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Global guidance on environmental life cycle impact assessment indicators: Impacts of climate change, fine particulate matter formation, water consumption and land use

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Corresponding Author:	Olivier Jolliet, Prof. University of Michigan Ann Arbor, MI UNITED STATES
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	University of Michigan
Corresponding Author's Secondary Institution:	
First Author:	Olivier Jolliet, Prof.
First Author Secondary Information:	
Order of Authors:	Olivier Jolliet, Prof.
	Assumpció Antón
	Anne-Marie Boulay
	Francesco Cherubini
	Peter Fantke
	Annie Levasseur
	Thomas E. McKone
	Ottar Michelsen
	Llorenç Milà i Canals
	Masaharu Motoshita
	Stephan Pfister
	Francesca Verones
	Bruce Vigon
	Rolf Frischknecht
Order of Authors Secondary Information:	
Funding Information:	UNEP-SETAC Life Cycle Initiative — Dr. Olivier Jolliet
Abstract:	Purpose Guidance is needed on best suited indicators to quantify and monitor the man-made impacts on human health, biodiversity and resources. Therefore, the UNEP-SETAC Life Cycle Initiative initiated a global consensus process to agree on an updated overall life cycle impact assessment (LCIA) framework and to recommend a non-comprehensive list of environmental indicators and LCIA characterization factors for 1) climate change, 2) fine particulate matter impacts on human health, 3) water consumption impacts (both scarcity and human health), and 4) land use impacts on biodiversity. Method

	The consensus building process involved more than 100 world-leading scientists in task forces via multiple workshops. Results were consolidated during a one week Pellston WorkshopTM in January 2016 leading to the following recommendations. Results LCIA framework: The updated LCIA framework now distinguishes between intrinsic, instrumental and cultural values to protect, with DALY to characterize damages on human health and with measures of vulnerability included to assess biodiversity loss. Climate change impacts: Two complementary climate change impact categories are recommended: a) The Global Warming Potential 100 years (GWP 100) represents shorter term impacts associated with rate of change and adaptation capacity, and b) the Global Temperature change Potential 100 years (GTP 100) characterizes the century-scale long term impacts, both including climate-carbon cycle feedbacks for all climate forcers. Fine particulate matter (PM2.5) health impacts: Recommended characterization factors (CFs) for primary and secondary (interim) PM2.5 are established, distinguishing between indoor, urban and rural archetypes. Water consumption impacts: CFs are recommended, preferably on monthly and watershed levels, for two categories: a) The water scarcity indicator "AWARE" characterizes the potential to deprive human and ecosystems users and quantifies the relative Available WAter REmaining per area once the demand of humans and aquatic ecosystems has been met, and b) the impact of water consumption on human health assesses the DALYs from malnutrition caused by lack of water for irrigated food production. Land use impacts: CFs representing global potential species loss from land use are proposed as interim recommendation suitable to assess biodiversity loss due to land use and land use change in LCA hotspot analyses. Conclusions The recommended environmental indicators may be used to support the UN Sustainable Development Goals in order to quantify and monitor progress towards sustainable production and consumption. These indicators will be periodically updated, establishing a process for their stewardship. Keywords LCIA framework, Climate change, Fine particulate, Human health, Water scarcity, Water consumption, Land use.
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Global guidance on environmental life cycle impact assessment indicators: Impacts of climate change, fine particulate matter formation, water consumption and land use

Olivier Jolliet[1], Assumpció Antón[2], Anne-Marie Boulay[3,4], Francesco Cherubini[5], Peter Fantke[6], Annie Levasseur[3], Thomas E. McKone[7], Ottar Michelsen[8], Llorenç Milà i Canals[9], Masaharu Motoshita[10], Stephan Pfister[11], Francesca Verones[5], Bruce Vigon[12], Rolf Frischknecht[13]

Corresponding author: Olivier Jolliet, ojolliet@umich.edu, Tel. +1 (734) 647 0394, Fax. +1 (734) 936 7283

[1] Environmental Health Sciences, School of Public Health, University of Michigan, Ann Arbor, MI, USA.
[2]IRTA, Institute for Food and Agricultural Research and Technology, Cabrils, Barcelona, Spain
[3]CIRAIG, Department of Chemical Engineering, Polytechnique Montreal, Montreal, Canada.
[4]LIRIDE, Sherbrooke University, Sherbrooke, Canada
[5]Industrial Ecology Programme, Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, Norway
[6] Department of Management Engineering, Quantitative Sustainability Assessment Division, Technical University of Denmark, Kgs. Lyngby, Denmark.
[7]School of Public Health, University of California, Berkeley, CA, USA
[8]NTNU Sustainability, Norwegian University of Science and Technology, Trondheim, Norway
[9]Economy Division, United Nations Environment Programme, Paris, France.
[10]National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan
[11]ETHZ - Swiss Federal Institute of Technology - Zurich, Zurich, Switzerland
[12]SETAC, Pensacola, FL, USA.
[13]treeze Ltd., Uster, Switzerland.

1. Abstract

Purpose Guidance is needed on best suited indicators to quantify and monitor the man-made impacts on human health, biodiversity and resources. Therefore, the UNEP-SETAC Life Cycle Initiative initiated a global consensus process to agree on an updated overall life cycle impact assessment (LCIA) framework and to recommend a non-comprehensive list of environmental indicators and LCIA characterization factors for 1) climate change, 2) fine particulate matter impacts on human health, 3) water consumption impacts (both scarcity and human health), and 4) land use impacts on biodiversity.

Method The consensus building process involved more than 100 world-leading scientists in task forces via multiple workshops. Results were consolidated during a one week Pellston Workshop^{TM} in January 2016 leading to the following recommendations.

Results

LCIA framework: The updated LCIA framework now distinguishes between intrinsic, instrumental and cultural values to assess, with DALY to characterize damages on human health and with measures of vulnerability included to assess biodiversity loss.

Climate change impacts: Two complementary climate change impact categories are recommended: a) The Global Warming Potential 100 years (GWP 100) represents shorter term impacts associated with rate of change and adaptation capacity, and b) the Global Temperature change Potential 100 years (GTP 100) characterizes the century-scale long term impacts, both including climate-carbon cycle feedbacks for all climate forcers.

Fine particulate matter ($PM_{2.5}$) health impacts: Recommended characterization factors (CFs) for primary and secondary (interim) $PM_{2.5}$ are established, distinguishing between indoor, urban and rural archetypes.

Water consumption impacts: CFs are recommended, preferably on monthly and watershed levels, for two categories: a) The water scarcity indicator “AWARE” characterizes the potential to deprive human and ecosystems users and quantifies the relative Available WAter REmaining per area once the demand of humans and aquatic ecosystems has been met, and b) the impact of water consumption on human health assesses the DALYs from malnutrition caused by lack of water for irrigated food production.

Land use impacts: CFs representing global potential species loss from land use are proposed as interim recommendation suitable to assess biodiversity loss due to land use and land use change in LCA hotspot analyses.

Conclusions The recommended environmental indicators may be used to support the UN Sustainable Development Goals in order to quantify and monitor progress towards sustainable production and consumption. These indicators will be periodically updated, establishing a process for their stewardship.

Keywords

LCIA framework, Climate change, Fine particulate, Human health, Water scarcity, Water consumption, Land use.

2. Introduction and goal of the harmonisation process

The current environmental pressure and, especially, its reduction according to the UN Sustainable Development Goals (United Nations 2015) in the coming years require the development of environmentally sustainable products and services. Because markets and supply chains are increasingly globalised, harmonised guidelines are needed on how to quantify the environmental life cycle impacts of products and services. In particular, guidance is needed on which quantitative and life cycle based indicators are best suited to quantify and monitor the man-made impacts on human health, biodiversity, water resources, etc. The ongoing developments in the application of life cycle assessment (LCA) to Product Environmental Footprint and to a wide range of products, calls for not only providing recommendations to method developers, but also to provide recommended globally applicable indicators that can then be used in such footprints within comprehensive life cycle impact assessment (LCIA) approaches. Following multiple open consultations and workshops in multiple continents (Jolliet et al. 2014), stakeholders in industry, public policy and academia thus agreed on the need for consensus and global guidance on environmental LCIA indicators.

