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1 **Bridging the gap between impact assessment methods and climate science**

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32 **Abstract**

33 Life-cycle assessment and carbon footprint studies are widely used by decision makers to  
34 identify climate change mitigation options and priorities at corporate and public levels.  
35 These applications, including the vast majority of emission accounting schemes and policy  
36 frameworks, traditionally quantify climate impacts of human activities by aggregating  
37 greenhouse gas emissions into the so-called CO<sub>2</sub>-equivalents using the 100-year Global  
38 Warming Potential (GWP100) as the default emission metric. The practice was established  
39 in the early nineties and has not been coupled with progress in climate science, other than  
40 simply updating numerical values for GWP100. We review the key insights from the  
41 literature surrounding climate science that are at odds with existing climate impact methods  
42 and we identify possible improvement options. Issues with the existing approach lie in the  
43 use of a single metric that cannot represent the climate system complexity for all possible  
44 research and policy contexts, and in the default exclusion of near-term climate forcings such  
45 as aerosols or ozone precursors and changes in the Earth's energy balance associated with  
46 land cover changes. Failure to acknowledge the complexity of climate change drivers and  
47 the spatial and temporal heterogeneities of their climate system responses can lead to the  
48 deployment of suboptimal, and potentially even counterproductive, mitigation strategies. We  
49 argue for an active consideration of these aspects to bridge the gap between climate impact  
50 methods used in environmental impact analysis and climate science.

51

52 **Keywords:** climate change; emission metrics; life cycle assessment (LCA); global warming  
53 potential (GWP).

## 54 1. Introduction

55 Human activities perturb the climate system through a variety of forcing agents. Over the  
56 industrial era, the total anthropogenic radiative forcing, a measure of the net energy  
57 imbalance of the Earth caused by a forcing agent, is  $2.29 [1.13 \text{ to } 3.33] \text{ W m}^{-2}$  [1]. The  
58 major contributors are carbon dioxide ( $\text{CO}_2$ ) and methane ( $\text{CH}_4$ ) emissions, which are  
59 responsible for about  $1.68 \pm 0.17 \text{ W m}^{-2}$  and  $0.97 \pm 0.17 \text{ W m}^{-2}$ , respectively [1]. The net  
60 contribution from so-called Near-Term Climate Forcers (NTCFs), that is, species with an  
61 atmospheric lifetime of less than about one year, is estimated to be a slight negative forcing  
62 (cooling) of  $-0.06 \text{ W m}^{-2}$  [1], with large uncertainty bounds largely due to the lack of  
63 scientific understanding of aerosol-cloud interactions [2]. The contributions from the direct  
64 forcing effect of single NTCFs range between  $-0.41 \pm 0.20 \text{ W m}^{-2}$  for sulphur oxides ( $\text{SO}_x$ )  
65 emissions and  $+0.64 [+0.25 \text{ to } +1.09] \text{ W m}^{-2}$  for black carbon (BC) emissions [1]. The  
66 radiative forcing values from historical land use changes for  $\text{CO}_2$  and surface albedo (the  
67 ratio between reflected and incident solar radiation at the surface) are of the same order of  
68 magnitude but opposite sign, with a warming effect of  $0.17 \text{ to } 0.51 \text{ W m}^{-2}$  for  $\text{CO}_2$  (1850-  
69 2000) and a cooling effect of  $-0.15 \pm 0.10 \text{ W m}^{-2}$  for surface albedo changes (1750-2011)  
70 [1]. The net effect from changes in emissions of biogenic volatile organic compounds  
71 (BVOCs) associated with this land use change is estimated to be an additional cooling  
72 contribution of  $-0.11 \pm 0.17 \text{ W m}^{-2}$  (1850-2000) [3].

73 Life cycle assessment (LCA) and carbon footprints are largely used to attribute climate  
74 change impacts to specific human activities like products, technological systems, or sectors  
75 [4]. Decision and policy makers widely rely on the outcomes from comparative climate  
76 impact analyses to promote mitigation options, and to design strategies for sustainable  
77 production and consumption at a public or corporate level. The most common approach is  
78 to aggregate emissions of well-mixed greenhouse gases to so-called “ $\text{CO}_2$ -equivalents”

79 using the 100-year global warming potential (henceforth GWP100) as the default emission  
80 metric. A similar procedure is frequently applied in international agreements, like the Kyoto  
81 protocol, the Intended Nationally Determined Contributions (INDCs) for mitigation  
82 obligations to 2030 and climate-oriented policy directives, such as those regulating the  
83 climate impacts of specific sectors. This practice does not take into account the impacts from  
84 emissions of NTCFs or biophysical factors arising from changes in land cover. It also  
85 overlooks the temporal and spatial heterogeneities of the climate system response to  
86 different forcing agents, and the consideration of emission metrics alternative to GWP100.  
87 Studies that have explored the influence of NTCFs [5, 6], of changes in surface albedo [7, 8],  
88 of temporal and spatial impact dynamics [9–11], and of metrics other than GWP100 [5, 12–  
89 15] on the climate impacts attributed to a specific human activity usually conclude that an  
90 international effort on improving existing methods is desirable to prevent the  
91 implementation of suboptimal mitigation pathways.

92 The Life Cycle Initiative under the United Nations Environment Program (UNEP) and the  
93 Society of Environmental Toxicology and Chemistry (SETAC) launched the Global Guidance  
94 on Environmental Life Cycle Impact Assessment Indicators to revise existing standard  
95 methodologies used in environmental impact categories of LCA and footprint studies [16,  
96 17], including climate change. Here, as part of the activities from the Global Warming Task  
97 Force, we identify key insights from the climate science related literature that are of  
98 relevance for advancing climate impact assessment frameworks.

99

## 100 **2. Life cycle impact assessment and emission metrics**

101 The life cycle impact assessment phase consists in the conversion of different well-mixed  
102 greenhouse gases (WMGHGs) to common units (kg CO<sub>2</sub>-eq) after multiplication of each

103 emission flow by the respective emission metric, [4]. Emission metrics, which in LCA are  
104 usually referred to as characterization factors, are typically simplified measures of the  
105 climate system response to forcing agents and are mostly based on outcomes from physical  
106 models of varying complexity linking emissions to impacts [1]. Metrics can be formulated in  
107 absolute terms, for instance based on the temporal evolution of a temperature impact, or in  
108 relative terms after normalization to a reference gas, usually CO<sub>2</sub> [5, 18]. Different  
109 emissions have different climate system responses, and a metric that establishes equivalence  
110 with regard to one effect does not usually result in equivalence with regard to other effects.

111 GWP is an integrative measure defined as the integrated radiative forcing of a gas between  
112 the time of emission and a chosen time horizon (TH) relative to that of CO<sub>2</sub>. The GWP was  
113 introduced by the first IPCC assessment report in 1990 with illustrative purposes and, by its  
114 own definition, it does not embed any climate system responses or direct link to policy goals  
115 [1]. Despite the rather cautious introduction by the IPCC, the United Nations Framework  
116 Convention on Climate Change, LCA and the majority of national and corporate emission  
117 accounting frameworks started to use this metric without any substantial modifications,  
118 with the exception of updating the GWP values according to the successive IPCC reports.

