some insightful papers discussed these aspects in detail [22, 31–34].

2. Methodology

2.1. Description of the case studies

A complete description of the case studies to which different metrics are applied is available in [30], and we only reiterate some key information here. Table 1 shows the total GHG emissions through the life cycle (from biomass harvest to combustion in a stationary plant) of the different heat production systems, as well as biogenic CO_2 emissions (both from direct combustion of the biofuel and oxidation during the various conversion stages). Values from changes in surface albedo are also reported. They occur after forest harvest and are of significance in regions affected by seasonal snow cover. This temporary perturbation causes a global cooling contribution thanks to the higher reflective property of snow-covered open land than forest canopy, and gradually decreases as albedo reverts back to the pre-harvest value after a certain time.

For these cases there is no land use change (LUC) because bioenergy is produced from already forested stands. We assume that such stands are carbon neutral along the rotation period. It follows that climate effects from biogenic CO_2 and albedo are only temporary. For deforestation or LUC cases the C-cycle and albedo change impacts would be clearly permanent.

2.2. The cause–effect chain

The impacts on climate of various GHGs or other climate forcings (that is any imposed perturbation of the Earth's energy balance) can be aggregated and evaluated at different points of the cause–effect chain, as shown in figure 1. There is more relevance for policy makers as the metric moves down the chain from emission to damage, but this often occurs

Table 1. Emissions per MJ of fuel combusted in the different energy systems and changes in surface albedo (instantaneous, at harvest) to be characterized with the metrics considered in this paper. Albedo values indicate the ratio between the local radiative forcing (W m^{-2}) and biomass yields (kg C m^{-2}). Abbreviations: Bio CO_2 = biogenic CO_2 emissions (from upstream carbon losses through conversion stages and combustion at plant); US = United States (east coast); PNW = Pacific Northwest; WI = Wisconsin; CA = Canada; NO = Norway; NO (fr) = Norway with collection of 75% of above ground forest residues; NG = natural gas. A complete description of the case studies is available in [30].

Heat	CO_2 (g/MJ_{fuel})	Bio CO_2 (upstream) (g/MJ_{fuel})	Bio CO_2 (combustion) (g/MJ_{fuel})	CH_4 (mg/MJ_{fuel})	N_2O (mg/MJ_{fuel})	Δ Albedo (W kg^{-1} C^{-1})
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Fossils, NG	73.1	n.a.	n.a.	1.82	0.32	n.a.
Fossils, Oil	92.9	n.a.	n.a.	52.3	1.92	n.a.
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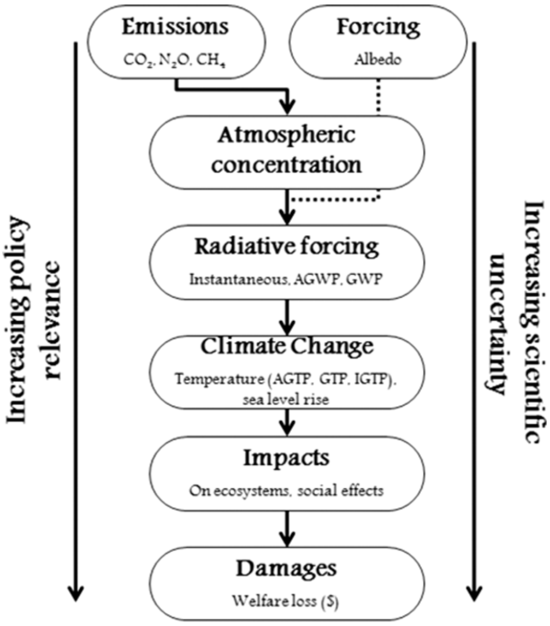

Figure 1. Cause–effect chain of the potential climate impact of emissions and climate forcings. Adapted from [11, 8].

at the expense of higher scientific uncertainty. Carbon debt studies sum CO_2 flows and stop at the first point of the chain. Moving down, emissions of GHGs cause a change in the respective atmospheric concentration of the gas, which then decays following its Impulse Response Function (IRF). This effect leads to some radiative forcing (ΔF), which is the perturbation of the Earth's energy balance at the top of the atmosphere by a climate change mechanism [35]. Radiative forcing is the basis for the most common emission metric GWP and it is the first end point that allows any direct comparability of the climate impact among GHGs and other climate forcing agents. However, ΔF implicitly assumes that all forcings have the same climate efficacy, i.e., forcings from different climate change mechanisms have the same climate response in terms of global surface temperature [9, 36]. Differences in these climate feedbacks associated with the various forcings are included in the effective forcing, which is based on agent-specific climate efficacies [37–39]. Despite some variations in climate efficacies from different models, N_2O and CH_4 are found to be more effective than CO_2, and the climate response to a change in snow albedo (either from soot deposition or snow-covered land use change) is between 1.5 and 5 times more effective than that of CO_2 [37, 38, 40, 41].

Impacts based on a climate response like changes in surface temperature are affected by higher levels of uncertainty than impacts on radiative forcing due to uncertainties in the response timescales and sensitivity of the climate system [31, 32]. After temperature change, other end points like sea level rise and ocean heat content are sometimes computed to reflect the time-integrated perturbation in air–sea fluxes [19, 31, 42]. Moving further down the chain would require additional assumptions regarding the relationships between temperature change and damage, and decisions that are beyond purely physical science considerations and involving value judgments, like the monetization of climate impacts and possible discounting [27, 43].