A series of complementary initiatives for LCIA consensus building have taken place since the early 1990s, striving towards providing recommendations and guidance for the development and use of LCIA methods. Two rounds of SETAC working groups led to category-specific recommendations for developing LCIA impact indicators (Udo de Haes et al. 2002), taking advantage of broader consensus efforts, such as those led by the Intergovernmental Panel on Climate Change for climate change issues. The LCIA program of the phase I and phase II of the UNEP-SETAC Life Cycle Initiative developed a combined midpoint-damage framework (Jolliet et al. 2004), and provided further recommendations for multiple impact categories. The UNEP-SETAC scientific consensus toxicity model was then developed and endorsed to estimate ecotoxicity and human toxicity impacts in LCA (Rosenbaum et al. 2008; Westh et al. 2015). In parallel, more emphasis was given to better frame resource-related categories, especially for land use (Milà i Canals et al. 2007) and water use, with the launch of a Water Use in LCA working group, WULCA (Köhler 2007). Since the launch of phase I of the initiative and the publication of its framework, several developments have been and are being carried out for developing worldwide applicable methods, with spatially differentiated impact indicators, at midpoint level (Hauschild et al. 2011 and 2013) and damage level (Bulle et al. 2016; Frischknecht et al. 2013; Huijbregts et al. 2014 and 2017; Itsubo and Inaba 2010). These developments now need to be accounted for in a global consensus building process.

To answer these needs, Phase III of the UNEP-SETAC Life Cycle Initiative launched a flagship project to provide global guidance and build consensus on environmental LCIA indicators. Initial workshops in Yokohama in 2012 and in Glasgow 2013 as well as a stakeholder consultation scoped this flagship project (Jolliet et al. 2014), focusing the effort in a first stage on a) impacts of climate change, b) fine particulate matter health impacts, c) water consumption and d) land use, plus e) crosscutting issues and f) LCA-based footprints. For each of the impact categories, the main objective of the flagship project is four-fold: (1) To describe the impact pathway and review the potential indicators. (2) Based on well-defined criteria, to select the best-suited indicator or set of indicators, identify or develop the method to quantify them on sound scientific basis, and provide characterization factors with corresponding uncertainty and variability ranges. (3) To apply the indicators to a common LCA case study to illustrate its domain of applicability. (4) To provide recommendations in term of indicators, status and maturity of the recommended factors, applicability, link to inventory databases, roadmap for additional tests and potential next steps. The scope of the work is not to cover comprehensively all relevant impact categories and the list of resulting impact category indicators should not be interpreted as a sufficient or complete list of impacts to address in LCA.

This paper presents the consensus building process and scientific approach retained, as well as the indicators selected and recommendations reached for the above-described selected impact categories and crosscutting issues. The first section describes the process and criteria used to select the recommended indicators. The second section presents the updated LCIA framework. The next sections describe the selected characterization factors and the main recommendations for each of the four impact categories considered. The paper ends by applying the recommended indicators to a rice case study, followed by conclusions and outlook that addresses potential concerns that such consensus processes may raise (Huijbregts, 2014). A more comprehensive description of the process and its outcome is further detailed in the first assessment report on LCIA guidance (Frischknecht and Jolliet 2016).

3. Process and recommendation criteria

Process: To achieve the goals of the LCIA harmonisation project, following open calls for interest and search for category specific specialists, task forces were set up involving more than 100 world-leading domain experts and LCA scientists, organized in impact category specific task forces (TFs) and complemented by a TF on crosscutting issues. Multiple topical workshops and conferences were organised by each individual TF to first scope the work and then develop scientifically robust state-of-the-art indicators suitable for a global consensus (Boulay et al. 2015c; Cherubini et al. 2016; Curran et al. 2016; Fantke et al. 2015; Hodas et al. 2016; Levasseur et al. 2016; Teixeira et al. 2016). This was followed by two overarching workshops and stakeholder meetings in Basel 2014 and in Barcelona 2015 to address specific critical crosscutting issues and collect feedback from multiple stakeholders. Section S1 of the supporting information further details the multiple workshops and communications carried out in each task force. Additionally, an LCA case study on the production and consumption of rice common to all TFs (Frischknecht et al. 2016) was developed to test the recommended impact category indicators selected in the harmonisation process and further help to ensure their practicality.

This first part of the consensus-finding process ended with a one week Pellston Workshop^{TM}. According to the standard operating procedures for SETAC-supported Pellston Workshops^{TM}, a steering committee was first appointed by the International Life Cycle Panel of the Life Cycle Initiative, with diverse members from government, academia/NGO and industry (steering committee composition in section S2 of supplementary information). The steering committee selected 40 invited experts and stakeholders from industry, academia, government and NGOs originating from 14 different countries, both among and outside the task forces to ensure a broad worldwide representativeness (see list of additional workshop participants in acknowledgments). The workshop took place in Valencia, Spain, from 24 to 29 January 2016 to make recommendations on environmental indicators for each of the considered impact category. This paper summarizes decisions reached at this workshop, complemented by work of the specific TFs.

Guiding principles for harmonisation: Building on the earlier work and process by Hauschild et al. (2011 and 2013), the following global guiding principles were identified and applied in the LCIA indicator harmonisation process: *Environmental relevance* to ensure that the recommended indicators address environmentally important issues; *completeness* to ensure they cover a maximum achievable part of the corresponding environmental issue with global coverage; *scientific robustness* to ensure they follow state-of-the-art knowledge and evidence rather than subjective assumptions; *documentation and transparency* to ensure that the recommended indicators are accessible and reproducible; *applicability and level of experience* to ensure that the recommended approaches can easily be implemented and applied in LCA databases, and have proven their practicality in a number of sufficiently diverse LCA case studies; and *stakeholder acceptance* to ensure that the indicators meet the needs and requirements of science and non-governmental organisations and of decision makers in industry and governments. Starting from a generic checklist, criteria were first customized for the considered impact category. Existing impact category indicators were then systematically evaluated and compared against these evaluation criteria, leading to white papers as inputs to the Pellston workshop. The scope of this harmonisation work was not to provide a complete set of environmental LCIA indicators nor to create a new and comprehensive LCIA method. The selection of impact categories in the present report was primarily based on potential for global consensus (Jolliet et al. 2014) and is not to be interpreted as an implicit expression of preference on these topics over others.

Levels of recommendations: The recommendations presented in this paper are the result of consensus-finding processes based on objectively supportable evidence, with the aim to ensure consistency and practicality. They however do not necessarily reflect unanimous agreement and the body of experts assigns levels of support for a practice or indicator, according to the workshop process principles and rules. These levels are stated by consistently applying the terminology of “strongly recommended”, “recommended”, “interim recommended”, and “suggested or advisable”.

4. LCIA framework and modelling guidance

4.1 Framework and damage categories

A consistent framework is key to ensure that new developments and findings can be integrated into LCIA in a way that makes environmental impact category indicators compatible. Building on the earlier LCIA framework of the UNEP-SETAC Life Cycle Initiative (Jolliet et al. 2004), Verones et al. (2017) proposed an updated framework, distinguishing three different kinds of values: 1) *Intrinsically valued systems* that have a value by virtue of their existence (e.g. ecosystem quality as well as human health), 2) *instrumentally valued systems*, which have a clear utility to humans (natural resources, ecosystem services and socio-economic assets), and 3) *culturally valued systems* which have a value to humans by virtue of artistic, aesthetic, recreational, or spiritual qualities. These cultural values have so far rarely been assessed in LCA, but could be included in the future.

Each environmental intervention (elementary flow) may have impacts on several of these values and impact categories that can be determined and reported separately.

In this updated LCIA framework , impact characterization models link the life cycle inventory results to impacts at midpoint level or at damage level. Impact categories at damage level are available on a disaggregated level (e.g. climate change or land use impacts), or can be aggregated into overarching areas of protection. Conversion factors that provide the linkage between midpoint level and damage level impacts may be spatially variable and therefore non-constant. Weighting or normalization of damage category scores are optional steps distinct from damage modelling.

