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Enhancing life cycle impact assessment from climate science: Review of recent findings and recommendations for application to LCA

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Abstract.

Since the Global Warming Potential (GWP) was first presented in the Intergovernmental Panel on Climate Change (IPCC) First Assessment Report, the metric has been scrutinized and alternative metrics have been suggested. The IPCC Fifth Assessment Report gives a scientific assessment of the main recent findings from climate metrics research and provides the most up-to-date values for a subset of metrics and time horizons. The objectives of this paper are to perform a systematic review of available midpoint metrics (i.e. using an indicator situated in the middle of the cause-effect chain from emissions to climate change) for well-mixed greenhouse gases and near-term climate forcers based on the current literature, to provide recommendations for the development and use of characterization factors for climate change in life cycle assessment (LCA), and to identify research needs. This work is part of the 'Global Guidance on Environmental Life Cycle Impact Assessment' project held by the UNEP/SETAC Life Cycle Initiative and is intended to support a consensus finding workshop. In an LCA context, it can make sense to use several complementary metrics that serve different purposes, and from there get an understanding about the robustness of the LCA study to different perspectives and metrics. We propose a step-by-step approach to test the sensitivity of LCA results to different modelling choices and provide recommendations for specific issues such as the consideration of climate-carbon feedbacks and the inclusion of pollutants with cooling effects (negative metric values).

Keywords. Climate change, Life cycle assessment (LCA), Climate metric, Well-mixed greenhouse gas, Near-term climate forcer

1. Introduction

Life cycle assessment (LCA) is a decision support tool that estimates the potential environmental impacts of any product system over its entire life cycle. It is commonly used to guide environmental policies and programs, to inform consumers' choices through environmental labeling and declarations, and to help industries reduce the environmental impact of their activities or design more sustainable products, amongst others (ISO 14044, 2006).

The first step in an LCA – after defining the goal and scope – is to develop an inventory of all environmental emissions from, and natural resource inputs to, each unit process in the system. The total environmental inputs and outputs from all activities are called the life cycle inventory (LCI). In life cycle impact assessment (LCIA), these environmental flows are classified according to the type of environmental impact they cause, and multiplied by characterization factors (CF) that express their contribution to that indicator. CFs are developed using environmental models that estimate the relative or absolute effect of each flow on a selected indicator, which is a quantifiable representation of an impact category. LCA practitioners usually select a specific LCIA method that proposes a series of CFs for different types of environmental impact (ISO 14044, 2006).

Emissions of CO_2 and other greenhouse gases (GHGs), aerosols, and ozone precursors are affecting the climate system as illustrated by the cause-effect chain presented in Figure 1. In current LCIA methods, CFs for the climate change impact category are usually proposed only for well-mixed greenhouse gases (WMGHG), using Global Warming Potential (GWP) values published in the Intergovernmental Panel on Climate Change (IPCC) assessment reports. Other anthropogenic causes of global warming such as near-term climate forcers (NTCF) or albedo changes are currently not considered in LCA (Levasseur, 2015). The important difference between WMGHGs and NTCFs is their lifetime. WMGHGs have atmospheric lifetimes long enough to be well mixed throughout the troposphere, and their climatic impact does not depend on the location of emissions. WMGHGs include CO_2, N_2O, CH_4, SF_6 and many halogenated species. By contrast, NTCFs have atmospheric lifetimes of less than one year so that their climatic impact depends on the emission location. NTCFs include ozone and aerosols, or their precursors, and some halogenated species that are not WMGHGs (Myhre et al., 2013).

Researchers have shown that cumulative emissions of WMGHG with a lifetime greater than 50-100 years dominate the peak warming (Smith et al., 2012). However, reducing emissions of NTCFs and WMGHGs with shorter lifetimes could reduce the rate of climate warming over the next few decades and, if emission reductions are sustained, also lower the peak temperature attained (Myhre et al., 2011; Penner et al., 2010; Rogelj et al., 2014; Shindell et al., 2012; Smith et al., 2012). If net CO_2 emissions do not decline significantly and eventually reach zero, mitigation of short-lived species will only postpone but not avoid the breaching of a temperature threshold in line with those adopted within the UNFCCC process (Allen et al, 2016; Bowerman et al., 2013).

There are two different types of CFs depending on the position of the selected indicator in the cause-effect chain (see Figure 1). Midpoint CFs refer to effects at an earlier stage of the cause-effect chain such as radiative forcing or temperature, while endpoint CFs are derived from relatively more complex mechanisms (with increased uncertainties) for translating emissions into impacts on human health (e.g. disability-adjusted life years caused by climate change) and ecosystems (e.g. potential disappeared fraction of species because of climate change) (Levasseur, 2015). All current LCIA methods offer midpoint CFs using GWPs published by the IPCC. The only distinctions between LCIA methods on this matter are the choice of time horizon and the issue year of the IPCC Assessment Report. Most LCIA methods use a 100-year time horizon to be in line with the time horizon selected for the application in the 1997 Kyoto Protocol, while a very few others use a 20- or 500-year time horizon (Levasseur, 2015). For instance, the ReCiPe method uses time horizons of 20, 100 and 500 years respectively for the individualist, hierarchist and egalitarian perspectives (Goedkoop et al., 2013). Users must choose between one of these perspectives to set the default value for some modeling choices.

Since the GWP was first presented in the IPCC First Assessment Report, the metric has been scrutinized and alternative metrics have been suggested. GWP was intended to clarify the relative contributions to global warming of different countries and different activities to help develop cost-effective emission policies at both national and international levels (Lahosf & Ahuja, 1990). However, Shine (2009) reminds us that the GWP concept was initially a simple approach adopted in part to illustrate the difficulties encountered when developing a single metric to assess climate impacts associated with GHG emissions of gases with very different physical and chemical properties. There exists a plethora of other metrics based on physical and biogeochemical aspects of climate change (e.g. Gillet & Matthews, 2010; Lauder et al., 2013; Peters et al., 2011a; Shine et al., 2005, 2015; Smith et al., 2012; Sterner et al., 2014; Tanaka et al., 2009; Wigley, 1998), and a large range of metrics where aspects of economics are also taken into account (e.g. Eckaus, 1992; Johansson, 2012; Manne & Richels, 2001; Rilley & Richards, 1993). In recent years, the issue of metrics has received increased political attention and several publications have addressed concerns regarding the use of appropriate climate metrics in an LCA context (e.g. Peters et al., 2011b; UNFCCC, 2012, 2014). The IPCC Fifth Assessment Report (5thAR) gives a scientific assessment of the main recent findings from physical climate metrics research and provides the most up-to-date values for a subset of metrics and time horizons (GWP and Global Temperature change Potential (GTP); see below). Crucially, the latest IPCC assessment emphasises that the choice of emission metric and time horizon depends on type of application and policy context and no single metric is optimal for all policy goals (IPCC, 2014a).