119 GWP is a metric that aligns well with the general principles of LCA. LCA privileges impacts  
120 integrated over time and space under the objective of avoiding burden shifting of impacts  
121 [4]. LCA also typically follows a “marginal change” approach, in the sense that an additional  
122 amount of a certain pollutant is assumed to introduce very small changes on top of a  
123 constant background. This approach allows the assessment of environmental impacts  
124 associated with the life cycle impacts of a single unit of a product, which gives only a small  
125 contribution to the total impact [19]. Common critiques to GWP concern the fact that,  
126 despite its name, it does not equate climate forcing agents on the basis of their effects on  
127 surface temperature, nor does it consider them under a specific climate policy target, such

128 as the goal to limit warming to 2 degrees above pre-industrial levels [18, 20–22]. The use of  
129 a TH of 100 years seems to be the result of an “inadvertent consensus” [23] and it is not  
130 directly linked to any particular climate policy objective. There are many emission metrics  
131 available from the climate science literature that focus on different characteristics of the  
132 climate system response to emissions [12, 18, 20, 21, 24–28]. By targeting different aspects  
133 of the climate impact cause-effect chain, such as radiative forcing [29], temperature [26,  
134 27], sea level rise [30], precipitation changes [31], or economic dimensions [28], these  
135 metrics compare emissions on the basis of their instantaneous [26] or time integrated  
136 impacts [25, 27]. They are computed under a constant [1, 24] or changing [18, 32]  
137 background climate and can be formulated around a fixed or a target-dependent TH [14,  
138 18, 33, 34]. A common alternative to GWP is the Global Temperature Change Potential  
139 (GTP), which is defined as the impact of a GHG emission pulse on global temperature at the  
140 chosen TH, again relative to CO<sub>2</sub> [26]. With the exception of some gases with very short  
141 lifetimes, values of GTP for a TH of about 40 years are usually similar to those of GWP100  
142 [35]. Recently, GWP100 is shown to approximately equate a pulse emission of a cumulative  
143 climate pollutant and an indefinitely sustained change in the rate of emission of short-lived  
144 forcers, introducing a new application for GWP100 in comparing WMGHGs with different  
145 lifetimes [36]. Within a context of emission accounting, some also argue against the practice  
146 of aggregating all WMGHGs to common units [29, 37, 38] and instead explore a multi-  
147 basket approach in which gases with similar lifetimes are grouped together [29, 37–41].  
148 Metrics that are further down the cause effect chain produce outcomes that are more policy  
149 relevant than those based on radiative forcing, but at the same time their embedded  
150 uncertainties increase. For instance, uncertainties for GTP are larger than those for GWP,  
151 because the latter does not embed the uncertainty of the climate system response.  
152 Temperature-based metrics involve a climate model, which can be a simple energy balance

153 model [25, 26], a temperature response function [24], or more sophisticated climate models  
154 [18, 24, 28, 42], and this generally makes results sensitive to the parameterization of the  
155 climate system [1]. Multi-model means are frequently used to mitigate these concerns [24]  
156 and to better understand uncertainties [42]. However, the subjective selection of a TH for the  
157 different metrics remain the most important factor that determines metrics variability [24],  
158 especially for the weight given to forcings with a relatively short lifetime, compared to forcings  
159 with long lifetimes [18]. This choice dependence introduces a strong, but often inadvertent  
160 and only implicit, value judgement that frequently makes results open to contrary outcomes  
161 [5, 15].

162

### 163 **3. Well-mixed GHGs (WMGHGs)**

164 CO<sub>2</sub>, CH<sub>4</sub>, nitrous oxide (N<sub>2</sub>O), and some groups of halogenated gases have atmospheric  
165 lifetimes longer than the hemispheric mixing time (up to a few years). They are generally  
166 considered well-mixed because their atmospheric concentration has sufficient time to  
167 become nearly uniformly distributed in the troposphere and their radiative forcing patterns  
168 are usually independent of the emission location [1]. Table 1 shows a classification of the  
169 main WMGHGs grouped by lifetimes, with information about their atmospheric  
170 concentration and radiative forcing in 2011, and their radiative efficiency per mass unit  
171 atmospheric burden (W m<sup>-2</sup> kg<sup>-1</sup>). For the purpose of a simple classification, we consider as  
172 “short-lived” those WMGHGs, like methane and most hydrofluorocarbons (HFCs) or  
173 hydrofluoroethers (HFEs), with atmospheric lifetimes shorter than the response timescale of  
174 the climate system, which is typically from two to four decades [20, 43]. Gases with lifetimes  
175 longer than about 50 years are sufficiently long-lived that the climate system has time to



176 fully respond to the perturbation, and their impact on temperature is more strongly  
 177 controlled by the amount of cumulative emissions [35, 40, 44].

178 The atmospheric decay of non-CO<sub>2</sub> WMGHGs is governed by relatively well-known  
 179 chemical and physical processes and can be simply described with exponential decay  
 180 constants corresponding to the respective lifetimes of the gases [45]. The constant decay-  
 181 time, however, remains an approximation since the lifetime of some gases is actually  
 182 affected by their own atmospheric concentration, and sometimes by that of other gases. For  
 183 instance, the atmospheric concentration of CH<sub>4</sub> or N<sub>2</sub>O feeds back on their own respective  
 184 lifetimes [46], CO<sub>2</sub> can be produced after oxidation of other carbon-containing gases [1,  
 185 47], or ozone can cause changes to the global land-carbon sinks [48]. Some short-lived  
 186 species are thus also responsible of long-term effects through the carbon cycle and climate  
 187 feedbacks [1, 47, 49, 50].

188 Table 1 WMGHGs grouped by atmospheric lifetimes. For atmospheric concentrations and radiative forcing  
 189 only the gas listed in Table 8.2 of the WGI 5<sup>th</sup> IPCC Assessment Report [1] are considered. Information on  
 190 lifetimes of the gases, atmospheric concentration, radiative forcing and radiative efficiencies are from the 5<sup>th</sup>  
 191 IPCC Assessment Report[1].

Group of lifetimes	Gases	Lifetime (years)	Atmospheric concentrations in 2011	Radiative forcing in 2011 (W m <sup>-2</sup> )	Radiative efficiency (W m <sup>-2</sup> kg <sup>-1</sup> )
Years	Some HCFCs, HFCs, Halocarbons, and HFEs	Between 1 and 10	21.4 ± 0.1 ppt HCFC-141b	0.0034 HCFC-141b	2.05E-11 HCFC-141b
Decades	CH <sub>4</sub> , CFC-11, CFC-113, CCl <sub>4</sub> , some HCFCs, HFCs, and HFEs	Between 10 and 100	1803 ± 2 ppb CH <sub>4</sub> , 238 ± 0.8 ppt CFC-11	0.48 ± 0.05 CH <sub>4</sub> , 0.062 CFC-11	4.65E-14 CH <sub>4</sub> , 3.84E-11, CFC-113
Centuries	N <sub>2</sub> O, HFC-23, HFC-236fa, HFE-125, NF <sub>3</sub> , some CFCs	Between 100 and 1,000	324 ± 0.1 ppb N <sub>2</sub> O, 528 ppt CFC-12	0.17 ± 0.03 N <sub>2</sub> O, 0.17 CFC-12	3.84E-13 N <sub>2</sub> O, 4.10E-11 CFC-12
Millennials	Fluorinated	Between	79 ppt CF <sub>4</sub>	0.0041 SF <sub>6</sub>	7.3E-11 SF <sub>6</sub>