It is acceptable, though not promoted, that, for the case that no relevant midpoint impact indicator can be identified along the impact pathway, proxy indicators can be designed, which are not defined along an impact pathway itself, such as for example water scarcity indicators (section 4.3 below). These proxies need to be thoroughly justified, clearly labelled and documented, in order to avoid confusion.

4.2 Damage category specific recommendations

The following recommendations are made for the indicators pertaining the three presently operational damage categories, for human health, ecosystem quality and natural resources.

Human health is an area of protection that deals with the intrinsic values of human health, addressing both their mortality and morbidity. It is recommended to continue using Disability-Adjusted Life Years (DALYs) in LCIA for human health, as proposed and motivated by Fantke et al. (2015), following the current Global Burden of Disease (GBD) approach (Forouzanfar et al. 2015) and not including age weighting nor discounting. It is also recommended to transparently document the different components of a DALY separately (e.g., the years of life lost-YLL, and the Years Lived with Disability-YLD).

Ecosystem quality is an area of protection dealing with terrestrial, freshwater, and marine ecosystems and biodiversity, focusing on their intrinsic value. It is recommended to characterize ecosystems and/or species in a way that takes resilience, rarity and recoverability into account. It is recommended that the unit at the damage level should be based on “potentially disappeared fraction (PDF) of species” (e.g. global or local PDF, PDF-m2-yr or PDF-m3-yr). Any method addressing biodiversity that includes units that are convertible to PDF related metrics is recommended to describe and report the conversion factors. It is recommended to develop CFs at local, regional and global levels, to reflect losses in local and regional ecosystem functionality and global extinction. We emphasize that impacts quantified at global level (i.e. species are completely lost from the Earth) cannot be directly compared with local or regional impacts (i.e. species are only extinct in a certain part of the world); thus method developers need to report very explicitly at which level their model was developed.

Natural resources are material and non-material assets occurring in nature that are at some point in time deemed useful for humans (Sonderegger et al. 2017). Ecosystem services are instrumental values of ecosystems and, therefore, impacts on ecosystem services are different from impacts on ecosystem quality, which represents an intrinsic value. It is recommended that method developers also address the instrumental value of natural resources and ecosystem services when developing impact indicators and CFs, considering the different nature of resources, i.e. stocks, funds and flows.

A number of recommendations are further detailed in Verones et al. (2017), regarding transparent reporting on reference states, spatial differentiation, and addressing uncertainties, as well as normalization and weighting.

5. Selected indicators, characterization factors and main recommendations

This section provides the background, the description of selected indicators and a summary of the calculation methods, a list of selected characterization factors and the main recommendations for each of the four impact categories considered. The full list of characterization factors is available for download on the UNEP-SETAC life Cycle Initiative website (http://www.lifecycleinitiative.org/applying-lca/lcia-cf/).

Table 1 Main characteristics of the first set of recommended LCIA indicators

Impact category & subcategory	Cause-effect description and impact addressed	Characterization factors retained: Metric & unit	Archetypes and key spatial and temporal aspects	Applicability domain	Recommendation level
a) Climate change impacts					
a1) Climate Change Shorter-term	Shorter term impacts, on adaptation capacity of humans and ecosystems, based on radiative forcing	Global Warming Potential GWP100 $kg_{CO2\text{-}eq.\ (shorter)}$[1]/$kg_i$ with climate-carbon feedbacks for all climate forcers.	- Global cumulative indicator, integrated radiative forcing over 100 years, similar to a temperature increase in 40 years.	Applicable to WMGHGs[2] as default. GWP20 and GWP100 of NTCFs[3] for sensitivity analyses	Strongly recommended
a2) Climate Change Long-term	Long-term climate effects, on global mean temperature, sea level rise, and their impacts on humans and ecosystems.	Global Temperature Change Potential GTP100 $kg_{CO2\text{-}eq.\ (long)}$[1]/$kg_i$, with climate-carbon feedbacks	- Global instantaneous indicator, temperature increase 100 years, numerical proxy for GWP over several hundreds years.	Applicable to WMGHGs[2]. GTP100 of NTCFs[3] for sensitivity analyses.	Strongly recommended
b) Impacts of fine particulate matter on human health					
Health impacts of fine particles	Human health effects due to indoor & outdoor primary and secondary fine particulate matter. Includes intake fractions (iF),exposure response (ERF) & severity (SF) for five diseases.	Number of deaths and Disability Adjusted Life-Years per kg emitted or formed $PM_{2.5}$ DALY/kg_i CF = iF × ERF × SF	- IF for indoor/outdoor; urban/rural; ground and various stack height. Average and marginal ERFs. CFs for 1) world average 2) continent-specific average cities, 3) 3646 cities.	Applicable to indoor and outdoor ground-level primary $PM_{2.5}$. Indoor and outdoor secondary $PM_{2.5}$; generic factors for stack heights.	Strongly recommended Interim recommended
c) Impacts of Water Consumption					
c1) Water scarcity	Potential to deprive human & ecosystems. Accounts for the Available WAter REmaining once aquatic eco-systems & humans demand is met.	Available WAter REmaining-AWARE $m^3_{world\ eq.water}/m^3_i$	- Substantial spatial variability (0.1 to 100 $m^3_{world\ eq.water}/m^3_i$). Integration to regions, countries, continents & the globe.	Applicable at monthly level to 11’000 water-sheds globally. CFs only for marginal change <5% in water consumption	Recommended
c2) Impacts of water consumption on human health	Potential damage of water consumption on malnutrition, due to food losses via reduced irrigation, locally or via trade	Disability Adjusted Life-Years per m^3 water consumed DALY/m^3_i	- Native scales: monthly agricultural/industrial use in 11'000 watersheds, for regions, countries, continents & the globe.	Applicable to marginal change. Caution when interpreting result for food-producing systems.	Recommended
d) Land use impacts on biodiversity					
Potential species loss due to land occupation & transformation	Displacement or reduction in species, which would otherwise exist on that land. Accounts for relative abundance of species and their global threat level.	Change in relative species abundance for the ecoregion, and globally, due to land occupation [PDF/m^2] & land transformation[PDF-yr/m^2]	- 5 taxa (birds, mammals, reptiles, amphibians and vascular plants). - 6 different types of land use for 800+ ecoregions. - Reference state: natural habitat.	Applicable to LCA hotspot analyses. Not to be used in comparative assertions disclosed to the public.	Interim recommended

[1] $kg_{CO2\text{-}eq.(shorter)}$ and $kg_{CO2\text{-}eq.(long)}$ are not additive and shall not be added. [2]WMGHG: well-mixed greenhouse gases; [3]NTCFs: Near-Term Climate Forcers

5.1 Climate change

5.1.1 Background and scope

LCA studies quantify the climate change impacts of greenhouse gas emissions due to human activities by aggregating them into a common unit, e.g. CO_2-equivalent (Hellweg & Milà i Canals 2014). Global Warming Potential (GWP, IPCC 2007) has been the default metric used in LCIA since its first publication in 1990 and none of the substantial advancements in climate science or new metrics (e.g. Global Temperature Change Potential – GTP, Shine et al. 2005) have been considered. Two main challenges were addressed towards more comprehensive LCIA indicators: a) how to best characterize gases with lifetimes ranging from a few years for methane (CH_4), up to several hundreds or thousands of years for well-mixed greenhouse gases (WMGHG) such as carbon dioxide or CFCs, and b) how to consider the new climate science developments on climate-carbon cycle feedbacks (the changing climate influencing itself, e.g. the rates of soil respiration and photosynthesis), and on the contributions from Near-Term Climate Forcers (NTCFs, like ozone precursors and aerosols such as black carbon). Climate change impacts from human-induced albedo changes were not considered.