2.3. CO_2 debt from cumulative fluxes

CO_2 emissions and removals can be summed with results presented as net emissions (first point of the cause–effect chain). Forest biomass energy systems are characterized by CO_2 fluxes distributed over long time scales, from combustion and decomposition of dead organic materials left in the forest to time-distributed CO_2 sequestration in re-growing biomass. Net CO_2 emissions of the bioenergy systems are sometimes directly compared to those from fossil energy systems, with the latter subtracted to the former [44–48]. If the net result is positive, the bioenergy system releases more CO_2 than the fossil system, so resulting in the so-called up-front C debt (here expressed as CO_2 debt), if negative it is the opposite. In general, this difference changes over time and is positive for the first years, because bioenergy systems are characterized by higher initial CO_2 emissions per unit of energy produced, which are compounded by additional emissions from dead organic materials left on site. We simulate a constant energy production over time in all the systems (1 MJ yr^{-1}). In this procedure, other GHGs and climate forcing contributions from albedo changes are not included in the results. In the literature, there is large variability concerning net CO_2 exchanges in mature/old forests, which can be either a carbon source or sink [49, 50]. The CO_2 that would have been sequestered if the forest was not harvested is sometimes taken into account (either subtracted from the reference system or added to the bioenergy system), but it is not considered here as such a counterfactual effect has no direct causal relationship to bioenergy [51, 52].

2.4. Impulse Response Functions (IRF), radiative forcing and temperature changes

Emission metrics are usually computed via IRFs [9, 31, 32] or simple climate models [22, 53–55]. The theoretical justification for using IRFs is that they represent a complete characterization of the linear response to an external perturbation, and they yield practically the same trend in global temperature response as complex climate models [56–58], given some limitations concerning the nonlinearities of the climate system, size of emissions, and background atmospheric composition [23, 31, 33, 59].

In simple terms, IRFs describe the atmospheric decay of the gas, i.e. the fraction of the initially added gas that is still found in the atmosphere over time. For GHGs like CH_4 and N_2O, the IRF is simply given by an exponential decay rate with lifetimes of 12 and 114 years, respectively. The IRF for CO_2 is more complex, as more than half of the initial input decays within a few decades (through uptake by the upper ocean layer and the fast overturning reservoirs of the land biosphere) but about one fifth remains in the air for millennia [60–62], and is commonly approximated as a sum of three exponentials:

$$\mathrm{IRF}_{\mathrm{CO}_2}(t) = a_0 + \sum_{i=1}^{3} a_i \mathrm{e}^{\left(\frac{-t}{\tau_i}\right)}, \tag{1}$$

where the coefficients a_i represent the fraction that is associated with the nominal lifetime τ_i, so that their sum equals 1. The value a_0 is about 0.22 and represents the asymptotic airborne fraction of CO_2 which remains in the atmosphere for millennia because of the equilibrium response of the ocean–atmosphere system. The parameters are usually taken from the fourth IPCC assessment report [63], which are based on an updated version of the Bern CC-model [64]. In this paper, we use a more recent multi-model mean resulting from a sum of exponential fit of the first one thousand years, whose parameters are $a_0 = 0.22$, $a_1 = 0.23$, $a_2 = 0.28$, $a_3 = 0.27$, $\tau_1 = 381.33$, $\tau_2 = 34.78$ and $\tau_3 = 4.12$ [31].

The response of atmospheric CO_2 concentration $f(t)$ (and subsequent end points like radiative forcing and global surface temperature) to any CO_2 perturbation flux can then be computed via convolution:

$$f(t) = \int_0^t p(t')\mathrm{IRF}_{\mathrm{CO}_2}(t-t')\,\mathrm{d}t', \tag{2}$$

where $p(t')$ represents any net CO_2 flux profile based on direct emissions from combustion or changes in forest carbon pools and sequestration fluxes. This equation can be also applied to the additional CO_2 flux (either positive or negative) that could have occurred if trees were not harvested. However, for consistency with the metrics presented later on, such events should be characterized individually and combined with the different scenario elements in the final stages of analysis, rather than embedded within the characterization factors [65].

This procedure is applied to derive IRFs for CO_2 emissions from biomass combustion[1], where emissions from combustion are modeled with a delta function and the additional CO_2 sink ensured by biomass re-growth (modeled as a negative distributed emission) is attributed to biogenic CO_2 emissions [25, 29, 30, 66–69]. This IRF is case-specific, as it depends on the CO_2 fluxes on site after harvest that are dependent on biomass species, harvest practice and geographic location (i.e., local climate). Chronosequences of Net Ecosystem Productivity (NEP; positive values means that the ecosystem is a CO_2 sink) can be used for this purpose. When harvested biomass is directly used for bioenergy the IRF of biogenic CO_2 is:

$$\mathrm{IRF}_{\mathrm{bioCO}_2}(t) = \mathrm{IRF}_{\mathrm{CO}_2}(t) - \int_0^t \mathrm{NEP}(t)\mathrm{IRF}_{\mathrm{CO}_2}(t-t')\,\mathrm{d}t', \tag{3}$$

where NEP(t) is the time profile of the NEP chronosequence representing the CO_2 fluxes between the forest and the atmosphere. NEP values can be directly measured on site with flux towers, estimated with allometric methods applied to sequential surveys, or indirectly modeled using site-specific carbon models [68, 70–73].