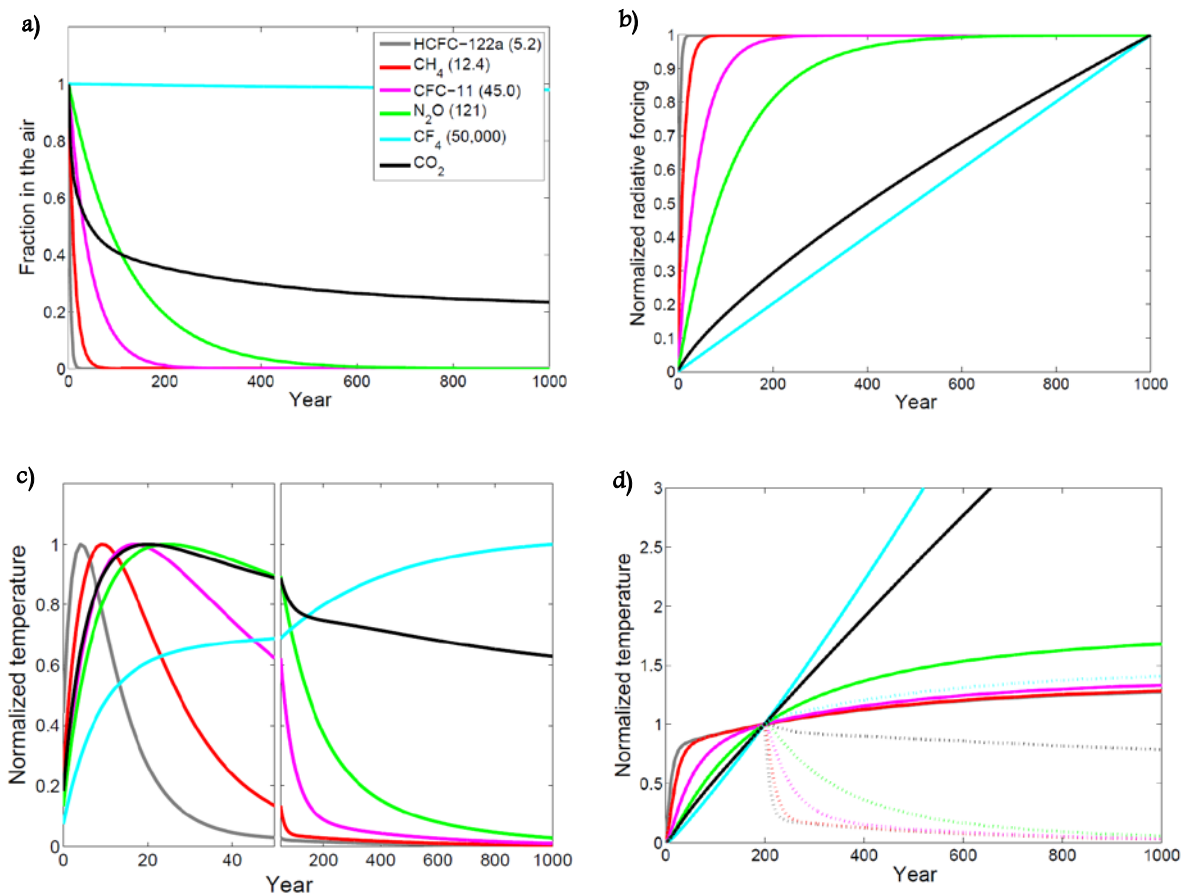
	gases (SF <sub>6</sub> , CF <sub>4</sub> , etc.), CFC-115	1,000 and 50,000			
Indefinite	CO <sub>2</sub>	n.a.	391 ppm	1.82 ± 0.19	1.81E-15

192

193 Among WMGHGs, CO<sub>2</sub> represents a special case. Unlike most other agents, it does not  
 194 decompose through atmospheric chemical reactions, nor it is deposited on the Earth surface,  
 195 but it is removed from the atmosphere by a variety of processes with different timescales  
 196 influenced by multiple nonlinear dependencies [24, 51, 52]. For a 100 GtC emission pulse  
 197 added to a constant CO<sub>2</sub> concentration of 389 ppm, 15–35% of the perturbation is still  
 198 found in the atmosphere after a thousand of years; the ocean has absorbed 59 ± 12% and the  
 199 land the remainder (16 ± 14%) [24]. Thereafter CO<sub>2</sub> concentration is only removed by  
 200 ocean–sediment interactions and the weathering cycle through timescales of hundreds of  
 201 thousands of years [51, 53].

202 We show the normalized temporal evolutions of the responses to emissions of selected  
 203 WMGHGs in Figure 1. These responses, computed for both a pulse emission (Figure 1a,c)  
 204 and constant sustained emissions (Figure 1b, d), are simulated following the approach used  
 205 in the 5<sup>th</sup> IPCC assessment report [1] (see Methods in the Supplementary Information for  
 206 details). The longer the lifetime of the gas, the higher the emission fraction remaining  
 207 airborne over time (Figure 1a). Under constant sustained emissions (Figure 1b), the  
 208 normalized increase in radiative forcing asymptotically tends towards a maximum that is  
 209 proportional to the product of the atmospheric lifetime of the gas, its radiative efficiency,  
 210 and the emission rate. The time taken to approach this maximum value is critically  
 211 dependent on the lifetime, because it determines how soon atmospheric concentrations  
 212 reach steady state. Short-lived species are near maximum within a few decades, while for  
 213 others the steady state will not be reached for centuries or millennia. The temperature  
 214 response to a pulse of short-lived emissions shows a roughly symmetric rise and fall (Figure

215 1c), because the climate system has insufficient time to fully respond before the perturbation  
 216 has disappeared [20]. On the other hand, gases with longer lifetimes are persistent enough  
 217 that the resulting long-term warming is governed by the equilibrium climate sensitivity [54]  
 218 and some do not dissipate even on millennial time scales [45, 53]. The result is that the  
 219 warming from long-lived GHGs remains almost constant or decreases only slowly after the  
 220 temperature peak or a hypothetical cessation of emissions, and for some gases it is nearly  
 221 irreversible over many human generations. In the case of  $\text{CO}_2$ , the temperature does not  
 222 decrease significantly even if emissions cease entirely (Figure 1d). For extremely long-lived  
 223 gases like  $\text{CF}_4$ , the temperature continues to rise for a century or more following cessation of  
 224 emissions owing to the multi-century timescales of the ocean/atmosphere adjustments to  
 225 constant warming [37, 45].



226 Figure 1 Temporal evolutions of the normalized responses of the climate system to some WMGHGs. a) Fraction  
227 of the gas remaining in the atmosphere following an emission pulse at year zero; b) normalized radiative  
228 forcing under constant emission rates; c) normalized global average surface temperature response to an  
229 emission pulse at year zero; d) normalized global average surface temperature response to constant emission  
230 rates (dotted lines show the response to a sudden cessation of emissions at year 200). Each curve is normalized  
231 to its maximum value in the one thousand year time interval in b) and c). The temperature responses are  
232 normalized to the respective value at year 200 in d). The selected gases are those found in IPCC AR5 Table 8.7  
233 [1], with the replacement of HFC-134a (a gas with lifetime similar to methane) with a gas with lifetime of a  
234 few years (HCFC-122a).

235

236 As pointed out in the climate science literature [20, 23, 33] and reiterated in the last IPCC  
237 5<sup>th</sup> Assessment Report [1], the aggregation of WMGHGs to CO<sub>2</sub>-equivalents is challenging  
238 because it groups together gases with lifetimes ranging from a few years to several  
239 thousands of years. Mitigation of either short-lived species or CO<sub>2</sub> achieves different goals  
240 that are not equivalent in terms of climate system responses. For mitigation actions taking  
241 place today, or several decades before a targeted temperature peak, metrics like GWP100  
242 overestimate the importance of short-lived gases but underestimate their impact on near-  
243 term change [18, 20, 33]. For example, HCFC-122a and N<sub>2</sub>O have very different lifetimes (5  
244 and 122 years, respectively) and temperature impact profiles. The temperature change from  
245 N<sub>2</sub>O is approximately 6.5 times larger than that from HCFC-122a 100 years after a pulse  
246 emission, whereas the temperature change from HCFC-122a is about 1.5 times higher than  
247 that from N<sub>2</sub>O after 20 years from a pulse emission. Despite these differences, they are  
248 considered as almost equal when converted to CO<sub>2</sub>-equivalents because they have relatively  
249 similar GWP100 values, 265 for N<sub>2</sub>O and 258 for HCFC-122a [1]. This example underlines  
250 the extent to which the choice of a metric can skew the apparent importance of different  
251 gases, and why the use of a diverse array of metrics is desirable for matching specific policy