The objectives of this paper are to perform a systematic review of available midpoint metrics for WMGHGs and NTCFs based on the current literature, to provide recommendations for the development and use of climate change CFs in LCA, and to identify research needs. We primarily discuss research findings on metrics presented in the IPCC 5thAR, which emphasized GWP and GTP, and under which circumstances these metrics could be applied to improve current climate change midpoint characterization factors in LCA. This work is part of the 'Global Guidance on Environmental Life Cycle Impact Assessment' project held by the UNEP/SETAC Life Cycle Initiative and is intended to support a consensus finding workshop

2. Emission metrics for climate change impacts

Emission metrics aim to compare the effects of different forcing agents on the climate system. They can be used in different contexts such as multi-component climate policies, comparison of emissions between regions or sectors, and LCA, amongst others (Kolstad et al., 2014; Myhre et al, 2013). As stated in the IPCC 5thAR, "the most appropriate metric will depend on which aspects of climate change are most important" (Myhre et al, 2013). Indeed, no single metric can adequately and simultaneously assess the impact of different climate forcers on different aspects of climate change such as the rate of change or long-term temperature increase. This section presents an overview of different midpoint emission metrics used to estimate the impact of climate forcers.

2.1. Development of emission metrics

Metrics are intended to be applied widely and with minimized value-judgements, but a number of choices have to be made in order to select a specific metric (Tanaka et al., 2010). This section presents the cause-effect chain of climate change from which an indicator must first be selected, as well as fundamental choices about some metric characteristics.

2.1.1. The cause-effect chain

The emission of WMGHGs and NTCFs leads to an increase of their concentration in the atmosphere. This increase in concentration results in radiative forcing [$W \cdot m^{-2}$], also called stratospherically adjusted radiative forcing, which is defined as the change in net downward radiative flux at the tropopause after the stratospheric temperature is readjusted to a radiative equilibrium, while surface and tropospheric temperature and state variables such as water vapour and cloud cover are held fixed at the unperturbed values (Myhre et al., 2013). An extension to this, the effective radiative forcing, considers the change in radiative flux after allowing for an adjustment of other physical variables such as cloud and snow cover. Effective radiative forcing is nearly identical to radiative forcing for WMGHGs but can differ significantly for aerosols because of their additional direct impact on clouds and snow cover. A positive radiative forcing warms the climate system, while a negative radiative forcing cools it.

WMGHGs and NTCFs cause radiative forcing when they are released in the atmosphere, which thus leads to a warming (most WMGHGs and NTCFs) or cooling (some NTCFs) impact on the land and sea surface temperature. This temperature change leads to different climate impacts such as sea-level rise, changes in precipitations, melting of polar ice-caps and glaciers, thawing of permafrost, etc. Aerosols can also affect climate directly through influencing cloud properties and formation and snow melt. These changes finally impact humans and ecosystems in different ways such as by increasing the incidence of certain diseases, flooded areas, changes in food production, droughts leading to malnutrition, species range shifts and possible extinctions etc. (IPCC, 2014b). Figure 1 presents a simplified diagram of the cause-effect chain from emissions to impacts as described above. The diagram shows only the most important pathways by omitting more detailed feedbacks such as climate-carbon cycle feedbacks (Friedlingstein et al., 2006).

Emission metrics are often used to quantify and compare the climate impacts of WMGHGs and NTCFs in different accounting methodologies such as LCA or GHG emission inventories. They are developed by choosing an indicator somewhere in the cause-effect chain and measuring the effect of an emission of each climate forcer on this indicator based on input from climate modelling. This paper focuses on midpoint indicators only.

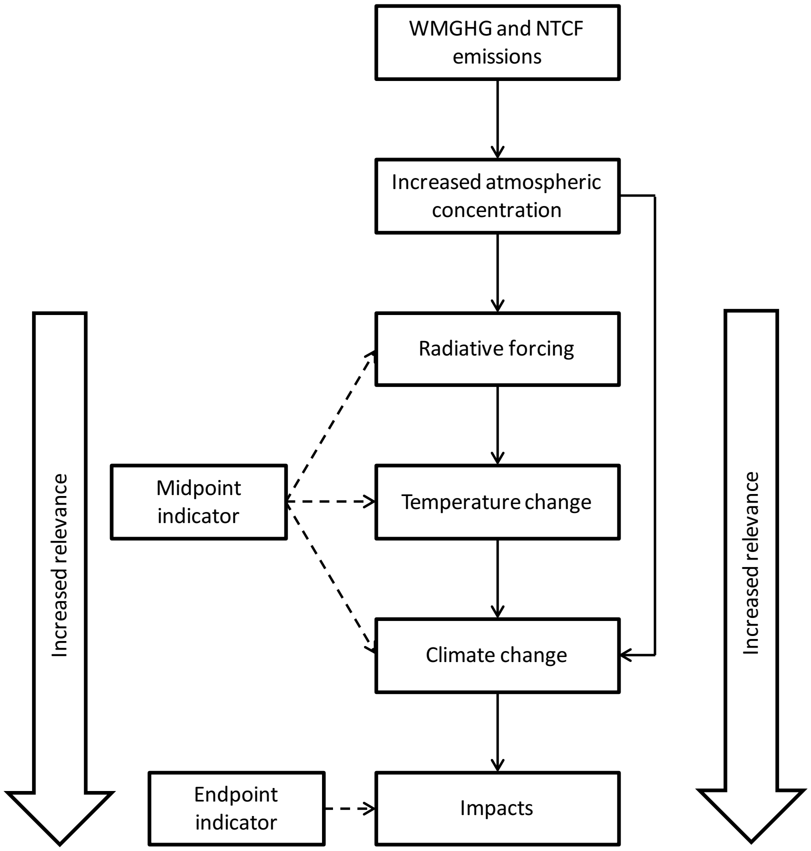

Figure 1. The cause-effect chain of climate change (modified from Figure 8.27 of IPCC 5th AR WGI)

2.1.2. Absolute versus normalized metrics

Absolute metrics estimate the value of the selected indicator for a given emission (e.g. Kelvin per unit emitted), while normalized metrics compare the value of the selected indicator for a given emission to the value of the same indicator for an equal mass of a reference substance emitted (i.e. a ratio of an absolute metric of a component of interest to the absolute metric of a reference gas). The reference substance used conventionally for climate metrics is CO_2, with emissions commonly expressed as so-called “CO_2-equivalent” emissions. While this may be justified given that CO_2 is the dominant cause of human-induced warming, this choice also introduces complexity related to the variety of physical and biogeochemical processes governing the atmospheric CO_2 concentration (namely the non-single exponential decay of a pulse emission into the atmosphere, with a fraction remaining for many thousands of years) as well as the fact that the climate effect due to a normalised pulse emission of this gas itself changes over time with changing background concentrations and on-going climate change (Joos et al., 2013).