5.1.2 Description of selected indicators

a) Selected indicators (Table 1a): There is no single metric that can adequately assess the different contributions of climate forcing agents to both the rapid shorter-term temperature changes and the long-term temperature increases that are associated with different types of damages. It is therefore recommended to adopt two distinct and complementary subcategories based on two separate indicators:

1) Shorter-term climate change, addressing shorter-term environmental and human health consequences from the ***rate of climate change*** (over next decades, e.g., lack of human and ecosystems adaptation), using **GWP 100** as indicator. By explicitly accounting for all the forcing of an emission until the time horizon, GWP100 captures the cumulative effects of climate pollutants that contribute to the rate of warming. As it is numerically close to GTP40 (Allen et al. 2016), it can be interpreted as a proxy for temperature impacts within about four decades, a time scale markedly shorter than that of GTP100.

2) Long-term climate change impacts, reflecting the ***long-term effects from climate change*** (over next centuries, e.g., future temperature stabilization, sea level rise), using **GTP 100** as indicator. GTP100 is an instantaneous indicator measuring the potential temperature rise still occurring 100 years after emission. Its numerical values are similar to GWP with a time horizon of several centuries, which would have also been a suitable indicator to reflect long-term effects from climate change. However, the IPCC does not provide GWP values for such long time horizons, since modeling too far in the future would lead to very high uncertainties.

Sensitivity analysis: Given the high uncertainty ranges associated with the CFs for NTCFs, these should only be considered in a sensitivity analysis using the range of values for each species. Results can be shown by taking the CFs representing a best case (using the lower end of the range) and a worst case (using the upper end of the range) scenario. It is also recommended to use GWP20 in a sensitivity analysis for assessing the dependency of the results on an indicator based on very short term climate change effects.

b) Calculation method: The GWP from the IPCC 5th Assessment Report (Myhre et al. 2013, Joos et al. 2013) are produced from models that give the temporal evolution of radiative forcing in response to an instantaneous emission of a climate forcer. For CO_2 the impulse response function consists of three terms governed by distinct decay time constants, and one time-invariant constant term that represents a variety of carbon cycle processes operating on a range of time scales (Joos et al. 2013). Simpler models are used for non-CO_2 climate forcers with simple exponential decays, accounting for indirect effects for CH_4 and N_2O. The GTP are obtained from models yielding the temporal evolution of global-mean temperature change due to changes in radiative forcing. These models are based on a short and a longer time constant that are calibrated using more complex models (Boucher and Reddy 2008). Further technical details can be found in Section 8.SM.11 of IPCC 5th AR, as well as in the two publications of the climate change TF (Levasseur et al. 2016; Cherubini et al. 2016).

c) Characterization factors: Table 2 provides the recommended values for a subset of the main greenhouse gases contributing to climate change. Additional values for GWP20 and NTCFs for sensitivity studies can be found in the climate change chapter of the full report (Frischknecht and Jolliet 2016, Chapter 3). Compared to earlier Global Warming potentials, the improvement of models and the inclusion of climate-carbon feedbacks for all climate forcers leads to an increased value of the shorter–term indicator GWP100 for methane from 25 (IPCC 2007) to 34 $kg_{CO2\text{-}eq.(shorter)}/kg_{CH4}$. When considering the long-term indicator GTP100, CH_4 impact is smaller relative to CO_2 and amounts to 11 $kg_{CO2\text{-}eq.(long)}/kg_{CH4}$. The factors for fossil methane include the degradation of fossil methane into CO_2 and thus are higher by 2 $kg_{CO2\text{-}eq.(long)}/kg_{CH4}$ for both indicators compared to the factor for biogenic methane. $kg_{CO2\text{-}eq.(shorter)}$ and $kg_{CO2\text{-}eq.(long)}$ are not additive and shall not be added, thus the indication in parentheses, i.e. (shorter) and (long).

Table 2 IPCC Characterization factors for selected greenhouse gases, representing shorter-term (GWP100) and long-term (GTP100) climate change impacts, according to Myhre et al. (2013, Table 8.A.1).

Well-mixed greenhouse gases	Chemical formula	Lifetime [years]	Shorter-term climate change GWP100 [$kg_{CO2eq.\ (shorter)}/kg_i$]	Long-term climate change GTP100 [$kg_{CO2eq.(long)}/kg_i$]
Carbon dioxide	CO_2	Indefinite	1	1
Methane biogenic	Biogenic CH_4	12.4	34	11
Methane fossil	Fossil CH_4		36	13
Nitrous oxide	N_2O	121	298	297
HCF-134a	CH_2FCF_3	13.4	1 550	530
CFC-11	CCl_3F	45	5 350	3 490
PFC-14	CF_4	50 000	7 350	9 560
Sulphur hexafluoride	SF_6	3 200	26 087	33 631

CFs for Near-Term Climate Forcers and GWP20 are available for download on the UNEP-SETAC life Cycle Initiative website (http://www.lifecycleinitiative.org/applying-lca/lcia-cf/) to perform the recommended sensitivity studies and assess very short-term climate change effects.

5.1.3 Recommendation and applicability

It is strongly recommended to use GWP100 for the shorter-term impact category related to the rate of temperature change, and GTP100 for the long-term impact category related to the long-term temperature rise for WMGHGs. Based on the IPCC AR5 recommendations, it is recommended to consistently use the characterization factors that include the climate-carbon cycle feedbacks for both non-CO_2 GHGs and CO_2. For the shorter-term climate effects, a sensitivity analysis may also include results from NTCFs and may apply GWP20 (in addition to GWP100) as CFs.

The use of two complementary climate change impact subcategories in LCA is an element of novelty compared to the traditional practice, which is based on the use of a single climate change indicator (usually GWP100). The proposed refinement will certainly require updates of CFs in common database and software providers, and the availability of characterization factors in the IPCC 5th AR can make this transition easy. Modest adaptation efforts from practitioners will ensure an important step forward in the robustness and relevance of climate change impact assessment in LCA.[1] For sensitivity analysis including NTCFs, it is also recommended to complement life cycle inventory

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[1] One participant expressed in a minority statement its concerns regarding the implications of recommending two impact categories for climate change for practical applications of LCA, with the risk that different climate change labels used on products present divergent information.

databases with explicit data on black carbon and organic carbon emissions, which are currently aggregated within particulate matter emissions.

5.2 Fine particulate matter impacts on human health

5.2.1 Background and scope

A number of health studies, in particular the global burden of disease (GBD) project series (Lim et al. 2012), reveal the significant disease burden posed by fine particulate matter ($PM_{2.5}$) exposures indoors (household and occupational buildings air) and outdoors (ambient urban and rural air) to the world population. However, clear guidance is currently missing on how health effects associated with $PM_{2.5}$ exposure can be consistently included in LCIA (Fantke et al. 2015). This section provides a consistent modelling framework elaborated by multiple world experts for calculating characterization factors for indoor and outdoor emission sources of primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursors.

5.2.2 Description of selected indicators

a) Selected framework and indicators (Table 1b): The general framework extends earlier work from the UNEP-SETAC life cycle initiative on the health effects from $PM_{2.5}$ exposure (Humbert et al. 2011, Humbert et al. 2015) and includes the combination of three factors and metrics, characterizing *exposure*, health *response* and *severity*:

Exposure: The intake fraction iF [$kg_{inhaled}/kg_{emitted}$], expressed as the fraction of an emitted mass of $PM_{2.5}$ or precursor ultimately taken in as $PM_{2.5}$ by the total exposed population (Bennett et al. 2002), was selected as the exposure metric for both indoor and outdoor primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursor emissions. Emission source types indoors and outdoors can be associated with a specific iF. Such an iF is easier to interface and combine at the level of human exposure than a field of indoor or ambient concentrations over a certain distance around the considered emission sources.

Exposure-response: The exposure-response slope factor ERF [deaths/ $kg_{inhaled}$] represents the change in all-cause mortality (or in specific disease endpoints) per additional population intake dose unit. This exposure-response slope is determined based on the non-linear integrated exposure-response model developed by Burnett et al. (2014) to support the 2010 GBD analysis. It synthesizes effect estimates from eight cohort studies of ambient air pollution, combined with effect estimates from indoor studies at much higher levels of exposure (second-hand smoke and active smoking, indoor air pollution from cooking).