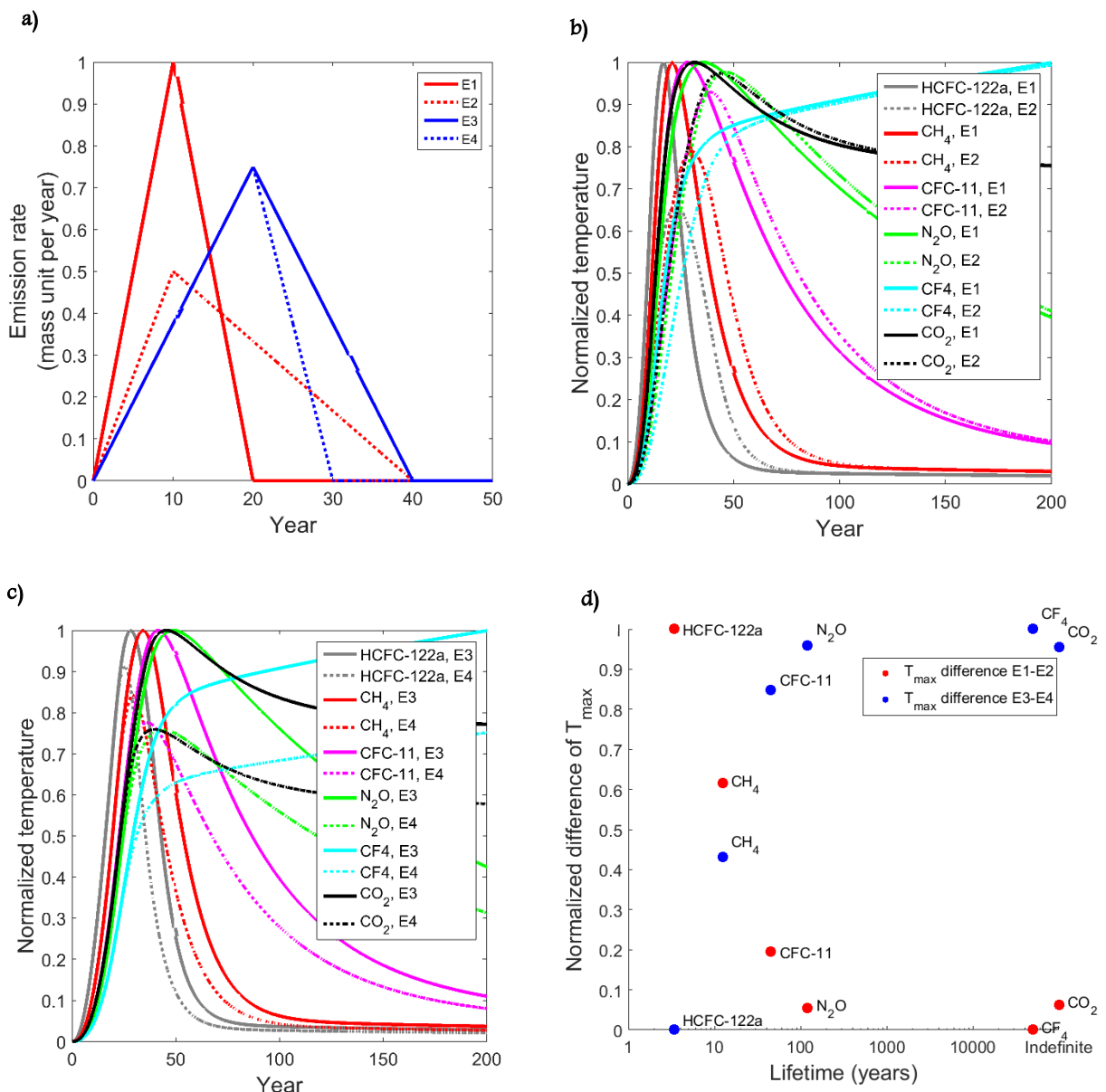
252 goals. The simple replacing of GWP100 with an alternative metric would not mitigate these  
253 concerns because any choice that works for one dimension of the climate system, e.g. short-  
254 term impacts, inevitably risks overlooking others, e.g. long-term impacts.

255

#### 256 **4. Emissions and temperature peaks**

257 There is a growing interest in the climate science community to infer simplified metrics and  
258 climate policy frameworks from the relationships between temperature peaks and emissions  
259 [40, 55–57]. In Figure 2, we show the temperature peak dynamics of different WMGHGs  
260 following four idealized emission trajectories. These trajectories, modelled with a triangular  
261 temporal distribution (Figure 2a), have either the same cumulative emissions and different  
262 maximum emission rates (E1 and E2), or the same maximum emission rate and different  
263 total emissions (E3 and E4). When the temperature responses to E1 and E2 are compared  
264 (Figure 2b), gases with short lifetimes have different temperature peak values (e.g., up to  
265 40% lower under E2 than E1 for HCFC-122a), whereas nearly identical maximum  
266 temperatures are achieved by gases with longer lifetimes. Under constant cumulative  
267 emissions, temperature changes from gases with short lifetimes are sensitive to the  
268 maximum rate at which emissions occur, and the sensitivity gradually decreases while the  
269 lifetime of the gas increases. Temperature changes from gases with longer lifetimes become  
270 more sensitive than short-lived species to specific emission trajectories if total cumulative  
271 emissions differ (Figure 2c). For instance, the temperature peak reached by CO<sub>2</sub> emissions is  
272 about 30% lower under E4 than E3. We compare the effect of emission rates and cumulative  
273 emissions on the temperature responses in Figure 2d, where the normalized temperature  
274 peak differences are plotted against the lifetime of the gases. Gases in the top right corner  
275 (CO<sub>2</sub> and CF<sub>4</sub>) have higher sensitivity to cumulative emissions, whereas if a gas lies in the

276 top left corner (HCFC122a) has a strong sensitivity to emission rates. The temperature  
 277 increase from short-lived emissions thus primarily depends on today emissions, which  
 278 mainly affect the rate and magnitude of climate change over the next few decades [37, 38,  
 279 40, 58, 59]. On the other hand, the temperature impact from long-lived gases like CO<sub>2</sub> and  
 280 CF<sub>4</sub> gradually accumulates over time and, rather than with the rate and timing of emissions,  
 281 it scales with the cumulative amount of emissions, including those occurred in the past [40,  
 282 53, 55, 60, 61].



283 Figure 2: Sensitivity of the temperature response of WMGHGs to emission rates. a) idealized emission rates  
284 peaking and declining. E1 and E2 have the same amount of cumulative emissions but different maximum  
285 emission rates ( $E1 > E2$ ); E3 and E4 have the same maximum emission rate but different cumulative emissions  
286 ( $E3 > E4$ ); b) normalized temperature responses to E1 and E2; c) normalized temperature responses to E3 and  
287 E4; d) normalized difference of the temperature peak ( $T_{\max}$ ), computed from the responses in b) and c), for  
288 each WMGHG as a function of the lifetime of the gas (logarithmic scale). The red dots indicate the normalized  
289 differences in the temperature peak values of each WMGHG to emission scenarios E1 and E2 (Figure 2b). The  
290 blue dots are for the normalized differences in  $T_{\max}$  under emission scenarios E3 and E4 (Figure 2c). Values  
291 close to 1 indicate high sensitivity of  $T_{\max}$  to emission rates (red dots) or cumulative emissions (blue dots). The  
292 profile for each gas in b) and c) is normalized to the respective maximum value from the emission scenario E1  
293 and E3, respectively. For  $CF_4$ , the temperature at 200 years is taken as the normalizing factor.