2.1.3. Instantaneous versus cumulative metrics

For the majority of suggested metrics it is possible to categorize them as either being instantaneous or cumulative. Instantaneous metrics estimate the value of the selected indicator at a given point in time after an emission (“snapshot metrics”), while cumulative metrics integrate the value of the selected indicator over a period of time up to a given time horizon. Given the very different atmospheric lifetimes of different GHGs, the choice between instantaneous and cumulative metrics has a fundamental bearing on the value accorded to relatively short-lived gases relative to those with longer lifetimes, as cumulative metrics ‘remember’ near-term warming even if a distant time horizon is chosen for evaluating climate impacts (Fuglestvedt et al., 2010; Myhre et al, 2013; Sterner et al., 2014).

2.2. Presentation of selected climate metrics

This section presents some specific instantaneous and cumulative metrics based on different indicators such as radiative forcing and temperature change that have robust literature behind them, some of them having been assessed by the IPCC. Each of these metrics embodies implications of different choices at various points in their development. Some of these choices are discussed further in Section 3.

2.2.1. Metrics based on radiative forcing

Some metrics use the radiative forcing caused by an emission as key parameter for indicating impacts of different climate forcers. Different models and assumptions can be used to estimate radiative forcing, which depends on the radiative efficiency of the climate forcer, its atmospheric lifetime by various removal processes, and any indirect effects.

The most widely used metric based on radiative forcing is GWP. This is largely because it was the only option considered by the IPCC in its First Assessment Report (IPCC, 1990) and adopted for the application of the Kyoto Protocol. GWP [$\mathrm{kgCO_2\text{-}eq \cdot kg^{-1}}$] is an example of a normalized and cumulative metric. It is the ratio of the Absolute Global Warming Potential (AGWP) of a given GHG to that of CO_2, the reference gas (Equation 4). AGWP [$\mathrm{W \cdot yr \cdot m^{-2} \cdot kg^{-1}}$], an absolute metric, is the cumulative radiative forcing caused by a unit-mass pulse emission calculated over a selected time horizon *TH* [yr] (Equation 1) (Myhre et al., 2013).

$$\mathrm{AGWP_x(TH)} = \int_0^{\mathrm{TH}} \mathrm{RF_x}(t)dt \qquad (1)$$

For non-CO_2 gases, *RF(t)* can be approximated by a first-order decay equation (see Equation 2) where A [$\mathrm{W \cdot m^{-2} \cdot kg^{-1}}$] is the radiative efficiency i.e. the radiative forcing caused by a marginal increase in atmospheric concentration of a given gas in the atmosphere and τ [yr] is the lifetime of the gas. Additional terms or adjustments may be needed in Equations 1 and 2 to account for effects such as climate-carbon cycle feedbacks or the oxidation of fossil CH_4 to CO_2.

$$RF_x(t) = \mathrm{A_x} e^{-t/\tau_x} \qquad (2)$$

For CO_2, in IPCC 5th AR as well as previous reports, *RF(t)* is given by a more complex formula (see Equation 3) derived as the average response across multiple carbon-cycle models of various complexities (Joos et al., 2013). This represents the response of the oceanic and terrestrial carbon sinks to an instantaneous increase in atmospheric CO_2.

$$RF_{CO_2}(t) = \mathrm{A}_{\mathrm{CO}_2}\left\{a_0 + \sum_{i=1}^{3} a_i e^{-t/\tau_i}\right\} \tag{3}$$

$$GWP_x(\mathrm{TH}) = \frac{AGWP_x(TH)}{AGWP_{CO_2}(TH)} \tag{4}$$

In each of its assessment reports, the IPCC publishes a list of updated values for the different parameters *A*, *a*, and *τ* [yr] for a constant (but updated) atmospheric background concentration, as well as GWP values calculated for some selected time horizons. Traditionally, GWP values were calculated for 20-, 100-, and 500-year time horizons. However, in its 5thAR, the IPCC shows values for 20- and 100-year time horizons only, stating that the confidence in providing useful metrics for time horizons longer than 100 years is very low due to associated uncertainties and strong assumptions of constant background conditions as well as ambiguity in the interpretation of such a long-integration metric (Myhre et al., 2013).

AGWP and GWP are cumulative metrics. However, a metric based on instantaneous radiative forcing using the same parameters as those used for AGWP could be developed using the value of *RF(t)* at a given time instead of integrating it over the time horizon (Edwards & Trancik, 2014; Michaelis, 1992). Such a metric would estimate the change in radiative forcing occurring at any given time following an emission. Another example of forcing-based metric is the Forcing Equivalence Index (FEI), a time-dependent metric to capture climate forcing along a prescribed scenario (Manning & Reisinger, 2011; Wigley, 1998).

2.2.2. Metrics based on temperature change

Some metrics go one-step further down the cause-effect chain and use the temperature change caused by an emission as an indicator to assess the impact of different climate forcers. The Global Temperature change Potential (GTP) proposed by Shine et al. (2005) is a normalized metric and was assessed in the IPCC 5thAR. It is an example of an instantaneous metric, defined as the change in global mean surface temperature at a chosen point in time *TH* [yr] after a pulse-emission, relative to the temperature change following a pulse emission of a unit quantity of CO_2.

GTP [$kgCO_2$-eq·kg^{-1}] uses the same parameters as GWP i.e. radiative efficiency A [$W\cdot m^{-2}\cdot kg^{-1}$] and atmospheric decay τ [yr], as well as the climate sensitivity and the exchange of heat between the atmosphere and the ocean using parameters c [$K\cdot(W\cdot m^{-2})^{-1}$]and d [yr]. Formulas have been proposed for sustained and pulse emissions, but only the ones for pulse emissions are presented in the IPCC 5th AR. The original AGTP formula has a single term for the time response of the climate system (Shine et al, 2005). Since then, some researchers have proposed formulas with two (Boucher & Reddy, 2008; Fuglestvedt et al., 2010; Geoffroy et al., 2013) and three response terms (Li & Jarvis, 2009; Olivié et al., 2012) to better represent the different time scales of the climate response. However, Li and Jarvis (2009) argue that too many terms are difficult to calibrate so that it is better to restrict to a two-term function. As an alternative to use analytical impulse response functions to estimate metrics, one can use numerical reduced-complexity climate models, such as MAGICC and ACC2 (e.g. Gillet & Matthews, 2010; Reisinger et al., 2010, 2011; Tanaka et al, 2009, 2013).

Because metrics based on temperature change are midpoint indicators further down the cause-effect chain than those using radiative forcing only as the key parameter, they may be more relevant for determining environmental consequences of emissions, even if they use additional uncertain parameters as indicated by Figure 1 in this paper as well as Figure 8.27 in Working

Group I IPCC 5th AR (Myhre et al, 2013). Indeed, the uncertainty in GWP and GTP cannot be directly compared since they are of different nature. However, the GTP values also depend on the response time of the climate system, which is uncertain. This uncertainty is a real feature of the climate response which is not captured by the GWP (Fuglestvedt et al., 2003; Reisinger et al., 2010).