The radiative forcing (ΔF) can be determined from the change in concentration of the climate forcing agent j assuming that the forcing is linearly proportional to the abundance of the gas:

$$\Delta F_j(t) = A_j \mathrm{IRF}_j(t), \tag{4}$$

where A_j is the radiative efficiency of the specific GHG, corresponding to 1.81×10^{-15} W m^{-2} kg^{-1} for CO_2, 1.82×10^{-13} W m^{-2} kg^{-1} for CH_4 and 3.88×10^{-13} W m^{-2} kg^{-1} for N_2O. The equation for computing the radiative forcing from a change in surface albedo can be found in [30]. The total radiative forcing is then given by the sum of the ΔF_j computed for the different forcings.

The effective forcing (EF) is obtained by the product between the radiative forcing and the climate efficacy E of the specific forcing agent j:

$$EF_j(t) = E_j \Delta F_j(t). \tag{5}$$

Values of the climate efficacies used here are given in [30], which are based on the climate simulations undertaken in [37].

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[1] CO_2 emissions from biomass combustion are labeled 'biogenic' with the intent to specify, beside their source or origin, the attribution of the additional carbon sink component present when emissions are from sustainably managed (i.e., regenerative) biomass. Evidently, CO_2 emissions from fossils or deforestation cannot be accredited with this sink, and the IRFs must be adapted to reflect this difference.

The radiative forcing drives a surface temperature change that can be computed through a temperature response function that approximates the temperature evolution in response to a radiative forcing profile. We use the function from an experiment conducted with the Hadley model [74] to simulate the climate response in terms of global surface temperature change T, here for a δ-pulse radiative forcing:

$$\delta T(t) = \sum_{i=1}^{2} \frac{c_i}{d_i} \mathrm{e}^{\frac{-t}{d_i}} \tag{6}$$

where the sum of the c_i coefficients is the equilibrium climate sensitivity and the coefficients d_i represent two timescales, due to the fact that the global surface temperature does not respond quickly to a climate forcing. The upper layer of the oceans is rapidly mixed by wind stress and convection, thus yielding a surface temperature response time of about a decade, whereas the exchange of water between the upper layer and the deeper ocean increases the surface temperature response time by an amount that depends on the climate sensitivity [57]. The response is therefore slowed by the thermal inertia of the oceans. The temperature response from [74] is preferred here over the response provided by the multi-model mean in [31] because the response shown above allows a direct adjustment of the climate sensitivity and temperature response to the specific forcing of agent j, as also done elsewhere [24, 54]. For consistency through climate models, climate sensitivities are adjusted following the values reported in [38] which are obtained from another version of the Hadley model (where a CO_2 concentration doubling causes a warming of 1.01 K W^{-1} m^2), and the response timescales are increased as the square of the climate sensitivity [75]. Parameters of equation (6) can then be specified for each forcing: CO_2 ($c_1 = 0.60, c_2 = 0.41, d_1 = 8.50, d_2 = 410$), N_2O ($c_1 = 0.73, c_2 = 0.50, d_1 = 8.81, d_2 = 410$), CH_4 ($c_1 = 0.84, c_2 = 0.57, d_1 = 9.27, d_2 = 410$) and snow albedo ($c_1 = 1.53, c_2 = 1.04, d_1 = 15.0, d_2 = 416$).

2.5. Emission metrics

The expressions introduced above for IRFs, radiative forcing, and temperature response can be used to compute several emission metrics, both absolute and normalized [7], for each forcing agent j. Absolute metrics compare the absolute impact caused by different emissions over time, while normalized metrics convert the impact of a specific climate forcing into that of CO_2 for a defined TH.

The time-integrated radiative forcing of a pulse emission is called the Absolute Global Warming Potential (AGWP):

$$\mathrm{AGWP}_j(t) = \int_0^t \Delta F_j(t)\,\mathrm{d}t. \tag{7}$$

AGWP is an integrative measure, meaning that species with short and temporary effects on climate are assigned to have a certain infinite impact, as the integration keeps memory of the forcing.

The global surface temperature change, usually labeled AGTP (Absolute Global Temperature Change Potential) can be estimated from a pulse of radiative forcing through a convolution integral:

$$\mathrm{AGTP}_j(t) = \int_0^t \Delta F_j(t')\delta T_j(t-t')\,\mathrm{d}t'. \tag{8}$$

In contrast to AGWP, AGTP assesses the instantaneous impact at a given time. The time integral of AGTP is the integrated AGTP (IAGTP), which has the same rationale of AGWP but applied to temperature:

$$\mathrm{IAGTP}_j(t) = \int_0^t \mathrm{AGTP}_j(t)\,\mathrm{d}t. \tag{9}$$

These absolute metrics based on single pulses can, besides giving fundamental information about the impacts of a single event, also be used for computing the response to emission scenarios through convolution [76, 77]. Metrics for sustained emissions (with equal pulse emissions per year over an indefinite time) are also available [18, 20]. The sustained AGTP (SAGTP) is given by the convolution between the AGTP and the specific emission profile of the gas $s(t)$, which is traditionally modeled as a continuous vector of equivalent unit pulses using a Heaviside step function:

$$\mathrm{SAGTP}_j(t) = \int_0^t s(t')\mathrm{AGTP}_j(t-t')\,\mathrm{d}t'. \tag{10}$$

As analytically shown elsewhere [19, 20, 24], SAGTP = IAGTP in a linear system. This means that the instantaneous climate impact (temperature, in this case) of a sustained emission is equal to the integrated impact of a pulse emission. The same analogy is of course valid when radiative forcing is used as basis instead of temperature.