294

295 The relationship between emissions and temperature peaks is used to produce simplified  
296 emission metrics and approaches [37, 40, 55, 56]. If climate policy is focused on avoiding a  
297 specific temperature threshold, its achievement largely depends on the cumulative emissions  
298 of long-lived gases until the year of the peak, and on emission rates of short-lived species in  
299 the one or two decades preceding the peak [40, 62, 63]. In such a context, emissions of  
300 short-lived gases should be progressively more weighted as the temperature peak is  
301 approached, and less if it is more distant. There are options to link metric values to the  
302 gradual approaching of climate targets, such as time dependent formulations of GWP or  
303 GTP [18, 28, 33] and other metrics explicitly connected to a climatic threshold [14, 34].  
304 Another option that is gathering increasing interest is the “transient climate response to  
305 cumulative carbon emissions” (TCRE) [60], which is formally defined as the warming due to  
306 one trillion ton of cumulative carbon emissions and is based on the linearity between  
307 temperature peak and cumulative emissions [55, 61]. Earlier estimates of the TCRE  
308 suggested an average value of  $1.6 \pm 0.5$  °C per Tera ton carbon (TtonC) emitted [61], while  
309 estimates from both observations and coupled models provide a wider range of 0.8–2.5 °C

310 per TtonC [60]. Although so far mainly validated for CO<sub>2</sub>, the concept of TCRE can also be  
311 extended to other long-lived GHGs [44]. Similarly, the temperature contribution from short-  
312 lived gases can be approximated using scaling factors applied to the maximum emission  
313 rates [37, 40, 58, 59]. The use of metrics based on temperature peak dependencies on either  
314 emission rates or cumulative amounts within an LCA framework has not been explored yet.  
315 On one hand, this approach would allow a multi-basket framework where the various  
316 forcing agents are grouped together on the basis of their lifetimes, thus avoiding the practice  
317 to group together species with very different lifetimes. On the other hand, different sets of  
318 emission metrics would still be needed to aggregate emissions to common units, and the  
319 selection of the metrics to be used in the different baskets would still remain based on value-  
320 laden choices, as it would be dependent on the preferred policy goal [41]. Still open is also  
321 the question on how to weight one basket with respect to the other, with some arguing that  
322 any trading between the different baskets should not be allowed [37, 38].

323

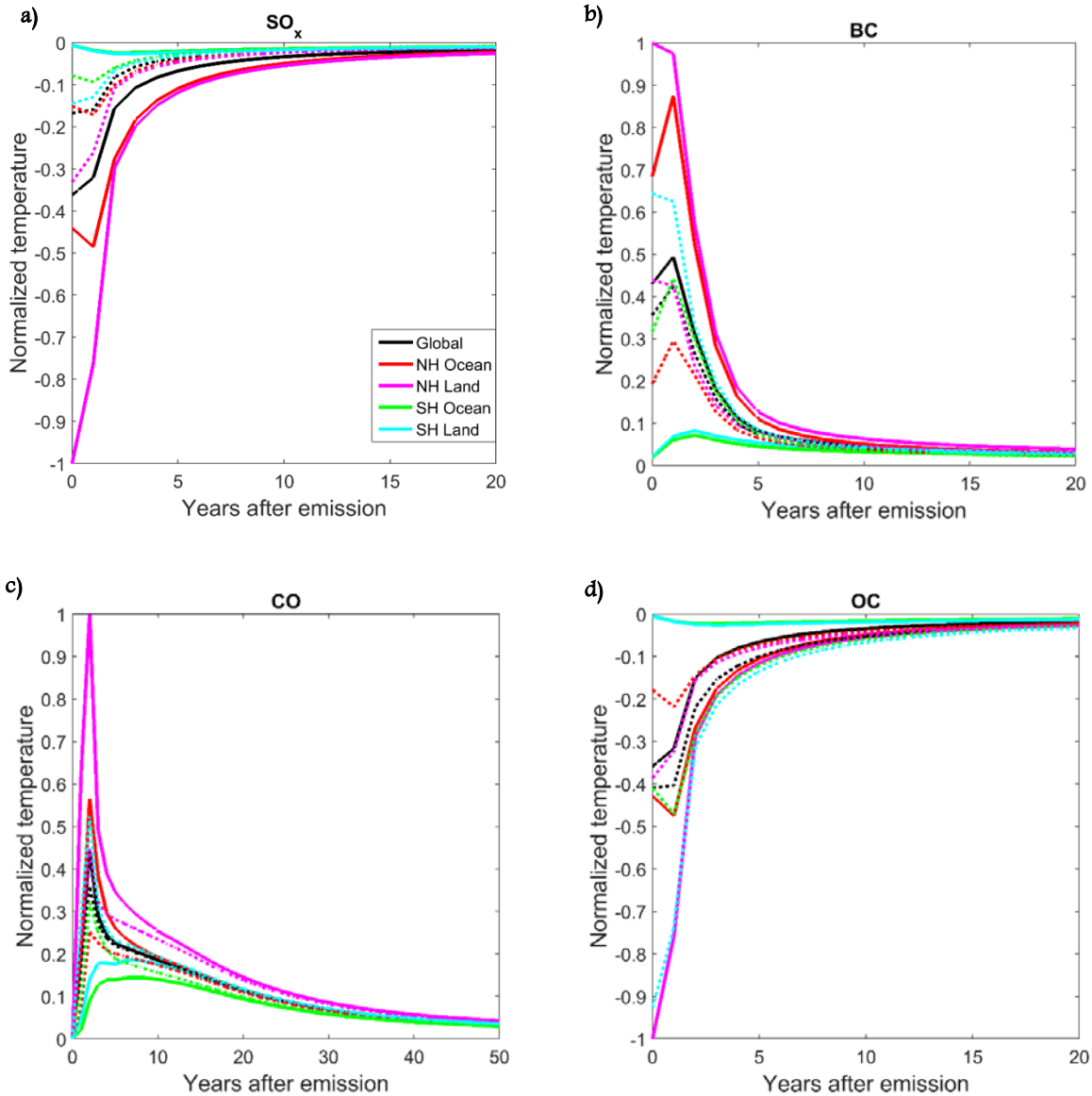
## 324 **5. Near-term climate forcers (NTCFs )**

325 In addition to emissions of WMGHGs, human activities perturb the climate system through  
326 emissions of pollutants such as nitrogen oxides (NO<sub>x</sub>), carbon monoxide (CO), volatile  
327 organic compounds (VOCs), black carbon (BC), organic carbon (OC), sulphur oxides (SO<sub>x</sub>),  
328 and ammonia (NH<sub>3</sub>). Some of these pollutants are precursors to the formation of  
329 tropospheric ozone (NO<sub>x</sub>, CO, VOCs), others are primary aerosols (BC, OC) or precursors to  
330 secondary aerosols (NO<sub>x</sub>, SO<sub>x</sub>, NH<sub>3</sub>). These species have lifetimes shorter than the  
331 hemispheric mixing time and are usually called near-term climate forcers (NTCFs). The  
332 atmospheric concentrations of NTCFs are very heterogeneous, with high concentrations  
333 around the emission source, and therefore the resulting impact largely depends on the



334 source region [64–67]. Although short-lived GHGs like CH<sub>4</sub> are sometimes referred to as  
335 NTCFs, we here restrict this definition to species with inhomogeneous atmospheric  
336 concentrations that are not well-mixed.