Metrics based on cumulative temperature change over the selected time horizon, also known as integrated GTP (iGTP), have been developed and analyzed (Azar & Johansson, 2012; Cherubini et al., 2013; Gillet & Matthews, 2010; Peters et al., 2011a; Rotmans & den Elzen, 1992). The iGTP for a given climate forcer and time horizon is under a range of circumstances approximately similar to GWP for WMGHGs, but may be quite different for NTCFs such as black carbon. TEMperature Proxy index (TEMP) is also a temperature-based metric (Tanaka et al., 2009). It is defined for a given emission scenario and aims to capture the relative contribution of different components to the temperature change.

Even though GTP is an instantaneous metric, it incorporates a degree of integration of radiative forcing, since the temperature change at any given point in time reflects changes in radiative forcing for up to several decades up to the temperature change. However, this ‘implicit integration’ performed by the GTP is heavily weighted towards radiative forcing in the decade immediately prior to the temperature change and depends on the time scales of the impulse response function. This can also be seen by the fact that iGTP (rather than GTP) attains very similar values to GWP for forcing agents with atmospheric lifetimes longer than a few years. Thus the choice whether to adopt a cumulative or instantaneous metric is more important than the implicit integration performed by metrics such as GTP which are further down the cause-effect chain.

2.2.3. Other types of metrics

Sterner et al. (2014) have developed instantaneous and cumulative metrics to compare the impact of different climate forcers on sea level rise: the Global Sea level rise Potential (GSP) and the Integrated Global Seal level rise Potential (IGSP). They estimate the sea level rise at a given time horizon (GSP) or the time integrated sea level rise (IGSP) caused by a pulse emission relative to that of a comparable emission of CO_2. They have shown that all climate forcers, including very short-lived ones, have considerable influence on sea level rise on the century time scale per unit emissions.

Shine et al. (2015) present a new metric concept named the Global Precipitation change Potential (GPP), which estimates the effect of various emissions on the global water cycle. The formulation of GPP consists of two terms, one dependent on the surface temperature change and the other dependent on the atmospheric component of the radiative forcing. For some forcing agents, and notably for CO_2, these two terms oppose each other. Since the forcing and temperature perturbations have different timescales, even the sign of the absolute GPP varies with time. One finding is a strong near-term effect of CH_4 on precipitation change and the role of sustained emissions of black carbon and sulphate in suppressing precipitation. The application of the GPP in practice could be challenged by the fact that depending on location, an increase or decrease in precipitation could be regarded as a negative or positive environmental impact.

The Climate Change Impact Potential (CCIP) is a metric that aims to capture a wide range of climate impacts in an aggregated manner (Kirschbaum, 2014). While CCIP is by definition an endpoint metric, it can be comparable to midpoint metrics because it is formulated as a function of a set of three midpoint indicators: namely, instantaneous, cumulative, and rate of temperature change. Quantifying climate impacts comprehensively is important but challenging, and this metric inherently contains strong implicit assumptions. Most notable are i) an equal weighting across the three impact terms using the midpoint indicators and ii) a fixed time horizon of 100 years.

Figure 2 presents an illustration of different kinds of metrics available and Table 1 shows the values of metrics for non-fossil CH_4. The weighting of CH_4 relative to CO_2 varies substantially between metrics and between time horizons, illustrating the significant implication of different choices for climate metrics. Depending on the metric and time horizon chosen, the different weight attributed to CH_4 emissions compared to CO_2 emissions could potentially lead to very different conclusions when comparing product systems or climate mitigation solutions using LCA.

Table 1. Values of midpoint metrics for non-fossil methane (kgCO_2-eq/kg) (FEI has been left out of the table because its structure is different and it is not calculated for a fixed time horizon)

Metric	Time horizon = 20 years	Time horizon = 100 years
GWP (without feedbacks)	84	28
GWP (with feedbacks)	86	34
GTP (without feedbacks)	67	4
GTP (with feedbacks)	70	11
iGTP	81	28
GSP	78	18
IGSP	95	39
GPP	120	8.1
CCIP (using RCP6 scenario)	N/A	23

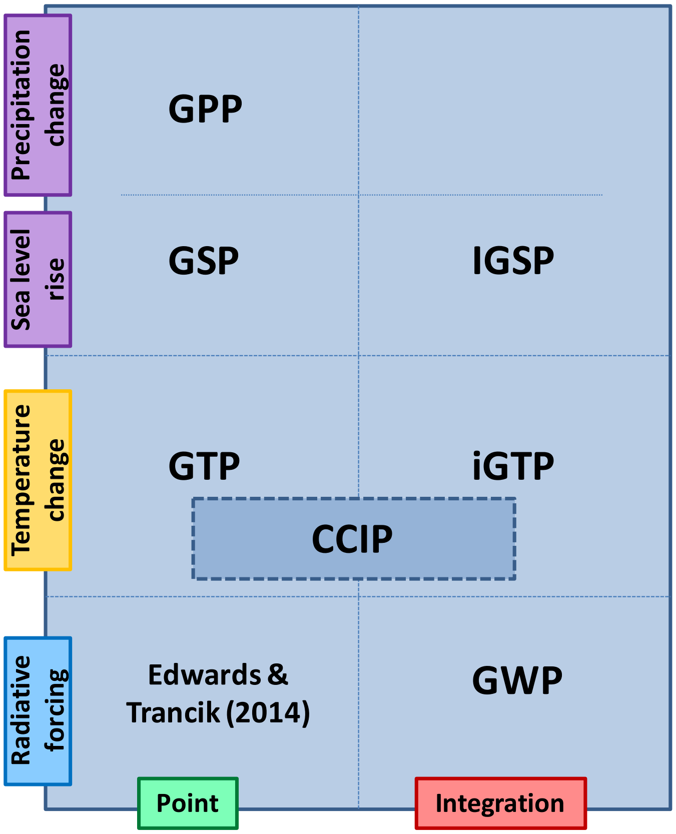

Figure 2. Illustration of different normalized metrics

3. Discussion of some key metric choices

This section discusses different key choices that one must make when selecting emission metrics. These choices may have significant impacts on the LCA results. For instance, using GWP values for a 20-year time horizon may lead to different conclusions than if GTP and a 100-year time horizon is used. Despite the fact that science is able to inform decision makers about the implications of these choices, it cannot objectively determine which ones are ultimately better because it depends on policy context and involves value judgments so that there is no single scientifically correct choice.