For the sake of a more comprehensive investigation, we introduce the sustained IAGTP (SIAGTP), given by a convolution of the emission profile $s(t)$ with the IAGTP:

$$\mathrm{SIAGTP}_j(t) = \int_0^t s(t')\mathrm{IAGTP}_j(t-t')\,\mathrm{d}t'. \tag{11}$$

Normalized metrics are computed for a certain TH by dividing the absolute metric of the climate forcing by the corresponding absolute metric of CO_2. The most common metrics are therefore computed with the following equations:

$$\mathrm{GWP}_j(\mathrm{TH}) = \frac{\mathrm{AGWP}_j(\mathrm{TH})}{\mathrm{AGWP}_{\mathrm{CO}_2}(\mathrm{TH})} \tag{12}$$

$$\mathrm{GTP}_j(\mathrm{TH}) = \frac{\mathrm{AGTP}_j(\mathrm{TH})}{\mathrm{AGTP}_{\mathrm{CO}_2}(\mathrm{TH})} \tag{13}$$

$$\mathrm{IGTP}_j(\mathrm{TH}) = \frac{\mathrm{IAGTP}_j(\mathrm{TH})}{\mathrm{IAGTP}_{\mathrm{CO}_2}(\mathrm{TH})} \tag{14}$$

$$\mathrm{SGTP}_j(\mathrm{TH}) = \frac{\mathrm{SAGTP}_j(\mathrm{TH})}{\mathrm{SAGTP}_{\mathrm{CO}_2}(\mathrm{TH})} \tag{15}$$

$$\mathrm{SIGTP}_j(\mathrm{TH}) = \frac{\mathrm{SIAGTP}_j(\mathrm{TH})}{\mathrm{SIAGTP}_{\mathrm{CO}_2}(\mathrm{TH})}. \tag{16}$$

Recall from above that IGTP = SGTP. The sustained integrated GTP (SIGTP) defined here can be seen similar to the TEMP [21, 22], which is also based on sustained emissions and integrated temperature changes.

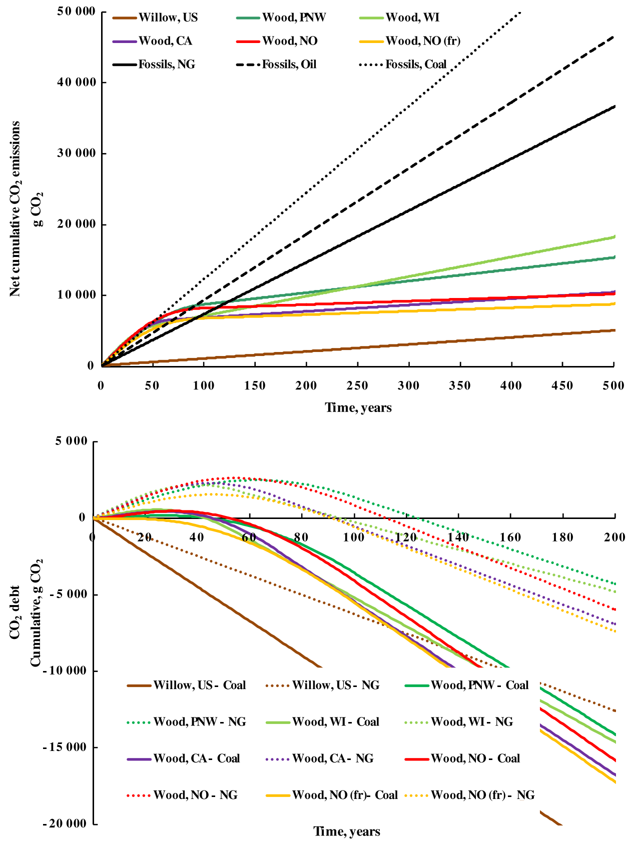

Figure 2. Upper panel: net cumulative CO_2 emissions per 1 MJ heat production per year in the investigated systems. Lower panel: CO_2 debt of the bioenergy systems after subtraction to the respective net cumulative emissions of the CO_2 from fossil systems (coal and natural gas; results for oil would approximately fall in between).

It is also possible to compute the mean temperature response of a pulse emission over a certain TH, and divide it by that for CO_2 to get the Mean Global Temperature change Potential (MGTP) [23]. However, we found this metric numerically and analytically equal to IGTP, as the division by TH cancels out in the ratio.

Normalized metrics are dependent on the selected TH, which necessarily requires value judgments [10, 12]. The three THs traditionally proposed for GWP (20, 100 and 500 years) follow illustrative examples of the first IPCC assessment report, and are somewhat arbitrary, having vague and provisional explanations [10]. Small THs are intended to focus on near term effects like rate of temperature change, while long THs are intended for cumulative impacts like sea level rise [78]. The TH can be also made flexible so to adapt while moving to the proximity of the target [79].