337 The considerations above associated with the characteristics of the temperature response to  
338 short-lived species also apply to NTCFs. Emissions of NTCFs may also have an effect on  
339 precipitation patterns through changes in cloud formation processes and cover [2], which  
340 have recently been quantified in terms of emission metrics [31]. In general, the confidence  
341 level in the predicted climate impacts from NTCFs is lower than that for WMGHGs,  
342 especially in the cases in which aerosol–cloud interactions are important (see section 8.5.1  
343 in ref. [1] and the latest specific IPCC chapter on the matter [2]). These emissions are  
344 coupled to the hydrological cycle and atmospheric chemistry and involve highly complex  
345 processes that are challenging to validate. The net climate impacts of NTCFs are the result of  
346 many opposing effects with different temporal evolutions at play. NO<sub>x</sub> species are very  
347 reactive and affect climate through many nonlinear chemical interactions with various  
348 timescales [21, 46], including nitrate and ozone formation, changes in CH<sub>4</sub> concentration  
349 and thereafter stratospheric water vapour [46, 50]. NO<sub>x</sub> also influences CO<sub>2</sub> and the global  
350 carbon cycle through the fertilization effect of nitrogen depositions. Other ozone precursors  
351 are CO and VOCs, which increase the concentration of ozone on short time scales and by  
352 affecting the levels of hydroxyl (OH) radical, and thereby of CH<sub>4</sub>, they also initiate a net  
353 positive long-term ozone effect [3, 65]. Aerosol species influence the climate mainly through  
354 absorption (BC) or scattering (OC, sulphate and nitrate) of solar radiation and other indirect  
355 effects, like deposition of BC on snow. Aerosols are either directly emitted from sources  
356 (primary aerosols, like BC and OC), or they are formed in the atmosphere via several  
357 processes (secondary aerosols, like sulphate after oxidation of SO<sub>2</sub>, and OC from  
358 condensation of organic compounds).



359 Figure 3 Global and regional normalized temperature responses to pulse emissions of selected NTCFs ( $SO_x$ , BC,  
 360 CO and OC) located in the northern or southern hemisphere. The responses to emissions in the northern  
 361 hemisphere (NH) are shown with solid lines, those to emissions from the southern hemisphere (SH) with  
 362 dashed lines. The temperature response is averaged globally and over the land and oceans of NH and SH. For  
 363 each specie, curves are normalized to the maximum (for BC and CO) or minimum (for  $SO_x$  and OC) value of  
 364 all the responses.

365

366 Figure 3 shows the normalized temperature effects from pulse emissions of three aerosol  
 367 species ( $SO_x$ , BC and OC) and one ozone precursor (CO). Emissions are located in the

368 northern or southern hemisphere, and the temperature response is averaged both globally  
369 and over macro regions like the land and oceans of the northern and southern hemispheres.  
370 The responses, which merely have illustrative purposes, are computed using the simplified  
371 climate model MAGICC6 [68], a model widely used in the climate science community (see  
372 Methods in the Supplementary Information). Emissions from different regions have different  
373 lifetimes and the responses are regionally dependent. The global averaged temperature has  
374 significant variations with respect to the regional trends. The climate impact response to an  
375 emission pulse is generally higher in the northern hemisphere, where there is the strongest  
376 sensitivity to forcing, and over the land than the oceans, due to differences on evaporation  
377 [69]. Emissions of BC have the largest impact on regional average temperature change when  
378 located in the northern hemisphere, because BC can be easily transported to the white  
379 surfaces of the arctic and thereby decrease albedo. The response to CO and VOCs are less  
380 heterogeneous because they have longer lifetimes (from one to three months) and are  
381 approximately well-mixed on a hemispheric spatial scale. As discussed elsewhere [20, 66,  
382 70], they are less dependent on emission location and model configurations, although the  
383 consideration of vegetation effects of ozone and aerosol responses can increase variability  
384 [48].

385 Climate impacts from NTCFs are currently excluded from LCA studies, carbon footprints, or  
386 international global climate agreements. Their possible inclusion has been debated [3, 5, 65,  
387 70, 71] and, in some cases, explicitly argued [3, 5, 71]. However, the characterization of  
388 NTCFs to CO<sub>2</sub> equivalents is even more difficult than it is for short-lived gases because of  
389 the very short lifetime of the forcing, its spatial heterogeneity, and the larger uncertainty.  
390 Global metrics like GWP normally use globally-averaged inputs to produce globally-  
391 averaged measures and give no information about the spatial variability of the impact.  
392 Global metrics available in the literature for NTCF emissions located in different regions are

393 presented and discussed in the 5<sup>th</sup> IPCC assessment report [1]. There is not a robust  
394 relationship between the region of the emission and the metric value [20], and the inter-  
395 model variability is sometimes larger than the variability between emission regions [50, 72].  
396 Measures that rely on global averages or long integration times do not fully represent the  
397 temporal and spatial characteristics of the responses [73, 74]. The application of a metric  
398 that is first calculated locally and then averaged globally could be one way of capturing a  
399 more complete and informative signal than one that uses global mean outputs [73].

400 Regional specific responses and emission metrics for NTCFs are also available [50, 64, 74,  
401 75]. Absolute Regional Temperature Potentials (ARTP) are computed using fully coupled  
402 atmosphere-ocean climate models and approximate the time-dependent temperature  
403 response at four latitude bands as a function of the regional forcing imposed by various  
404 climate pollutants in all bands [75]. These metrics allow the assessment of the climate effects  
405 from NTCFs with some regional resolution without coupling the analysis with sophisticated  
406 climate models. However, additional studies are required to determine the robustness of  
407 ARTPs and explore their feasibility for life cycle impact assessment methods. Existing climate  
408 impact frameworks rely on the assumption that the emission location does not affect the  
409 response of the climate system and the climate change impact category has a global scale.  
410 These assumptions hold for WMGHGs but not for all NTCFs. Species like NO<sub>x</sub>, SO<sub>x</sub>, BC and  
411 OC would ideally require the formulation of sub-global emission locations and impact  
412 categories for using the corresponding regional metrics.

413 There are other important caveats associated with the accounting of the climate impacts  
414 from NTCFs. As they can have significant contributions to global warming, their inclusion in  
415 LCA can make their mitigation an attractive proposition to achieve multiple environmental  
416 goals at the same time [76], because these species have adverse effects in other  
417 environmental impact categories than climate change, like human and ecosystem health .

418 On the other hand, some NTCFs have cooling effects, and their accounting may result in a  
419 partial offsetting of the warming effect of the total aggregated emissions. This would result  
420 in the attribution of climate benefits to species which are responsible of air pollution and  
421 damage to ecosystems. LCA methodology includes many environmental impact categories  
422 and is by definition well suited to inform about the possible shifts of impacts across  
423 categories. However, risks of this type are higher in carbon footprint studies or other  
424 applications where the goal is limited to the assessment of climate change impacts only.  
425 Accounting for NTCFs using metrics like the GWP100 would bring to common unit species  
426 with very different climate impact profiles and expand the abatement options available.  
427 Decision-makers could for instance prioritize mitigation of NTCFs and delay reductions in  
428 long-lived species like CO<sub>2</sub>, thereby causing irreversible long-term warming for the sake of  
429 reducing near-term rate of warming. Another important aspect is the consideration that  
430 NTCFs are frequently co-emitted, and this has implications for the benefits that can be  
431 achieved by their mitigation [62, 63]. For instance, with approximately 0.64 W m<sup>-2</sup>, BC is  
432 the third largest radiative forcing component for the period 1750–2011 after CO<sub>2</sub> and CH<sub>4</sub>  
433 [1]. One can therefore argue that a reduction in BC emissions will bring considerable  
434 benefits for the climate. However, the benefits from a decrease in BC emissions are  
435 dampened by the simultaneous reduction of emissions of species like SO<sub>x</sub> and OC, which  
436 have cooling contributions [62, 63].