3.1. Instantaneous versus cumulative metrics

Climate impacts are diverse, and different types of emission metrics are needed to reflect the different aspects, as summarized by Kirschbaum (2014). Instantaneous metrics based on temperature are relevant when assessing the potential impacts caused by an absolute temperature increase, which are closer to climate damages related for instance to heat waves (Huang et al., 2011), extreme weather events (Webster et al., 2005), or coral bleaching (Baker et al., 2008). Cumulative metrics based on temperature or radiative forcing are relevant when assessing potential climate impacts associated with cumulative warming, which are for instance loss of permanent ice and associated sea-level rise (Vermeer & Rahmstorf, 2009) or shut-off of thermohaline circulation (Lenton et al., 2008). However, some researchers have shown that sea level rise or thermohaline circulation, for instance, cannot be appropriately assessed by cumulative metrics (Herrington & Zickfeld, 2014; Sterner et al., 2014), nor by instantaneous metrics expressing the temperature increase in exactly one specific future year. Finally, the rate of change of atmospheric and oceans temperature strongly influences whether species and humans have time to adapt to climate change (Peck & Teisberg, 1994). A relevant metric for this type of impacts would be based on the derivative of the function describing an instantaneous metric (Hammit et al., 1996), but can also be reflected by the choice of shorter time horizons when using a cumulative metric.

3.2. Constant versus variable background atmosphere and climate

GWP and GTP values proposed in the IPCC ARs have been calculated for respective present-day constant background atmosphere concentrations (391 ppm CO_2 for the 5th AR) and climate conditions. Values can also be calculated for variable conditions as already done (Joos et al., 2013; Olivié et al., 2012; Reisinger et al., 2011; Tanaka et al., 2013). Considering variable conditions may lead to more representative results since atmospheric concentrations and climate conditions affect adjustment times and the concentration-forcing-temperature relationship (Myhre et al., 2013). However, doing so requires assumptions to derive future emission scenarios such as those used by the IPCC which increases the dependence of metric values on subjective judgements (van Vuuren et al., 2011). The dependence of metrics on background conditions also implies that metrics values inevitably change over time as background concentrations change as a result of human activities, posing a challenge for the consistency of LCIA results with emissions that take place over time. For instance, Reisinger et al. (2011) have found a 100-year GWP value 20% higher than today for methane under the lowest RCP for an emission occurring in 2100 and 10% lower by mid-century than today under the highest RCP. This further exemplifies that LCA practitioners cannot avoid subjective judgments when choosing a metric; they can only assess the consequences of alternative choices and communicate to end-users whether the results of LCA are robust across a wide range of different metric approaches or highly contingent on particular choices.

3.3. Climate-carbon cycle feedbacks

In the IPCC 4th AR, climate-carbon cycle feedbacks were included in the calculation of AGWP for CO_2 but not for other GHGs (Forster et al., 2007). This inconsistency led to an underestimation of GWP and even more for GTP values for non-CO_2 GHGs relative to CO_2, because the warming caused by emission of a non-CO_2 gas causes CO_2 already in the atmosphere at this time to persist for longer and thus add to the total warming effect caused by the non-CO_2 emission (Myhre et al., 2013). Indeed, the consideration of these feedbacks may have a significant impact on emission metrics values. For instance, Gillet and Matthews (2010) found an increase of 20% in GWP for CH_4 and N_2O (results were similar for both gases) and 80% in GTP for CH_4 for a 100-year time horizon when adding climate-carbon cycle feedbacks. Collins et al. (2013) found that the climate-carbon cycle feedbacks approximately double methane GTP for 100 years. In its 5th AR, the IPCC provides tentative values for illustration with and without considering climate-carbon cycle feedbacks for some non-CO_2 forcers, with the 100-year GWP increasing by 12 and 21% for N_2O and CH_4, respectively, and the 100-year GTP increasing by 27% for N_2O and more than doubling for CH_4, if climate-carbon cycle feedbacks are included. Furthermore, there are also other feedbacks that can, for some forcers, be significant and that are often not included in the calculation of GWPs. For example, these feedbacks relate to atmospheric chemistry interactions (Shindell et al., 2009) and tropospheric O_3-carbon cycle interactions (Collins et al., 2010).

Feedback mechanisms are very complex and can increase the uncertainty in a metric value. For instance, the uncertainty in AGWP associated with climate-carbon cycle feedbacks may reach ±100% of its best estimate (Myhre et al., 2013). In other words, uncertainties related to feedback effect are comparable in magnitude to the strength of the feedback itself. The consideration of these feedbacks thus results in a trade-off between accuracy, consistency and comprehensiveness, but there is a clear case that climate-carbon cycle feedbacks should be treated consistently as they are a well-understood (even if difficult to quantify) feature of the climate system.

3.4. Regional variations

The global mean temperature change depends on the location of emissions for NTCFs. These regional variations may be addressed using different metric values for region of emission (e.g. Berntsen et al., 2005; Stohl et al., 2015). Indeed, climate impacts of WMGHGs do not depend on the location of emissions because they have lifetimes long enough so that they get well mixed in the troposphere. However, NTCFs have much shorter lifetimes and impacts depend on where emissions occur. Metrics for NTCFs may thus be given for region of emission. The IPCC 5th AR presents the results of GWP and GTP for NO_x, CO, VOC, black carbon and organic carbon from different studies. For instance, Fry et al. (2012) and Collins et al. (2013) have calculated GWP and GTP values for 20- and 100-year time horizons for four regions (East Asia, European Union and North Africa, North America, and South Asia) for NO_x, CO and VOC. For NO_x, GWP varies from -40.7 to 6.4 $kgCO_2$-eq/kg for 20 years and from -25.3 to -5.3 $kgCO_2$-eq/kg for 100 years, showing the influence of the location of emission on the results. The results obtained by Shindell & Faluvegi (2009), Fuglestvedt et al. (2010), Bond et al. (2011, 2013), and Aamaas et al. (2015, 2016) also show a high regional variability for GWP and GTP of NTCFs.

On the other hand, the climate response also varies from one region to another. These regional variations may be addressed using different metric values for region where climate impacts occur (Collins et al., 2013; Shindell & Faluvegi, 2009). Some researchers have worked on the development of metrics that take into account the regional variability of climate impacts (e.g. Collins et al., 2013; Lund et al., 2012; Shindell, 2012) and the application of these metrics has begun (Lund et al., 2014; Stohl et al., 2015; Sand et al., 2016). The conclusions from the IPCC 5th AR are that additional studies are still needed to ensure their robustness (Myhre et al., 2013).

3.5. The time dimension

The time horizon defines the length of time over which impacts of climate forcers are integrated for cumulative metrics, or the number of years into the future at which an instantaneous metric is evaluated. Fixed time horizons are usually applied in LCA. This means that impacts are assessed over a fixed period of time (e.g. 100 years) following each emission. The use of a fixed time horizon for GWP ensures equal inclusion and weighting of actual impacts from emissions, regardless of when in a product life cycle they occur (Peters et al., 2011b; Jørgensen & Hauschild, 2013). Impacts are thus assessed over a sliding time window if emissions are spread over several years as shown in Figure 3a. On the other hand, the use of a variable time horizon depending on the relative timing of life cycle emissions allows the assessment of climate change impacts with regard to a fixed future reference time as shown in Figure 4b. This approach implies that only impacts up to the fixed point in time are deemed relevant, which may be relevant in some decision contexts. For instance, it has been used in recent literature in the dynamic LCA approach and for the calculation of payback times for land use change emissions mitigation (Levasseur et al., 2010; O'Hare et al., 2009) or for the computation of emission metrics for biogenic emissions from long rotation biomass amongst others (Cherubini et al., 2016; Guest et al., 2013; Schivley et al., 2015).