3. Results and discussion

Absolute and normalized metrics are applied to characterize the emissions reported in table 1 for the different woody bioenergy systems. For absolute metrics:

$$\mathrm{AM}(t) = \sum_j \mathrm{EM}_j \mathrm{AM}_j(t) \tag{17}$$

where $\mathrm{AM}(t)$ (in *unit* per MJ) is the net impact in terms of absolute metrics like effective forcing or temperature (either instantaneous or integrated), t is the time dimension, EM_j is the emission intensity of component j (from table 1, in g MJ^{-1}), and $\mathrm{AM}_j(t)$ is the respective absolute metrics of the specific component j (in W m^{-2} kg^{-1} or K kg^{-1}). For normalized metrics:

$$CO_2\text{-eq.(TH)} = \sum_j \mathrm{EM}_j \mathrm{NM}_j(\mathrm{TH}), \tag{18}$$

where CO_2-eq.(TH) is the common unit that gives the net impact in CO_2 equivalents at the selected TH and $\mathrm{NM}_j(\mathrm{TH})$ is the normalized metric (like GWP or GTP). While $\mathrm{AM}(t)$ is given as function over time, NM(TH) is a scalar (although it can be sometimes shown as a function of TH itself). Characterization of changes in surface albedo is based on radiative forcing and follows the approach described in [30]. For the simulations about the response to a sudden cessation of emissions, the Heaviside step function used to simulate sustained emissions is forced to zero after 200 years. We follow the frequent and common assumption in climate metric science of using a constant background condition for atmospheric GHG concentration [31, 63]. The results should not be interpreted as an absolute contribution to atmospheric GHG concentrations, radiative forcing, or temperature change, but rather, they show how the investigated systems would affect the climate if no other variables were to change.

3.1. CO_2 debt

Figure 2 shows the net cumulative emissions of the systems and the resulting CO_2 debt (contributions from albedo and other GHGs not included). The instantaneous emission profiles and the CO_2 debt in terms of net instantaneous emissions are shown in supplementary figure S1 (available at stacks.iop.org/ERL/8/014049/mmedia). Net cumulative CO_2 emissions are similar between fossil and bioenergy systems for the first years, but after the first rotation period the dynamics clearly diverge. In the bioenergy systems, continuous biogenic CO_2 emissions take some time to be offset by the CO_2 sequestration that gradually becomes uniformly distributed across the landscape. After that, the only further addition of CO_2 to the atmosphere is given by fossil CO_2 emissions through life-cycle operations. Bioenergy from willow, a fast growing species with a rotation period of three years, provides the lowest cumulative emissions, as the rotation period is so short that biogenic CO_2 does not accumulate in the air and net emissions are mainly due to fossil CO_2 from life-cycle activities. The resulting CO_2 debt of bioenergy systems when compared to fossil systems gradually decreases over time and is shorter if net instantaneous emissions are considered and coal is displaced, while it is longer for net cumulative emissions and natural gas displacement. The CO_2 debt becomes longer in cases where old forests are assumed to be strong carbon sinks and the analysis embraces estimates regarding the level of foregone C sequestration.

3.2. Absolute metrics

Using absolute metrics it is possible to undertake detailed analyses and compare emission profiles of single climate forcings (or the entire systems after aggregation of the climate impact) as a function of time in absolute units. Absolute metrics for a single pulse normalized to 1 kg of emission for the single species are shown in the supplementary data (supplementary figures S2–S7 available at stacks.iop.org/ERL/8/014049/mmedia). The figures show the IRF for the various GHGs, the instantaneous and integrated effective forcings, the instantaneous and integrated surface temperature change, and the instantaneous and integrated effect on surface temperature of sustained emissions. The responses to pulse emissions represent the building blocks on which all the subsequent metrics are built, and important findings can be derived from studying their dynamics. Instantaneous effects show that biogenic CO_2 emissions and albedo changes cause perturbations that are temporary, i.e., the climate forcing is restricted to some decades. Therefore, their instantaneous contributions to global warming tend to disappear over time, while impacts from N_2O are still substantial for some centuries and those for fossil CO_2 for millennia. IRFs of biogenic CO_2 show some negative values at some times (figure S2). This means that the atmospheric CO_2 concentration is for a brief period lower than what was present before the initial emission, even if the system is carbon neutral along the rotation period. Such a peculiarity has a physical explanation in the fast interactions with the upper layer of the oceans, and has been discussed in details elsewhere [66, 80, 81]. When integrated absolute metrics are considered, temporary forcings are memorized by the metrics so that the profiles tend to increase (or decrease, in case of albedo) until the temporary forcing is present, and then flatten towards a stable level (see figures S4 and S6). Fossil or LUC CO_2 is an exception, because the non-zero asymptotic value of the response causes a continuous increase in its cumulative impact.