437

## 438 **6. Land use and land cover change (LULCC)**

439 Climate impacts from a change in land use or management are frequently associated to  
440 emission or removal of WMGHGs like CO<sub>2</sub>, N<sub>2</sub>O and CH<sub>4</sub>. Direct GHG emissions from land  
441 use changes such as deforestation or afforestation, as well as those from changes in above-

442 ground or soil carbon content after a change in management, are usually accounted for in  
443 LCA, when data are available [4, 77]. The consideration of possible emissions associated with  
444 indirect land use changes via market-mediated effects, that is the change in land use in one  
445 place caused by a change in production in another place, is widely debated [78, 79]. Land  
446 use without land-cover change (e.g., managed or harvested forests) have traditionally been  
447 treated under a default carbon neutrality assumption [80], thus ignoring the temporal  
448 asymmetry between CO<sub>2</sub> emission and uptake fluxes, which can be rather significant for  
449 forests. Recent studies show how the climate forcing impact from this asymmetry can be  
450 assessed through site-specific emission metrics that embed post-disturbance carbon  
451 dynamics [81]. Emission metrics or temporally differentiated emission inventories are also  
452 used to compute the climate change implications of anthropogenic carbon sequestration and  
453 storage in products [11, 82–84].

454 Relatively more challenging and less common is the quantification of the biogeophysical  
455 effects following a change in land use or land cover. Modifications of the surface energy  
456 balance through changes in surface albedo, evapotranspiration (the fluxes of heat and water  
457 between the vegetation and the atmosphere), and surface roughness (the aerodynamics of  
458 the vegetation cover), can have implications for the local [85–87] and global [88–90]  
459 climate, either directly or indirectly [89, 91]. The global temperature impact from these  
460 effects can be of the same order of magnitude as the impact associated with CO<sub>2</sub> emission or  
461 removal fluxes [88, 90, 92, 93], whether or not the land cover change is long lasting, such  
462 as in afforestation or deforestation [90, 94], or transient, such as in forest management or  
463 post-fire forest recovery [7, 95]. Nevertheless, accounting for changes in albedo and other  
464 biogeophysical properties is not currently required in the formal rules for quantifying the  
465 climate effects of land use activities [96]. This is despite the large evidence from climate  
466 simulation studies [88, 90, 96–98] or empirical observations [86, 99], where the importance

467 to go beyond a simple carbon accounting framework when assessing the impacts of LULCC  
468 activities on climate is frequently highlighted [7, 92, 96–98]. It has been explicitly argued  
469 that “ignoring biophysical interactions could result in millions of dollars being invested in  
470 some mitigation projects that provide little climate benefit or, worse, are counter-  
471 productive” [96].

472 Biogeophysical properties vary with surface cover and have high spatial and seasonal  
473 variations. There are differences between summer and winter, especially in areas affected by  
474 seasonal snow cover. For instance, forests usually have lower albedo than open lands such as  
475 grassland or cropland, especially during snow covered periods. Biogeochemical effects  
476 following a change in forest cover usually dominate at low latitudes, while biogeophysical  
477 contributions are stronger at high latitudes [88–90, 100]. Biogeophysical effects are  
478 significant also when changes in management occur on the same land use type, such as  
479 irrigation, crop rotation, and forestry [7, 98, 99]. In general, climate impacts vary in spatial  
480 scale and depend on complex, and often nonlinear, mechanisms. Compared to grass, trees  
481 are generally more efficient in transferring water from the soil to the atmosphere because of  
482 their deeper roots and larger leaf area, and forests thus tend to maintain a cooler local  
483 surface temperature by releasing more energy in the form of latent heat than sensible heat.  
484 Hence, conversion from forest to grassland tends to warm the local surface, and it also tends  
485 to reduce the roughness of the landscape and thus to reduce the turbulence in the boundary  
486 layer. However, it is difficult to predict the effect that this reduction may have on surface  
487 temperature, because the reduction of heat and water vapour transport associated with  
488 reduced turbulence may be compensated by greater gradients of humidity and temperature  
489 between the surface and the atmosphere [89, 96].

490 Biogeophysical effects differ in nature. Changes in surface albedo and emissivity modifies  
491 global temperature by directly altering the Earth’s radiative balance, while changes in

492 evapotranspiration and surface aerodynamics do not imply any direct perturbation to the  
493 earth's radiative balance [89]. The quantification of the climate change effects from  
494 evapotranspiration and surface roughness is complex. The attribution of regional and global  
495 climate change effects to these forcing agents is highly uncertain and limited in evidence,  
496 owing to a wide spread in model estimates and differences between observations and model  
497 results [87, 91, 101]. Modelling changes in evapotranspiration and surface roughness also  
498 requires knowledge of numerous vegetation structural, physiological, and environmental  
499 parameters [97, 101], posing formidable challenges for the accounting of these effects in  
500 climate impact assessment studies. On the other hand, changes in surface albedo are rather  
501 more certain and less challenging to quantify. The 5<sup>th</sup> IPCC assessment report classified the  
502 radiative forcing estimates from surface albedo changes with a *high* confidence level, as it  
503 has robust evidence with well documented high precision measurements [1]. Surface albedo  
504 is also the most important biogeophysical mechanism influencing the global climate in  
505 extra-tropical regions, especially in areas experiencing seasonal snow cover [88, 90, 98].  
506 Because they can be measured in terms of radiative forcing, impacts from changes in  
507 surface albedo are frequently converted to CO<sub>2</sub> equivalents using either carbon equivalent  
508 factors [97, 102] or more conventional emission metrics like GWP or GTP [13]. However,  
509 because of the non-linear and high spatial heterogeneity of the climate forcings from land-  
510 atmosphere perturbations as well as the different temporal behaviour, the development and  
511 possible routine applications of climate metrics for LULCC in LCA need to be land cover-  
512 and location-specific. Like for NTCFs, radiative forcing from albedo changes located in  
513 different regions affect climate heterogeneously [89, 90], with radiative forcings at high  
514 latitudes being more effective in changing global temperature than radiative forcing at low  
515 latitudes [103]. Because changes in land surface aerodynamic and physiological properties  
516 often dampen the radiative temperature change at the local surface [89], global radiative



517 forcings from WMGHGs, like CO<sub>2</sub>, and LULCC do not produce the same global mean  
518 temperature response when added together, and more accurate estimates are achieved when  
519 the individual climate responses are used [104]. However, the lack of regional temperature  
520 response functions and metrics for radiative forcings originated from changes in  
521 biogeophysical effects at various locations has so far limited the possibilities to perform  
522 temperature-based analyses without coupling the study with global climate models.

523 In addition to WMGHGs and surface albedo, changes in land cover have a third direct effect  
524 on the global radiation balance by altering emissions of biogenic VOCs (BVOCs), which  
525 rapidly oxidize in the atmosphere generating multiple warming and cooling climate  
526 pollutants like ozone and biogenic secondary organic aerosols [3, 105]. The photochemical  
527 processing of BVOC emissions influences the oxidation capacity of the atmosphere, which  
528 affects the lifetime of CH<sub>4</sub> and the production of other secondary aerosols (sulphate and  
529 nitrates). Even if BVOC emissions are formally quantified as a terrestrial biogeochemical  
530 feedback that responds to anthropogenic climate change [52], we briefly discuss them here  
531 given the strict link they have with LULCC. As for the other NTCFs, the net radiative patterns  
532 are highly spatially inhomogeneous. The net radiative forcing from historical BVOC  
533 emission reductions from expansion of agricultural areas is estimated in a negative (cooling)  
534 contribution [3]. Conversely, increasing BVOC emissions following LULCC involving  
535 reforestation or afforestation strategies cause a positive radiative forcing [71]. Despite  
536 relevant recent progress, important uncertainties still persist. Current generation models  
537 underestimate the amount of organic aerosols in the atmosphere and are unable to fully  
538 reproduce the variability found in the measurements [1]. As NTCFs, BVOC oxidation  
539 products are also important for the growth of newly formed particles up to cloud  
540 condensation, so they indirectly influence climate through changes in cloud albedo [106].  
541 These atmospheric aerosol processes changing cloud droplet concentrations and radiative

542 properties are among the least understood in climate research, and their contributions to the  
543 global radiation budget are considered as one of the largest source of uncertainty in the  
544 estimation of radiative forcing over the industrial period [106]. Results are not consistent  
545 across models, with estimates ranging between  $+0.23 \text{ W m}^{-2}$  and  $-0.77 \text{ W m}^{-2}$  [3]. All these  
546 aspects make a possible consideration of the contributions from aerosol–cloud effects in LCA  
547 and similar studies unrealistic for the short and medium term.