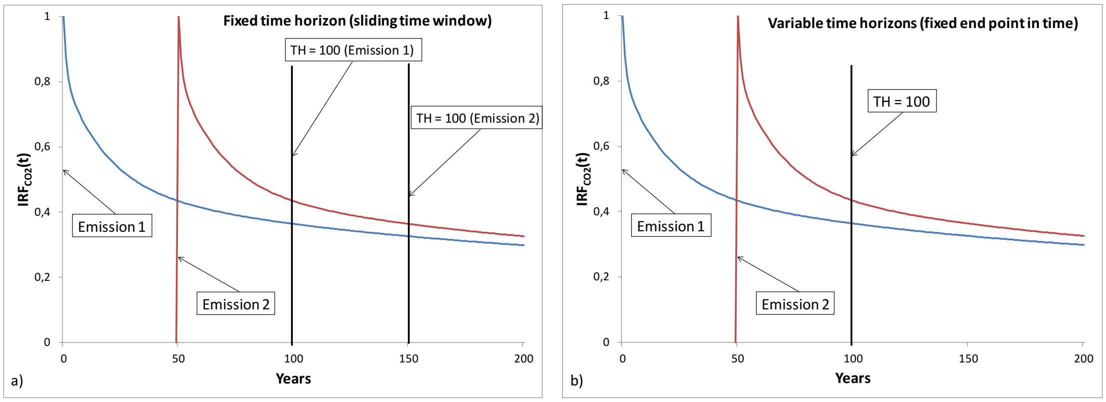

Figure 3. Fixed time horizons (Sliding time window) (a) are usually applied in LCA. Variable time horizons (Fixed end point in time) (b) may also be relevant in some decision contexts

3.5.1. Choice of a time horizon

LCA practitioners can choose different time horizons, leading to different metric values. For instance, the value of GWP for short-lived WMGHGs and NTCFs decreases with increasing time horizon as the integrated radiative forcing of the reference gas CO_2 in the denominator continues to increase, as shown in Figure 8.29 of the IPCC 5th AR (Myhre et al., 2013). The 100-year time horizon is applied most often because of its adoption for the Kyoto Protocol. However, Shine (2009) argues that a 100-year time horizon was selected as an "inadvertent consensus" probably because it was the middle value between those used by the IPCC for its calculations (20, 100, and 500 years). The use of this time horizon is thus not scientifically more justified than any other time horizon, but rather a value-based choice that must be based on considerations that include both science and ethics (Fuglestvedt et al., 2003; Levasseur et al., 2012; Shine, 2009; Tanaka et al., 2010). For instance, the use of a 500-year time horizon has the advantage of indicating the persistence and long-term warming effect of some gases, and selecting a shorter time horizon may violate the principle of inter-generational equity widespread in LCA, because future impacts beyond the time horizon are ignored entirely (Brandão et al., 2013).

On the other hand, a longer time horizon relies on the modelling of atmospheric or climate processes that will occur far in the future, leading to higher uncertainties, and the relevance of a midpoint metric for a future society several hundred years into the future is very difficult to quantify. In its 5th AR, the IPCC does not provide values for a 500-year time horizon due to large uncertainties and strong assumptions of constant background conditions, as well as ambiguity related to what the metrics indicate on such timescales, which is especially the case for GWP (Myrhe et al., 2013).

As shown in Figure 4, the selection of a time horizon strongly affects the value of metrics, especially for climate forcers with a lifetime of less than roughly 100 years (Smith et al., 2012). It is thus critically important to understand the underlying implications of the choice of time horizon. Figure 4 shows how the instantaneous forcing, cumulative forcing, and temperature change profiles of CO_2 and CH_4 pulse emissions evolve over time (for the sake of presentation, CO_2 emissions are adjusted to match CH_4 emissions in magnitudes in terms of GWP100). At a time horizon of 40 years, CO_2 has a higher instantaneous forcing and lower cumulative forcing, and the temperature change of the two emissions is nearly identical (given an emissions pulse of CO_2 28 times larger than that of CH_4). This is, of course, different from the conclusion that would be reached with a time horizon of 20 or 100 years. The wide range in metric values for a relatively short-lived WMGHG such as methane reflects a fundamental difference in how different components affect the climate over time. Methane has a strong short-term forcing that almost disappears after a few decades as it leaves the atmosphere. In contrast, CO_2 has a more persistent effect, leading to greater impacts than methane in the more distant future.

A short time horizon will put emphasis on short-term impacts (or rate of change) and thus gives a higher relative importance to short-lived WMGHGs and NTCFs, while a longer time horizon will do the opposite. The choice of a time horizon for instantaneous metrics can be aligned with, in the case of GTP, the estimated peaking year of the global mean surface temperature. In that case, this would reflect a primary goal of limiting peak warming. However, for LCAs that consider emissions occurring over several years, fixing the end of the time horizons to a given calendar year requires the use of a variable time horizon for climate metrics depending on the timing of each emission relative to that calendar year as shown in Figure 3b.

3.5.2.Discount rates

Some methods have also been proposed to develop emission metrics while avoiding the use of a time horizon entirely (e.g. Boucher, 2012; Cherubini et al., 2014; Smith et al., 2012; Wigley, 1998). Some forms of discounting are usually present in such metrics and the selection of any discount rate requires value judgments and cannot be based on science alone, as the economic literature amply attests (e.g. Anthoff et al., 2009; Goulder & Williams, 2012). This choice of discount rate is in terms of value judgements similar to the choice of time horizon when using cumulative metrics. The selection of a fixed time horizon for cumulative metrics is thus a particular case of discounting using a 0% rate for impacts occurring prior to the end of the time period, and an infinite discount rate for impacts occurring beyond, which are still significant for long-lived gases such as CO_2 (IPCC, 2014a; Myhre et al., 2013; Tol et al., 2012). At the same time, selection of an instantaneous metric such as GTP evaluates warming only in one specific year and thus discounts entirely the warming for any other year before or after this target year (Tol et al., 2012).