Severity: The severity factor, SF [DALYs/death], represents the change in human health damage expressed as disability-adjusted life years per death, as summarized in the GBD (Lim et al. 2012; Forouzanfar et al. 2015). The health metric chosen for exposure to $PM_{2.5}$ indoors and outdoors is the Disability-Adjusted Life Year (DALY) without age weighting and without discounting (see Section 4.2), summing up Years of Life Lost (YLL) and Years Lived with Disability (YLD). The latter includes a weighting factor describing the quality of life during the period of disability (Murray 1994).

The resulting characterization factors, CF [DALY/$kg_{emitted}$], are then determined as the product of these three metrics:

$$CF = iF \times ERF \times SF \tag{1}$$

b) Calculation method - spatial/temporal differentiation: Data for calculating the *intake fraction* iF are mainly based on Apte et al. (2012) for outdoor urban environments and on Brauer et al. (2016) for outdoor rural environments. These outdoor urban and rural/remote area archetypes are further disaggregated to account for ground level, low stack, high stack, and very high stack emissions. We distinguish outdoor archetypes at three levels of detail (Fantke et al. 2017): At generic level 1, default iF values are calculated reflecting a population weighted average intake fraction. At intermediary level 2, iF are provided for continent-specific average cities, to represent urban areas for a continental and sub-continental regions. The characteristics of each of the 3646 cities with more than 100000 inhabitants are used in the detailed level 3 iF calculation. The basic ground work for calculating iF for different indoor source environments is provided by Hodas et al. (2015). The considered archetypes differentiate high, medium and low ventilation rates, further subdivided into with and without $PM_{2.5}$ filtration, and into indoor spaces with high, medium and low occupancy. The coupled indoor-outdoor emission-to-exposure framework is available as a spreadsheet and fully described in Fantke et al. (2017).

The ERF slope for total mortality is determined at the working point for exposure to $PM_{2.5}$ in indoor and outdoor environments based on the supralinear integrated risk function of Burnett et al. (2014), with data for outdoor background mortality rates based on Apte et al. (2015). The marginal slope at the working point is provided when small changes are expected, and the average slope between the working point and the minimum risk is given for large variations.

The typical time scale considered are a few days or weeks for fate and exposure - to assess cumulative exposures, and decades or lifetime for exposure-response functions - to account for long-term mortality.

c) Characterization factors: Table 3 provides the global generic level 1 recommended default values. Marginal $PM_{2.5}$ CFs vary by up to 5 orders of magnitude, ranging from 1.4×10^{-5} DALY/$kg_{emitted}$ for outdoor rural high stack emissions up to 1.7 DALY/$kg_{emitted}$ for indoor emissions in low background $PM_{2.5}$ concentration situations.

Table 3 Summary of default intake fractions (based on Fantke et al. 2017) and characterization factors for human health impacts of primary $PM_{2.5}$ emissions and of secondary $PM_{2.5}$ precursor emissions, applying the marginal and the average exposure response slope at working point.

Pollutant	Emission compartment	Emission source type	iF $kg_{intake}/kg_{emitted}$	$CF_{marginal}$ $DALY/kg_{emitted}$	$CF_{average}$ $DALY/kg_{emitted}$
$PM_{2.5}$	outdoor urban	ground level*	3.6×10^{-5}	3.4×10^{-3}	4.9×10^{-3}
		low stack	1.2×10^{-5}	1.2×10^{-3}	1.7×10^{-3}
		high stack	9.5×10^{-6}	9.1×10^{-4}	1.3×10^{-3}
		very high stack	5.2×10^{-6}	4.9×10^{-4}	7.0×10^{-4}
	outdoor rural	ground level	6.3×10^{-6}	9.8×10^{-5}	2.3×10^{-4}
		low stack	2.2×10^{-6}	3.4×10^{-5}	8.0×10^{-5}
		high stack	1.7×10^{-6}	2.6×10^{-5}	6.2×10^{-5}
		very high stack	9.1×10^{-7}	1.4×10^{-5}	3.3×10^{-5}
	indoor low concentration	–	1.5×10^{-2}	1.7	2.3
	indoor high concentration	–	6.4×10^{-4}	5.1×10^{-3}	1.7×10^{-2}
NO_X	outdoor urban	–	2.0×10^{-7}	2.5×10^{-5}	3.1×10^{-5}
	outdoor rural	–	1.7×10^{-7}	1.4×10^{-6}	4.0×10^{-6}
SO_2	outdoor urban	–	9.9×10^{-7}	1.3×10^{-4}	1.5×10^{-4}
	outdoor rural	–	7.9×10^{-7}	6.5×10^{-6}	1.9×10^{-5}
NH_3	outdoor urban	–	1.7×10^{-6}	2.2×10^{-4}	2.6×10^{-4}
	outdoor rural	–	1.7×10^{-6}	1.4×10^{-5}	4.0×10^{-5}

*Reference emission scenario.

5.2.3 Recommendation and applicability

Overarching recommendations are summarized and prioritized below:

Strong recommendations: The intake fraction metric is strongly recommended to capture source-receptor relationships for indoor and outdoor primary $PM_{2.5}$, using the archetypes of Table 3 to differentiate exposure and where possible city-specific intake fractions to capture the large interurban variability. Proper application of the well-vetted exposure-response models for assessing both total mortality and disease-specific DALYs requires to account for background $PM_{2.5}$ exposure. *Recommendations:* it is recommended that the LCA practitioner qualitatively and (when possible) quantitatively characterizes variability and uncertainty, based on information given in Hodas et al. (2016) and Fantke et al. (2017). *Interim Recommendations:* Using current literature values for secondary $PM_{2.5}$ formation indoors and outdoors and generic factors for low, high, and very high stack emissions based on the use of ground level emissions (Humbert et al. 2011) are interim recommendations that can be readily used by practitioners as implemented in Fantke et al. (2017).

The provided factors capture the global central values for CFs but also allow for exploration of variability among subcontinental regions and cities, via a stepwise application from global averages to subcontinent and city specific CFs.

5.3 Water scarcity index

5.3.1 Background and scope

Water consumption can lead to deprivation and impacts on human health and ecosystems quality and is a relevant impact category to integrate in LCA, as framed by previous work of the WULCA working group Bayart et al. (2010), Kounina et al. (2013) and Boulay et al. (2015a,b,c). According to the ISO water footprint standard (ISO 2014), water scarcity is the "extent to which demand for water compares to the replenishment of water in an area, such as a drainage basin". While most existing water scarcity indicators were defined to be applicable either for human health or ecosystems impacts, there is a need for a generic water scarcity indicator, which explicitly represents the potential to deprive both human and ecosystems users.

This section describes the generic consensus scarcity index to assess potential impacts associated with a marginal water consumption, addressing the following question: What is the potential to deprive another user (human and ecosystems) when consuming water in a considered area?

5.3.2 Description of selected indicators

a) Selected indicators (Table 1c): Multiple indicators (Withdrawal-to-Availability, Consumption-to-Availability, corrected Demand-to-Availability and Availability-minus-Demand) were first compared and analysed based on the following pre-defined criteria: stakeholders acceptance, robustness with closed basins, main normative choice and physical meaning. Based on this comparison, the inverse of the Availability-minus-Demand (1/AMD) has been retained as a basis for the scarcity indicator method, called Available WAter REmaining – AWARE.

This indicator builds on the assumption that the less water remaining available per area, the more likely another user will be deprived. This assumes that consuming water in two regions is considered equal if the amount of regional remaining water per m^2-month – after human and aquatic ecosystem demands were met – is the same, independently of whether the driver is low water availability or high water demand. (Boulay et al. 2017). Water remaining available per unit area (A [m^2]) refers to water remaining after subtracting human water consumption (HWC) and environmental water requirement (EWR) from the natural water availability in the drainage basin and is defined as AMD. The characterization factor is then normalized by the world average AMD and calculated as:

$$CF_{\min} = 0.1 < CF_i = \frac{AMD_{world\ average}}{AMD_i} = \frac{AMD_{world\ average}}{\left(Availability_i - HWC_i - EWR_i\right)/A} < CF_{\max} = 100 \text{ m}^3{}_{\text{world eq.water}}/\text{m}^3{}_i \quad (2)$$

Where $AMD_{world\ average}$ =0.0136 and 1/AMDi can be interpreted as the Surface-Time equivalent required to generate one cubic meter of unused water in water basin i.