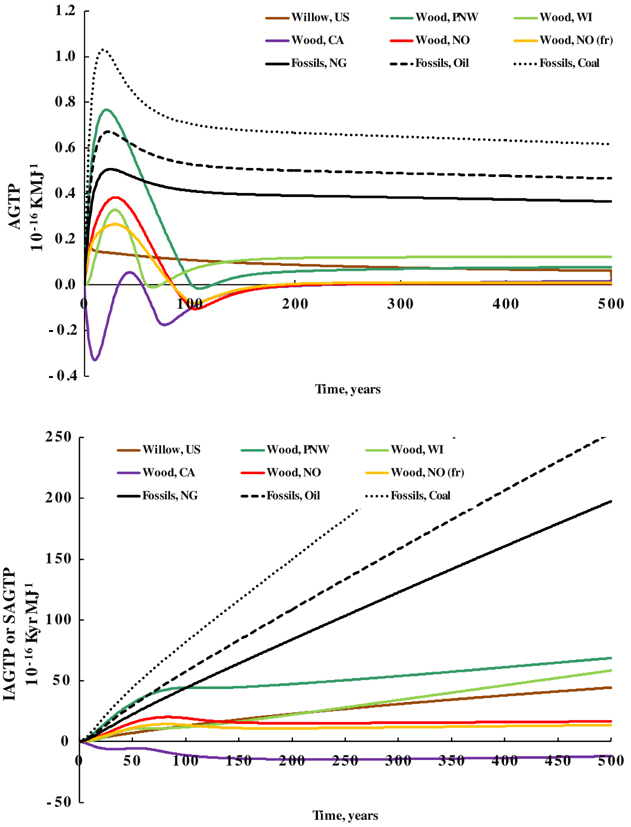

Figure 3. Instantaneous (AGTP) and integrated (IAGTP) or sustained (SAGTP) changes in global surface temperature in the bioenergy and fossil fuel systems.

Figure 3 shows the net impact of the investigated heat production systems in terms of the instantaneous (AGTP), integrated (IAGTP), or sustained (SAGTP) temperature responses per MJ of fuel combusted. Figure S8 in the supplementary data (available at stacks.iop.org/ERL/8/014049/mmedia) shows the SIAGTP. The AGTP of bioenergy systems shows large variations during the first decades, where temporary perturbations are significant. In the medium-long term, all the curves progressively forget these temporary forcings and the profiles are mainly affected by the residual long term impacts of fossil CO_2 emissions from life-cycle operations. In cases where a strong contribution from changes in surface albedo is present, the effects of biogenic CO_2 emissions can be more than offset, such as in the Canadian case. A qualitative comparison with the fossil energy system reveals that the effects are comparable with those of forest bioenergy for which cooling contributions from albedo are small during the first years, after which the dynamics clearly diverge. The temperature increase caused by production of 1 MJ of heat from fossil fuel combustion lasts for centuries, while from biomass combustion is restricted to few decades, with the possibility to have negative values (i.e., yielding a cooling effect) at some times. When the effects on global surface temperature are time-integrated (IAGTP), the temperature impact cumulates over the years and the temporary effects of early years are still embedded in long term results. Two contrasting examples are bioenergy from PNW and Canada, with the former burdened with the high impacts in early years persisting for centuries, and the latter benefiting from early cooling.

Of interest is the degree of permanence of the impacts on global surface temperature after cessation of continuous emissions (see figure 4), tested with an ideal simulation where sustained emissions are stopped after 200 years. In the fossil systems, the decrease in temperature is relatively small, with an approximately constant trend well above the initial temperature. This is in line with observations reported in other analyses [81–83], where near-zero emissions are found necessary to stabilize global surface temperature. More diverse responses are found in bioenergy systems, which have contrasting trends. When the cooling effect from albedo is small, such as in the PNW case, a strong decrease in temperature can be observed. This is due to the fact that the forest can grow and keep the gradually sequestered carbon out of the atmosphere, thereby offsetting much of the warming caused in the previous years (the profiles are still positive because of the 'life-cycle' emissions of fossil CO_2 and other

Table 2. Normalized metrics (GWP, GTP, IGTP or SGTP, and SIGTP) for the three most common time horizons (20, 100 and 500 years) to be used for the characterization of GHG emissions. Biogenic CO_2 emissions have site-specific characterization factors that take into account both C-cycle dynamics (Bio CO_2) and albedo effects. Because of the inclusion of climate efficacies, GWP values computed here slightly differ from those reported in the fourth IPCC assessment report [63]. Abbreviations are listed in the caption of table 1.

	GWP			GTP			IGTP and SGTP			SIGTP		
	20	100	500	20	100	500	20	100	500	20	100	500
CO_2	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
CH_4	96.3	34.5	10.6	79.3	8.34	3.43	108	38.3	12.8	119	56.0	19.5
N_2O	336	348	179	375	336	90.0	356	369	220	347	372	275
Bio CO_2. NO	1.25	0.62	0.11	1.28	−0.13	−0.02	1.25	0.71	0.13	1.22	0.97	0.00
Albedo. NO	−0.94	−0.42	−0.13	−0.92	−0.12	−0.03	−0.95	−0.53	−0.15	−0.95	−0.69	−0.25
Net. NO	0.32	0.20	−0.02	0.36	−0.26	−0.05	0.30	0.19	−0.02	0.27	0.29	−0.25
Bio CO_2. NO (fr)	1.07	0.51	0.09	1.06	−0.11	−0.01	1.07	0.58	0.11	1.07	0.80	0.21
Albedo. NO (fr)	−0.85	−0.38	−0.12	−0.84	−0.11	−0.03	−0.86	−0.48	−0.14	−0.86	−0.62	−0.22
Net. NO (fr)	0.22	0.12	−0.03	0.22	−0.22	−0.04	0.21	0.10	−0.03	0.21	0.18	−0.01
Bio CO_2. US PNW	1.04	0.58	0.10	1.00	−0.12	−0.01	0.99	0.59	0.10	0.98	0.79	0.20
Albedo. US PNW	−0.14	−0.07	−0.02	−0.14	−0.02	0.00	−0.15	−0.08	−0.02	−0.15	−0.11	−0.04
Net. US PNW	0.90	0.51	0.08	0.86	−0.14	−0.01	0.85	0.51	0.07	0.84	0.68	0.16
Bio CO_2. US WI	1.08	0.32	0.06	1.05	−0.09	−0.01	1.09	0.37	0.07	1.09	0.63	0.14
Albedo. US WI	−1.10	−0.38	−0.12	−0.97	−0.07	−0.02	−1.17	−0.46	−0.13	−1.23	−0.67	−0.22
Net. US WI	−0.02	−0.06	−0.06	0.08	−0.16	−0.03	−0.07	−0.09	−0.06	−0.14	−0.04	−0.07
Bio CO_2. CA	1.13	0.42	0.08	1.13	−0.13	−0.01	1.13	0.49	0.09	1.11	0.77	0.18
Albedo. CA	−1.60	−0.61	−0.19	−1.49	−0.12	−0.04	−1.66	−0.75	−0.22	−1.71	−1.04	−0.35
Net. CA	−0.47	−0.18	−0.11	−0.35	−0.25	−0.05	−0.53	−0.25	−0.12	−0.60	−0.27	−0.16
Bio CO_2. willow	0.09	0.02	0.00	−0.01	0.00	0.00	0.08	0.01	0.00	0.15	0.02	0.00