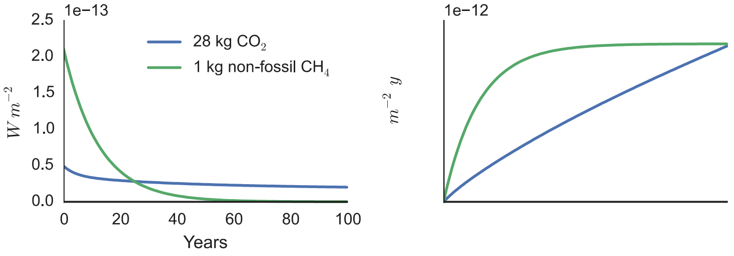

Figure 4. Instantaneous radiative forcing, cumulative radiative forcing, and instantaneous temperature change over time caused by emissions of 28 kg CO_2 and 1 kg non-fossil CH_4

3.5.3. Considering the timing of emissions

Approaches have been proposed to compare LCA results using a fixed end point in time for global warming impacts. All of them are based on the use of time horizon-dependent CFs to take into account the number of years occurring between the emission to assess and the chosen end-time for the analysis following the approach shown in Figure 3b (Cherubini et al., 2011; Kendall, 2012; Levasseur et al., 2010). The use of such methods implies the elaboration of temporal emission profiles compared to aggregated emissions, as currently done in LCA, because one needs to know the time elapsed between the each emission and the fixed end point in time selected to use the right characterization factors. Moreover, as explained by Jørgensen and Hauschild (2013), using a fixed end point in time as shown in Figure 3b makes emissions occurring later have less impact, compared to similar emissions occurring earlier. However, these approaches are useful to look at the evolution of impacts through time such as done with dynamic LCA (Levasseur et al., 2010) or when only impacts until a specific point in time are deemed relevant.

Timing is also critical when assessing the climate impacts of emissions of different forcers in relation to a climate stabilisation limit, e.g. the 2°C limit. The GWP has been criticised as being economically inefficient and indeed inconsistent with the ultimate objective of the UNFCCC to stabilise greenhouse gas concentrations at a given level (Manne & Richels, 2001; Myhre et al., 2013; Shine et al., 2007; Johansson, 2012; Tol et al., 2012). When assessing emissions in relation to its contribution to remain within a pre-defined limit, it is therefore essential to have an estimate of the year in which the temperature threshold will be reached. A time-dependent GTP was therefore proposed to deal with this situation (Shine et al., 2007), where the metric time horizon is based on the time left to the year the temperature peak is reached (Manne & Richels, 2001; Michaelis, 1992; Shine et al., 2007). Other approaches, where the metric time horizon is based on the time left to the year a prescribed limit is reached, exist as well, e.g. the climate tipping potential (CTP) proposed by Jørgensen et al. (2014). For this approach, a 'planteray boundary' context is included, as the absolute, cumulative impacts of GHG emissions, up until the year in which a predefined limit will be reached, are expressed as a fraction of the 'capacity' left before exceeding the predefined limit. However, as shown by Persson et al. (2015), adopting a time-dependent metric implies a commitment to significantly higher metric values for NTCFs and short-lived WMGHGs as we get closer to the time when peak temperatures are reached. To avoid disregarding longer term impacts beyond the chosen time horizon, an approach that both consider the time until a threshold is reached and the climate impacts beyond that point in time might be useful (Johansson, 2012; Jørgensen et al., 2014; Smith et al., 2012).

4. Recommendations

The use of GWP with a fixed time horizon has come under increased scrutiny as awareness of its limitations has become more widespread over the recent past. GWP was the only metric presented and discussed in the IPCC First AR. The IPCC 4th AR was the first to introduce and discuss an alternative metric, i.e., GTP, but still considered that GWP was a "useful metric for comparing the potential climate impact of the emissions of different [long-lived gases]" (Forster et al., 2007). The IPCC 5th AR shows an evolution in the thinking, clearly stating that the selection of a metric depends on the policy goal to achieve, and that different metrics may lead to different valid conclusions about the relative importance of emissions (Myhre et al., 2013). For instance, Allen et al. (2016) showed that the GWP100 measures the relative impact of both cumulative species and short-lived climate forcers on realized warming 20-40 after the time of emissions. This metric is thus less suitable to account for long-term climate change impacts. In this section, we first provide recommendations for a more robust assessment and interpretation of potential climate change impacts in LCA following the most recent climate research findings presented in this review. However, since current LCIA methods use cumulative metrics such as GWP and do not account for the timing of emissions, we then present some recommendations regarding the integration of the most recent findings of the IPCC 5th AR and concurrent scientific research in LCA practice.

4.1. Improving climate change impact assessment in LCA

Emission metrics are used to help decision makers identify how emissions of different climate forcers compare in terms of impacting specific aspects of climate change. The appropriateness of a climate change metric for a given application thus depends on the purpose that it is meant to serve i.e., the overall goal of climate policies and which aspects of climate change are deemed relevant (Fuglestvedt et al., 2003; Myhre et al., 2013). In an LCA context, we consider it critical that practitioners assess whether their results depend strongly on the choice of metric. This will depend on the purpose an LCA is intended to serve (i.e. comparison of carbon footprints of two products, or long-term company-wide mitigation strategy). The choice of metric thus cannot be made independently of the values, goals, and scope of the end-user of an LCA.

In practice, it can make sense to use several complementary metrics that will serve different purposes, and from there allow LCA practitioners to get a better understanding about the robustness of the LCA study to different metrics during the interpretation phase of LCA. LCA methodology and software should gradually move towards a situation where the state-of-the-art is represented by the use of several sets of CFs based on different metrics and/or time horizons. Analysts can then test how robust the overall conclusions are with respect to such different choices. If results differ significantly for different metrics, they can argue or demonstrate why one metric choice would be preferable to the others for a given purpose. The range of results from different metrics should become part of communicating the ambiguity and uncertainty of LCA results (where 'uncertainty' reflects the scientific uncertainty and 'ambiguity' the dependence on human choices in methodologies or purposes of the LCA). This will certainly require an initial transition phase for adaptation of practitioners and updates of CFs in the common databases and software providers for LCA analyses. However, the availability of characterization factors in the IPCC 5th AR makes this transition easier, and relatively little adaptation efforts will ensure an important step forward in the robustness of climate change impact assessment in LCA. We believe that this increased transparency about the hidden value judgements in LCA is critical to ensure that an LCA actually serves the intended purpose.

The use of multiple indicators for assessing climate change impacts in other branches derived from LCA like carbon footprints and product labels can be more challenging. The different groups and stakeholders should start a debate on how to reflect these considerations in the different applications. The alternative, if they simply continue to rely on a 'preferred' metric independently of its meaning and end user goals, this could lead to perverse outcomes. For example, imagine a consumer keen to support the rapid reduction of CO_2 emissions, consistent with the finding by the IPCC that CO_2 emissions have to drop to zero before 2100 to limit warming to 2°C. Faced with the choice of whether to purchase product A or product B, the consumer will rely on the reported carbon footprint. But product A might have a very large CH_4 component while product B may release almost exclusively CO_2. Product A may have a larger carbon footprint in the metric that practitioners have decided to use, and the consumer would therefore purchase product B, even though this results in greater CO_2 emissions that lead to long-term climate change. The extent to which the complexity of alternative choices can be communicated successfully to end-users will of course depend strongly on the context; while it is unlikely to be successful for product labels in supermarkets, such a conversation should be entirely feasible and in fact an obligation where LCA practitioners interact with individual clients from industry or government (including, in fact, the owners of supermarket chains that decide on what labelling system they wish to use and communicate).