548

## 549 **7. The way forward**

550 Anthropogenic global warming is caused by a variety of forcing agents with different  
551 physical properties and lifetimes ranging from few days, like black carbon, to several  
552 thousands of years, like  $\text{CF}_4$ . Climate impact methods used in LCA are challenged when it  
553 comes to dealing with aspects like the various timescales of the responses to different GHGs,  
554 impacts from NTCFs and LULCC, and their temporal and spatial variability. Emissions can  
555 also be aggregated by metrics other than GWP100. Alternative metrics would allow the  
556 representation of different dimensions of climate change impacts, but would not sidestep the  
557 value–laden considerations of the relative weighting. Value judgements are embedded in  
558 metric formulations, most notably through the choice of time horizon, of climate impact  
559 parameters, and by whether the indicator refers to a time–integrated or instantaneous  
560 quantity. Any preference of one metric over another arguably favours the representation of  
561 some aspects of the climate system response and at the same time discount others.

562 There are considerable uncertainties in the attribution of climate impacts to specific forcing  
563 agents. Scientific uncertainties are larger for temperature–based metrics than for those  
564 based on radiative forcing, and for NTCFs, BVOCs, or non–radiative LULCC mechanisms  
565 than for WMGHGs or changes in surface albedo following LULCC. The presence of

566 uncertainties should not *per se* be an overriding constraint for using metrics and modelling  
567 impacts [20]. If the main policy goal is to keep global temperature below a certain threshold,  
568 the uncertainties and timing of political choices (i.e. a delay in action) are often those with  
569 the largest cost–risk distributions, and may actually swamp the uncertainties associated with  
570 the parameterization of the climate system [107].

571 Concerning the aggregation to common units, it is impossible to identify a single metric that  
572 can produce a balanced representation of the overall climate impact from such a diversity of  
573 forcing agents. Different climate policy goals may lead to different conclusions about what  
574 is the most suitable metric to assess that policy. For instance, the use of GWP100 in LCA has  
575 the inadvertent consequence of assessing emissions for their contributions to global  
576 temperature over a timeframe of about four decades [35, 36], with no direct connections to  
577 peak warming. GWP100 only becomes an indication of the contributions to peak warming  
578 under the arguably optimistic assumption that global CO<sub>2</sub> emissions will approach zero  
579 within about 40 years, so that the global temperature will approach stabilization. The  
580 characterization of different emissions to CO<sub>2</sub>-equivalents implicitly suggests that one can  
581 freely choose which emissions to reduce in order to achieve the same improvement in the  
582 climate system performance of a product. However, the same net reduction of the total  
583 aggregated emissions in CO<sub>2</sub>-equivalents will have different climate effects at different  
584 times, depending on whether it is obtained through a reduction in long-lived or short-lived  
585 species. If emissions of long-lived gases continue to rise, the mitigation of short-lived species  
586 would temporarily reduce the rate of warming but cannot avoid the risk of passing  
587 warming thresholds, because as long as the concentration of CO<sub>2</sub> is allowed to keep  
588 growing, the reaching of those thresholds is only temporally postponed. Any delay in  
589 mitigation of CO<sub>2</sub> emissions will lead to nearly irreversible warming. Within the global  
590 policy goal of limiting warming to 2°C above pre-industrial levels, mitigation of CO<sub>2</sub>

591 emissions is thus identified as a non-negotiable objective in strategies aiming at constraining  
592 maximum temperature [35, 37, 44, 55, 57, 63], because any deferral in mitigating long-  
593 lived emissions progressively closes the door for achieving ambitious peak temperature  
594 targets.

595 Bridging life cycle impact assessment methods with climate science is essential to provide  
596 decision makers with more robust climate change impact studies that acknowledge the  
597 variety of forcing agents at play and the caveats of their aggregation. There are metrics other  
598 than GWP100 and climate forcing agents other than WMGHGs. Explicit consideration of  
599 alternative metrics by LCA practitioners would allow the characterization of climate change  
600 impacts over multiple timescales and with regard to diverse and contrasting policy goals.

601 For instance, the use of metrics like GWP20 or GWP100 can provide information about the  
602 time-integrated contributions to global warming in a short/medium term, whereas GTP100  
603 provides information about the instantaneous contributions to global warming on a longer  
604 timeframe. If GWP aligns well with the LCA ambition to prefer integrated impacts, GTP  
605 provides the possibility to explicitly link global warming contributions to a climate target,  
606 based on planetary boundary and/or policy considerations. In general, the utilization of  
607 multiple metrics provides complementary information on the implications of mitigating  
608 gases with varying lifetimes, and shows the extent to which results are sensitive to the  
609 choice of metric or robust across a range of choices. The inclusion in existing LCA databases  
610 and impact assessment methods of the spectrum of the metrics available in the latest IPCC  
611 assessment report will facilitate their application by LCA practitioners.

612 The consideration of NTCFs in LCA presents challenges at an inventory and characterization  
613 level. Most of the NTCFs are already tracked by the majority of the life-cycle inventory  
614 databases, as they contribute to other environmental impact categories, except for BC and  
615 OC emissions. Although they can be indirectly quantified from emissions of particulate

616 matter, their explicit inclusion in emission inventories is desirable to facilitate applications.  
617 Characterization of their impacts on climate should consider the higher level of  
618 uncertainties associated with metrics for NTCFs, and ideally consider the range of possible  
619 metric values summarized in the latest IPCC report. The LCA community should closely  
620 follow updates on quantification of impacts from NTCFs as the climate science community is  
621 continuously improving the robustness of characterization factors for NTCFs.

622 Regional climate change categories can also be formulated in the future when robust  
623 estimates of metric values for regional responses to NTCFs become available. Inventory  
624 databases should already be adapted by elaborating spatial-explicit emission inventories  
625 that keep track of emission regions.

626 The time is ripe for the LCA community to consider the complexity of climate science and  
627 gain insights on the implications associated with the selection of emission metrics for the  
628 intended goal of the analysis. Rather than using a single default metric for WMGHGs in all  
629 applications, analysts should acknowledge the various forcing agents and the caveats  
630 associated with the aggregation of species with different lifetimes to common units. The  
631 sensitivity of the results to the type of metric used should be explored. When a choice is to  
632 be made, this can be done consistently with the aspects of climate change that are most  
633 relevant for the particular application. In any case, it is important to be aware and  
634 transparent about the choice of metric, its meaning, and the inherent value judgments it  
635 entails when interpreting and communicating results. A continuous bridge between the two  
636 communities is desirable in the future to keep LCA methods up-to-date with the latest  
637 developments in climate science, and simultaneously engage climate scientists to shape  
638 emission metrics and approaches to fit environmental impact assessment frameworks.

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