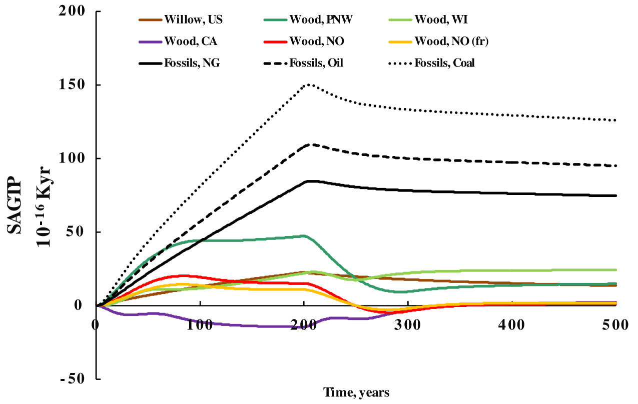

Figure 4. Instantaneous global surface temperature response to a sudden cessation of continuous emissions after 200 years.

GHGs). However, when the albedo impact is strong, the warming induced by the darkening of the surface by growing and standing trees contrasts with the cooling effects ensured by CO_2 sequestration, so that the two effects tend to cancel out each other and temperature does not show large variations.

3.3. Normalized metrics

Normalized metrics are characterization factors used to convert a specific emission into mass of CO_2-equivalents for the selected TH. Standard practice in most LCA applications and emission accounting mechanisms is to use GWP with a TH of 100 years. Table 2 shows values for GWP, GTP, IGTP or SGTP, and SIGTP for the three most common THs. Factors for biogenic CO_2 emissions are site-specific and take into account both the climate response to CO_2 and albedo effects. GWPs computed here differ from those reported in the last IPCC report [63] because they are based on a more recent IRF for CO_2 and embed climate efficacies. Similarly, temperature-based metrics differ from those elaborated elsewhere owing to the use of different climate sensitivities.

GWP, IGTP and SIGTP are integrated metrics and represent the cumulative impact up to the TH, while GTP and SGTP are instantaneous metrics and their values represent the instantaneous effects only at the specific point in time identified by the TH, without considering previous contributions. As discussed above, the instantaneous effect of sustained unit pulse emissions corresponds to the cumulative effect of a unit pulse emission, so that IGTPs are identical to SGTPs. SIGTP is the integrated effect on temperature of sustained emissions, which is similar to the other cumulative metrics for TH = 20, but it shows higher values for TH = 100 due to the double cumulative perspective (from sustained emissions and from the integrated effect). Significant differences are found between GWPs and GTPs, especially for THs of 100 years and for temporary forcings like those from biogenic CO_2 and albedo change. As an example, the net GWP factor for biogenic CO_2 in the Norwegian case (NO) is 0.20 for TH = 100, while for GTP it is of opposite sign, −0.26. The reason for this is that GTP takes the instantaneous values at TH, and the AGTPs in supplementary figure S5 (available at stacks.iop.org/ERL/

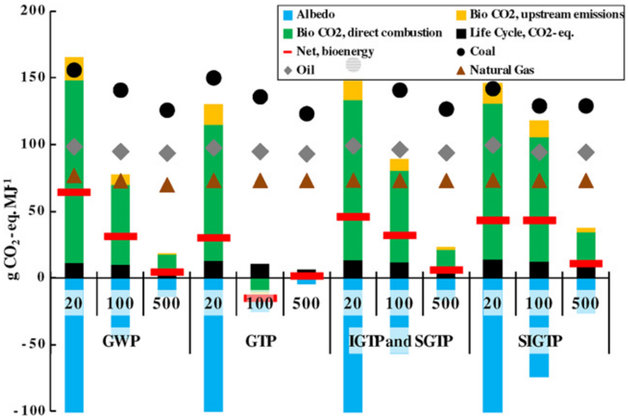

Figure 5. Characterized results in terms of g CO_2-eq. MJ^{-1} for the forest bioenergy case study NO, with breakdown of the contributions from the various forcing agents, according to different normalized metrics (GWP, GTP, IGTP or SGTP, and SIGTP) and THs (20, 100 and 500 years).