Based on these findings, we recommend the following step-by-step approach:

a) Selection of a few metrics and time horizons that differ in the type of climate response they capture for both WMGHGs and NTCFs. In addition to using GWP100 for comparability purposes, and potentially one or several other well thought-through choices of metrics and time horizons based on the goal and scope of the study, we recommend to perform a sensitivity analysis. For this purpose, GWP20 and GTP100 may provide a suitable range of metric values as they allow LCA users to explore their results using either a short-term perspective with very high (GWP20) or a long-term perspective with very low (GTP100) weighting for short-lived WMGHGs and NTCFs.
b) Calculation of impact scores using the selected metrics to get a sense of whether the results are critically dependent on the metric choice.
c) If the conclusions of the LCA study (relative to the specific purpose it seeks to serve) do not change significantly using different metrics or time horizons, there is no need to communicate on several metrics.
d) If the conclusions of the LCA study vary using different metrics or time horizons, the results must be communicated very carefully, explaining how the answer differs between metrics and time horizons and why, and guiding users as to whether a particular metric choice may be more suitable than others for the particular purpose and ultimate goals that the end-user may have in mind.

Some choices must be made when selecting emission metrics regarding the characteristics and modelling conditions presented in the previous sections: type of effect modelled (radiative forcing, temperature, etc.), instantaneous vs. cumulative, time horizon and/or discounting, constant vs. variable background, etc. Some of these choices are scientific, while others are more policy-related and cannot be based solely on scientific studies (Tanaka et al., 2010). The choice of metric type and time horizon as proposed in this step-by-step approach may have much larger effects on decisions than the improvement of input parameters to the metrics (Myhre et al., 2013).

4.2. Updating GWP and GTP according to IPCC 5th AR

Working Group I produced a long list of updated GWP and GTP values for 20- and 100-year time horizons and GTP values for 50-year time horizon in the IPCC 5thAR for more than 200 GHGs, including the quantification of uncertainties. We recommend that these values (or updated values from a more recent IPCC AR when available) are used in LCA if GWP or GTP are selected as climate change midpoint indicator. The following recommendations regard the consideration of climate-carbon cycle feedbacks for non-CO_2 GHGs, and the development of CFs for NTCFs.

4.2.1. Consideration of climate-carbon cycle feedbacks for non-CO_2 components

As explained in section 3.3, the use of GWP values including climate-carbon cycle feedbacks for CO_2 but not for other GHGs is inconsistent and leads to lower relative impacts for non-CO_2 GHGs. However, high uncertainties are associated with the inclusion of feedbacks for non-CO_2 GHGs because there are still just a few values available in the literature. Research is still needed to improve the reliability of these GWP values. We thus recommend including climate-carbon cycle feedbacks for all GHGs, providing associated uncertainty values with CFs, and performing an uncertainty analysis. This could be done by simple estimates based on the uncertainty ranges for metric values or using a Monte Carlo method. If this cannot be done, we recommend calculating impact scores with and without the inclusion of climate-carbon cycle feedbacks for non-CO_2 GHGs to determine if their inclusion changes conclusions significantly. If it is the case, we recommend discussing the importance of this choice when communicating results (this process is similar to steps b-d in the above recommended steps for evaluation of different metrics).

As a rule of thumb, the inclusion of climate-carbon cycle feedbacks tends to have a smaller effect on metric values for NTCFs and short-lived WMGHGs than alternative metric choices (e.g. GTP instead of GWP) and time horizons. If the sensitivity test regarding alternative metrics shows little effect on the overall LCA result, then testing for the sensitivity of climate-carbon cycle feedbacks could perhaps be omitted.

4.2.2. Development of CFs for NTCFs

As discussed in section 3.4, climate impacts of NTCFs depend on the location of emissions. Global scale metrics may thus not be the most appropriate. Moreover, NTCFs are tightly coupled to the hydrological cycle and atmospheric chemistry which are very complex processes difficult to model and validate. The values associated to NTCF metrics are more uncertain then for WMGHGs and there are substantial variations across studies (Myhre et al., 2013).

The quality of the metrics of NTCFs may improve over the next years as research goes on, even though they will always be more uncertain and sensitive to assumptions than the metrics of WMGHGs. However, for some sectors or activities, NTCFs can make an important contribution to the climate impact category (e.g. Fuglestvedt et al, 2008). We thus recommend calculating impact scores with and without NTCFs using global average values (i.e. not specific to selected regions) from the literature as presented in the IPCC 5th AR. Once again, if their consideration changes conclusions, we recommend discussing it when communicating results, explaining uncertainty and regional variability issues. If the location of emissions is known and a regionalized life cycle assessment approach is used, we recommend using region-specific GWP and GTP values for NTCFs to reduce uncertainties. Indeed, if the location of emissions is known, it is conceptually easy to use emission-region-specific CFs that express the global climate impact of NTCFs, although not all LCA software or life cycle inventory databases support this feature yet.

Some NTCFs (e.g. SO_2 and organic carbon) have negative metric values because of their cooling effect when in the atmosphere as illustrated in FAQ 8.2 Figure 1 of the IPCC 5th AR (Myhre et al., 2013). Globally, the combined cooling effect is significant and considered to have offset some of the warming from WMGHGs that would otherwise have occurred. However, concerns may be raised regarding the inclusion of pollutants with a cooling effect in the global warming impact category because they may cause other type of environmental impacts such as acidification for the case of SO_2. This means that one could favour a high GHG and high SO_2 emitter compared to a lower GHG and no SO_2 emitter if only the global warming LCA result is considered, leading to higher other environmental impacts such as acidification or human health issues. This example shows why it is crucial to use multiple indicators, as LCA usually does, to guide choices. We thus recommend including climate forcers with negative metric values if NTCFs are considered at all for consistency purposes. However, the warming and cooling effects should be presented separately to facilitate transparency and analysis of results.

In conclusion, given the many relevant metrics and the broad set of emission components and effects acting on very different timescales, LCA studies may benefit from moving away from single-metric studies towards a multi-metric perspective and sensitivity tests, combined with (or followed by) a careful exchange with the end-users of LCA to ensure that those value judgements that have to be made serve the intended purposes of those who use the resulting information. This will help to communicate the complexity of the system and processes and at the same time increase the transparency regarding value related choices inherent to LCA results.

Acknowledgments.

This work has been done on a voluntary basis through the Global Warming Task Force of the project 'Global Guidance on Environmental Life Cycle Assessment Indicators' of the United Nations Environment Programme (UNEP) / Society of Environmental Toxicology and Chemistry (SETAC) Life Cycle Initiative. Public and private sector sponsors are listed on the Initiative's website (www.lifecycleinitiative.org). The views expressed in this article are those of the authors and do not necessarily reflect those of the various affiliated organizations. DJAJ contribution was financed by the Swedish Energy Agency.

Note.

The first author of this article is the chair of the task force and main author of this paper. The last author is the co-chair of the task force. Other authors are members of the task force and are ordered alphabetically.

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