The CF contains a normative selection of the cut-off values, which has the objective to limit the potential influence of extreme low or high values while minimizing the number of watersheds having a CF above the maximum cut-off value 100 (<1 to 5% of watersheds) or below the minimum cut-off value 0.1 (<1% of watersheds). This normative choice aims to avoid that an even infinitesimal water consumption in an area with AMD_i close to zero, could entirely dominates the water scarcity score. As further discussed by Boulay et al. (2017) “such normative choices are often unavoidable when modeling impacts in LCA, but they should be transparent and relevant to best of the available knowledge”, as tested in the present case via multiple case studies.

b) Calculation method: Characterization factors were computed using monthly estimates of sectoral consumptive water uses (i.e. water that is either evaporated, integrated into products or discharged into the see or other watersheds; also referred to as blue water consumption) and river discharge of the global hydrological model WaterGAP (Müller Schmied et al. 2014) in more than 11’000 individual watersheds. Environmental Water Requirements (EWR) were included based on Pastor et al. (2014) which quantifies the minimum flow required to maintain ecosystems in “fair” state (with respect to pristine), ranging between 30-60% of potential natural flow.

c) Characterization factors spatial/temporal differentiation: Table 4 provides typical values for the characterization factor that ranges from 31 to 77 $m^3_{world\ eq.}/m^3_i$ between continents. Spatial variability is substantial and covers the entire potential range of 0.1 to 100 $m^3_{world\ eq.}/m^3_i$. Temporal variability may also be large and important to consider, especially for agricultural water consumption in water scarce areas.

Table 4 Average water scarcity characterization factors for agricultural, non-agricultural (i.e. power production, industrial and domestic use) and unknown water consumptions (based on all water use) in the main regions of the world

Region	Agricultural Use [$m^3_{world\ eq.}/m^3_i$]	Non-agricultural Use [$m^3_{world\ eq.}/m^3_i$]	Unknown Use [$m^3_{world\ eq.}/m^3_i$]
Europe (RER)	40.0	21.0	36.5
Africa (RAF)	77.4	51.3	73.9
Asia (RAS)	44.6	26.0	43.5
Latin America & Caribbean (RLA)	31.4	7.5	26.5
North America (RNA)	35.7	8.7	32.8
Middle East (RME)	60.5	40.9	60.0
OECD	41.4	20.5	38.2
OECD+BRIC	36.5	19.5	34.3
Oceania	69.6	19.8	67.7

5.3.3 Recommendation and applicability

It is recommended to use the “AWARE” approach, which is based on the quantification of the relative Available WAter REmaining per area once the demand of humans and aquatic ecosystems has been met. Due to the conceptual difference of this AWARE method with previously existing scarcity indicators, it is strongly recommended to perform a sensitivity analysis with a conceptually different method to test robustness of the results. Any aggregation shall include uncertainty information induced by the underlying variability.

The recommended characterization factors are available on a monthly level for about 11’000 watersheds with global coverage. It is strongly recommended to apply CF at monthly and watershed scale if possible. If for practical reasons (e.g. background data) this is not possible, it is strongly recommended to use sector-specific aggregation of CF on country and/or annual level (differentiated for agricultural and non-agricultural use). The least recommended approach is to apply generic CFs on country-annual level. World default CFs are not recommended to be used.

The method was tested on 10 case studies (see WULCA webpage), including sensitivity analyses using other conceptually different methods, uncertainties on EWR (EWR ranges) and analysis of the consequences of the maximum cut-off (10 to 1000). The studies revealed general agreement of trends but also highlighted differences, which are judged to be reasonable with no major discrepancy. The provided characterization factors are recommended for applications to marginal water consumption only (e.g. changing the current watershed water consumption by less than 5%).

5.4 Impacts of water consumption on human health

5.4.1 Background and scope

Water deprivation may cause a variety of potential human health impacts, when affecting those uses that are essential, mainly domestic and agricultural uses (Kounina et al. 2013; Murray et al. 2015). Water deprivation for domestic use may increase the risks of intake of low quality water or lack of water for hygienic purposes that may result in the increase in infectious diseases and diarrhea. Water deficit in agriculture and fisheries/aquaculture may decrease food production and consequently result in malnutrition due to food shortage. Regarding the state of available data and science, this work has focused on the development of indicators for assessing the potential damage of water consumption on malnutrition from agriculture water deprivation.

5.4.2 Description of selected indicators

a) Selected indicators (Table 1c): Building on earlier work from Pfister et al. (2009), Boulay et al. (2011) and Motoshita et al. (2014), the following indicator has been retained for agriculture water deprivation caused by any water consumption:

$$CF_{agri} = \frac{HWC_{total}}{AMC} \times \frac{HWC_{agri}}{HWC_{total}} \times SEE_{malnutrition} \qquad (3)$$

Where:

HWC_{agri} [m^3] is the Human Water Consumption for agricultural use;

HWC_{total} [m^3] is the Human Water Consumption for all uses;

AMC [m^3] is the Availability Minus Consumption, i.e. the water available minus human water consumption by all users (similar to the water scarcity indicator, AWARE, but not considering the environmental requirement and not divided by area);

The first term of the equation represents the competition of available water between users, and the second term allocates the fraction of water deprivation due to agricultural users.

$SEE_{malnutrition}$ [DALY/m^3] is the socio-economic effect factor of agricultural water use accounting for both the local malnutrition and the international trade effect. This factor accounts for the food production losses as a result of reduced irrigation [kcal / m^3], the domestic supply ratio of dietary energy from food [-] (including trade adaptation capacity) and the health effect factor of 4.55×10^{-8} [DALY/kcal], locally or via international trade. Additional detail is provided in Subchapter 5.2 of Frischknecht and Jolliet (2016).

b) Calculation method - spatial/temporal differentiation: The fate factor HWC_{agri} / AMC describes the effect of the consumption of 1m^3 of water in a watershed on the change of water availability for agricultural use, assuming that agriculture suffers proportional to the share of current agricultural water consumption. The socio-economic effect factor of agricultural water use is the product of the food production losses associated with irrigation multiplied by the health effect factor. Food production losses are defined by the ratio of production amount attributable to irrigation divided by irrigation water consumption (kcal/m^3). The health effect factor is determined as the average DALY of protein-energy malnutrition damage (taken from GBD 2013) per unit food deficiency in kcal, as calculated in Boulay et al. (2011).

The effect of international trade is also taken into account, based on the fraction of food exports and imports, as well as on the trade adaptation capacity. Countries with a high trade adaptation capacity can reduce food exports or increase imports when their domestic food production decreases due to reduced water availability, which may reduce food availability in other countries (Motoshita et al. 2014).

c) Characterization factors: Two types of characterization factors are provided for agricultural water consumption and of non-agricultural water consumption (Table 5), with usually higher CFs for agricultural water consumption since scarcity is usually higher during periods with high irrigation requirements. Damages per m^3 range from 0 to $4.4 \cdot 10^{-5}$, with monthly variation ranging from 0.15 to 3.46 of the annual average. Table 5 presents representative CFs for United Arab Emirates as an example of a developed economy, with no national damage but high trade-induced damage. Tunisia has intermediary impacts for both national and trade-induced damage. Nepal is an example for developing countries with highest impacts for both national and trade-induced damage.