8/014049/mmedia) show that at 100 years both the curve 'bio CO_2 NO' and 'albedo NO' are negative at year 100, so yielding negative instantaneous impacts (while integrated values are positive as they are the cumulative impacts over the years).

Figure 5 shows an application of these metrics to one case study, the bioenergy system located in Norway ('NO'), using the characterized results for the fossil energy systems as a benchmark. The aforementioned difference between GWP and GTP here appears clearly, with net impacts on surface temperature from bioenergy being much smaller than those from the fossil counterparts in the short run (TH = 20). For GTP TH = 100 yr , the bioenergy system even causes a net cooling (with negative contributions from both albedo and biogenic CO_2), and for GTP TH = 500 it is approximately climate neutral.

Results for all case studies following application of GWPs are shown in [30], and in supplementary figure S9 (available at stacks.iop.org/ERL/8/014049/mmedia) we show those after application of GTPs, with the contributions from the single climate agents. Bioenergy systems perform much better if assessed under the temperature-based metric, with net impacts lying around zero or even negative in some cases. Supplementary figure S10 (available at stacks.iop.org/ERL/8/014049/mmedia) shows a comparison of the results obtained using the different normalized metrics shown in table 2 to characterize emissions reported in table 1. In general, the choice of GTPs assigns lower impacts, both if positive (NO) or negative (CA), especially when bioenergy systems are evaluated with a TH of 100 years, for which most temporary effects are forgotten and the temperature response to pulse emissions of biogenic CO_2 has negative values (and corresponding normalized factors of GTP in table 2 are negative). In all the cases, differences are larger for TH = 20 and tend to decrease with increasing TH. Following the outcomes reported for short-lived active forcing agents [8, 13], results are particularly affected by the choice of the metric when forcings from temporary agents are strong, like in the cases of forest wood use, while fossil options and the willow case study (that is mainly affected by the conventional GHGs) show smaller variations.

4. Conclusions

Following the cause–effect chain, a variety of emission metrics with different time horizons can be used to characterize climate forcing agents, yielding different and sometimes contrasting information. Computation of emission metrics should minimize the presence of any value-laden aspect, so that they may be applied explicitly by each user in different applications. The choice of one metric over another ultimately depends on the research question or policy objective that the application aims to fulfil. In practical terms, metrics based on pulse emissions (GWP, GTP, etc) would be appropriate for assessing bioenergy systems under a single harvest perspective, while for continuous operating systems sustained metrics (SGTP and SIGTP) would be a more obvious choice. However, the former are the basis for the latter, and each preference will always embed some sort of value-judgment, as there can be different valid reasons to use one metric over another.

The simple consideration of cumulative emissions and CO_2 debt can be used as proxy for contributions on peak temperature, but many relevant insights embracing the timing of the climate response and non-CO_2 climate agents would be overlooked. On a technical basis, GWP puts equal weight on all years along the path up to the TH, so keeping memory of the temporary forcings in the first years (like those from biogenic CO_2 and albedo).

The impact from CO_2 is always high under both instantaneous and cumulative measures because the physical effect occurs immediately and is long-lived, while impacts from temporary effects are more affected by the metric choice. Because their instantaneous impact is limited to the first years, they are of main importance for short THs, and their contributions only persist if time-integrated.

Instantaneous absolute metrics are more transparent than integrated metrics in the sense that they show results for the specific point in time of interest and the variations over time. Even if absolute metrics can be more attractive from a clarity point of view, normalized metrics can still be preferred in LCA (either attributional or consequential) and similar analyses as they favor routine applications and can deliver a higher degree of synthesis which is needed in policy.

We have seen that the climate performance of forest bioenergy systems can drastically change if instantaneous metrics like GTPs are used instead of GWPs or cumulative emissions, especially when temporary forcings from biogenic CO_2 and changes in albedo are significant (see example in figure 5). In these cases, the use of metrics considering a temperature response, either as effective forcings or (A)GTPs, is scientifically motivated by the need to meaningfully combine forcings from various climate agents having different climate efficacies. Such a need goes together with the higher policy relevance and public understanding of temperature-based metrics, even if at the expense of additional uncertainties. In a policy making context, an increased scientific uncertainty can be sometimes tolerated if the relevance of the environmental effect is clearly higher. Tipping points are also frequently estimated in terms of temperature change [84, 85], and an international agreement on those can act as a basis for analysts in the definition of the best metric and related TH to be used.

Simulations with sustained emissions also show that most of the climate impacts from bioenergy are reversible, i.e. concentration or temperature changes reverse or stay relatively low after emission cessation, while climate impacts from fossil energy persist for centuries if not millennia.

We hope that our efforts here can help LCA practitioners and the bioenergy climate impact community acquire deeper insights on the effective responses of the climate system. Given the temporary nature of the climate effects from forest bioenergy systems, the net global warming contributions have complex dynamics which can be only partially represented by a single metric. Rather than using cumulative CO_2 and/or GWP by default, primary research efforts such as forest C dynamic and LCA studies should make the choice of the metric flexible and in line with the research question at hand, or ideally show the results according to more than one metric. At the same time, policy directives and accounting mechanisms should also adapt, and consider the non-negligible contributions from climate forcing agents other than GHGs along with the insights from instantaneous temperature metrics.

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