Table 5 Characterization factors for human health impacts of water consumption in representative countries

		CFs for agricultural water consumption [DALY/m^3]		CFs for non-agricultural water consumption [DALY/m^3]	
		National damage	Trade-induced damage	National damage	Trade-induced damage
Developed economy	United Arab Emirates	0	$7.72 \cdot 10^{-6}$	0	$2.95 \cdot 10^{-6}$
Middle income country	Tunisia	$5.76 \cdot 10^{-6}$	$1.07 \cdot 10^{-5}$	$2.66 \cdot 10^{-6}$	$4.96 \cdot 10^{-6}$
Developing country	Nepal	$1.86 \cdot 10^{-5}$	$1.35 \cdot 10^{-5}$	$1.56 \cdot 10^{-5}$	$1.13 \cdot 10^{-5}$

5.4.3 Recommendation and applicability

Human health impacts due to domestic and agricultural water scarcity have been recognized as a relevant pathway in which water consumption may lead to damage on human health. The recommended CFs are for marginal applications only and are provided on watershed and monthly level. It is strongly recommended to apply them at this level of resolution, since using annual country or global averages substantially increases uncertainty. Caution is required when interpreting impacts caused by food-producing systems, since the produced kcal associated with the functional unit might compensate and offset the calculated potential impact on human health.

The indicator is based on a series of potentially valid assumptions. Refinements are especially needed for modelling the adaptation capacity, the trade effect (account for price elasticity), and for the regional health responses to malnutrition. Additional analyses are required for damage associated with the lack of water for domestic uses (i.e. water-related diseases). Differentiating between groundwater and surface water would be nice to have for both the human health impacts and the water scarcity indicators, but constitutes a topic for further developments since present data availability did not allow for a reliable differentiation.

5.5 Land use impacts

5.5.1 Background and scope

Land use and land use change are main drivers of biodiversity loss and degradation of a broad range of ecosystem services (MEA 2005). Despite substantial contributions to address land use impacts on biodiversity in LCA in the last decade (Milà i Canals et al. 2007, Schmidt 2008, de Baan et al. 2013, Koellner et al. 2013, Coelho and Michelsen 2014, Curran et al. 2016), no clear consensus exists on the use of a specific impact indicator, thus limiting the application of existing models and the comparability of results between different studies evaluating land use impacts. This section therefore aims to provide guidance and recommendations on modelling approach and related indicator(s) adequately reflecting impacts of land use on biodiversity.

Workshops with domain experts revealed the importance of considering different geographical levels, the state of the ecosystems at the assessed location and the land use intensity levels. Although agreement on optimal Indicators to measure biodiversity should be described (Woods et al. 2017) in terms of three levels (genes, species, ecosystems) and three attributes (composition, function, structure), species richness was discerned as practical proxy and good starting point for assessing biodiversity loss. However, complementary metrics need to be considered in modelling, such as habitat configuration, inclusion of fragmentation and vulnerability (Teixeira et al. 2016).

In addition, Curran et al. (2016) carried out as part of the consensus process a comprehensive review of existing methods, evaluating these according to ILCD criteria. This review revealed the need for including both local and regional/global impacts on biodiversity. The local impact component focuses on what and how an activity is performed, while the regional/global impact components focus on where an activity is performed. These are not mutually exclusive and both should be included. In addition, it was concluded, that a good indicator should include weighting factors, associated with the habitat vulnerability of specific regions.

5.5.2 Description of selected indicators

a) Selected indicators (Table 1d): The selected indicator is the potential species loss (PSL) from land use based on the method described by Chaudhary et al. (2015). The indicator represents regional species loss. It takes into account 1) the effect of land occupation, displacing entirely or reducing the species which would otherwise exist on that land, 2) the relative abundance of those species within the ecoregion, and 3) the overall global threat level for the affected species. The indicator can be applied both as a regional indicator (PSL_{reg}), which represents the changes in relative species abundance within the ecoregion, and as a global indicator (PSL_{glo}) which also accounts for the threat level of the species on a global scale (Chaudhary et al. 2016).

The indicator focuses on 5 taxonomic groups of macro-species; birds, mammals, reptiles, amphibians and vascular plants. The taxonomic groups can be analyzed separately or can be aggregated to represent the Potentially Disappeared Fraction (PDF) of species. Land use types covered include annual crops, permanent crops, pasture, urban, extensive forestry and intensive forestry.

b) Calculation method - spatial/temporal differentiation: The characterization factor for local species loss (CF_{loc} , dimensionless) is a function of the ratio of species richness between each land use and reference state; It is calculated for the six land use types, five taxa, and 804 terrestrial eco-regions, covering all biomes. The data are sourced from plot scale biodiversity monitoring surveys, which were obtained from over 200 publications giving more than 1000 data points. The regional and global CF were then calculated at ecoregion level as follows: Regional species loss is calculated using a species area relationship model (SAR) for each land use type - referred to as the Countryside SAR model. The regional characterization factors (CF_{reg}) are aggregated to provide a single value for potential species loss from land use - regional (PSL_{reg}), using equal weighting for animal (average of four taxa) and vegetal (one taxon). To determine an estimate of the permanent, global (irreversible) species loss, the regional CFs for each taxon and ecoregion are multiplied by a vulnerability score (VS) of that taxon in that ecoregion. This vulnerability score is based on the proportion of endemic species in an ecoregion and the threat level assigned by the IUCN red list.

The current approach to determine the impacts of land transformation is to take the regeneration time of each land use type to return to the reference state into account, following Curran et al. (2014) and to multiply the occupation impact by half of the reference time, as suggested in Milà i Canals et al. (2007). Land transformation CFs are therefore also provided ad interim as the land occupation CFs multiplied by the half of the estimated years for the ecosystem to regenerate without human interference, based on a recent study from Curran et al. (2014). This approach is simplistic as linear recovery is assumed and refinement would be beneficial and might be problematic in case of global species disappearance. The reference state used in the model is referred to as natural undisturbed habitat, which could be seen as synonymous with potential natural vegetation PNV. This is the mature state of vegetation in the absence of human interventions (Chiarucci et al. 2010), which at times might be challenging to identify. Using the PNV as a reference is better adapted to support decisions considering long-term effects of land use policies, rather than shorter-term effects (Antón et al. 2016).

c) Characterization factors: Table 6 provides the world average characterization factors for 6 different types of land use, with the smallest CF for extensive forestry, a factor 7 smaller than the highest value for urban land use. This factor seven and the relative ranking between land types remain approximately the same for land occupation and transformation at regional and at global scales. Specific characterization factors for each ecoregion are available for download on the UNEP-SETAC life Cycle Initiative website: http://www.lifecycleinitiative.org/applying-lca/lcia-cf/

Table 6 World average characterization factors for regional and global land occupation and transformation impacts (Chaudhary et al. 2016)

Land use type	occupation average regional [PDF/m^2]	transformation average regional [PDF year/m^2]	occupation average global [PDF$_{global}$/m^2]	transformation average global [PDF$_{global}$ year/m^2]
Annual crops	1.98×10^{-14}	2.88×10^{-12}	2.10×10^{-15}	2.50×10^{-13}
Permanent crops	1.56×10^{-14}	2.31×10^{-12}	1.50×10^{-15}	1.80×10^{-13}
Pasture	1.24×10^{-14}	1.88×10^{-12}	1.30×10^{-15}	1.50×10^{-13}
Urban	2.91×10^{-14}	4.43×10^{-12}	2.40×10^{-15}	2.90×10^{-13}
Extensive forestry	3.93×10^{-15}	6.08×10^{-13}	3.70×10^{-16}	4.20×10^{-14}
Intensive forestry	1.05×10^{-14}	1.48×10^{-12}	1.10×10^{-15}	1.10×10^{-13}

5.5.3 Recommendation and applicability

The selected model and indicator builds on species richness, incorporates the local effect of different land uses on biodiversity, links land use to species loss, includes the relative scarcity of affected ecosystems, and includes the threat level of species. Global average characterization factors (CFs) are interim recommended to quantify potential species loss (PSL) from land use and land use change, suitable for hotspot analysis in LCA. It is strongly recommended not to use these CFs for comparative assertions. Practitioner also need to be careful when using PSL and comparing it with other impact categories in which the regional species loss is quantified without vulnerability score. A conversion factor might have to be applied to the other impact categories for comparison with PSL, e.g. as suggested by Chaudhary et al. (2006, Eq. 11.17).

Developments are required before upgrading this interim recommendation to a full recommendation of CFs. These improvements comprise 1) the refinement of land use classes considered including different management regimes, 2) the inclusion of additional taxa, with special interest in the possibility to include micro-organisms, 3) the development of best practice information for use and interpretation of the impact assessment results as well as 4) the test of CFs in sufficient case studies to explore the robustness and ability of the model to differentiate potential biodiversity impacts.

6. Application to a rice case study

A rice production and consumption LCA case study was developed and its inventory described in detail by Frischknecht et al. (2016) to illustrate and test the applicability and practicality of the recommended life cycle impact category indicators. It is not meant to be fully representative for rice production and consumption in the regions covered. The life cycle inventory was established for three distinctly different scenarios of producing and cooking rice, corresponding to three different regions: 1) Rural India - rice production of 3500 kg/ha consuming 0.826 m^3_{water}/kg_{rice}, processing, distribution and three stone open cooking with firewood, all in rural India; 2) Urban China - rice production of 6450 kg/ha consuming 0.487 m^3_{water}/kg_{rice} and processing in rural China, distribution and cooking in electric rice cooker in urban China; 3) USA-Switzerland - rice production of 7452 kg/ha consuming 0.835 m^3_{water}/kg_{rice} and processing in the USA, distribution and cooking in a gas stove in Switzerland.

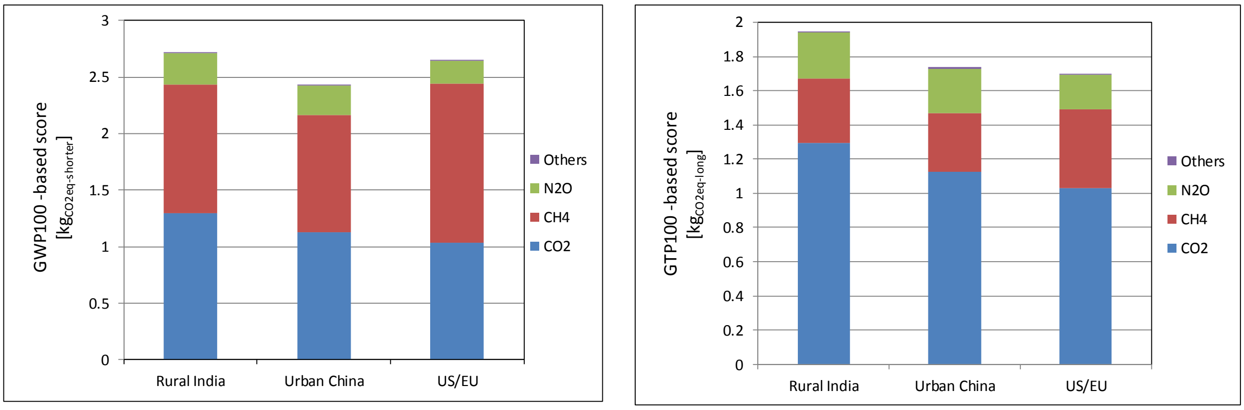
Figure 1 compares the impact scores calculated per functional unit (FU) of 1kg cooked white rice for the three scenarios, using the main recommended indicators presented in section 4.

For climate change, figure 1 shows the contribution of the main greenhouse gases to shorter-term climate change impacts (Fig. 1a), and to long-term climate change impacts related to the long-term temperature rise (Fig. 1b), including climate-carbon feedbacks for all gases. Emissions of methane, mainly caused by rice cultivation, contribute substantially to shorter-term climate change impacts. Because methane is a rather short-lived GHG, its contribution to long-term climate change is smaller, which may affect the ranking between scenarios. The complementary sensitivity analysis performed for Near-Term Climate Forcers (NTCFs) (Frischknecht and Jolliet 2016, chapter 3) shows that the ranking between scenarios is only affected for the NTCFs high-end factors, in particular for rural India. This scenario includes emissions of substantial amounts of CO and black carbon from the wood stove, showing the importance to report separately black carbon and organic carbon in life cycle inventories databases.

For impacts of fine particulate matter on human health, figure 1c demonstrates the importance of also including indoor sources of $PM_{2.5}$ and related health impacts in addition to outdoor-related impacts. Indoor cooking with wood stoves (solid fuel combustion) makes the rural India scenario having by far the highest impacts. Gas stove-related indoor air emissions have a much smaller but still important contribution for the USA-Switzerland scenario. This calls for including relevant indoor emissions in LCA case studies, which is further substantiated by Fantke et al. (2017). Outdoor related impacts are mainly due to primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursor emissions from rice production, thus the importance to distinguish between rural and urban outdoor archetypes. These archetypes are able to capture important variabilities in exposure between urban and rural areas, compared to currently available spatial modelling approaches that lack a sufficiently high spatial resolution to capture these differences at the global scale.

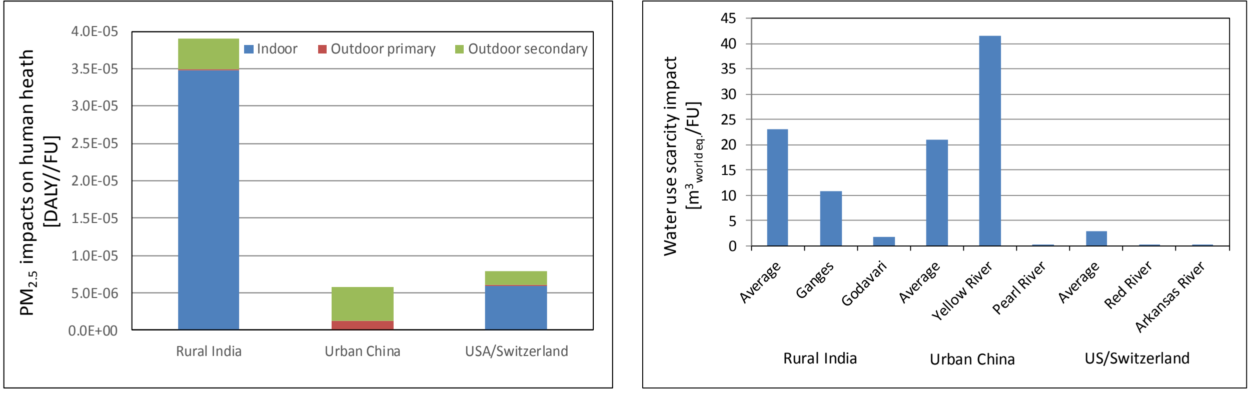
The analysis of the impacts of water consumption focuses on the rice cultivation phase, which induces more than 99.4% of the water consumed. *For water scarcity impacts*, national average characterization factors for agricultural production are similar in all three countries (China, India, USA) and average results reflects the water consumption considered in the life cycle inventory. This leads to comparable impacts in India and China and substantially lower impacts in US (Fig. 1d). This case study also demonstrates the importance to differentiate the rice production locations in each country as recommended in section 4.3. Considering two specific water basins with substantial rice production in each of the three countries leads to substantial variations from the average: In rural India and US, the main considered watersheds have lower characterization factors than the national average (incl. the case study region watersheds “Ganges” and “Arkansas River”). In the case of China, the Yellow River has an AWARE factor of twice the national average, whereas production in the Pearl river area (case study region) leads to negligible water scarcity impacts. For impacts of water consumption on human health associated with malnutrition (Fig. 1e), relative variations between locations mostly reflect the AWARE water scarcity ranking (Fig. 1d). Both national and trade have important contributions in India and China, whereas trade mostly contribute to the US average impacts.

For impacts of land use, figure 1f shows that impacts are driven by agricultural land use, and to a lesser extent by forest land use when fuelwood is used, and by urban land use in the US/EU scenario. Higher impacts for rural India are not only due to low yield ratios but also to specific characteristics of ecoregions. Therefore, the variation between scenarios also demonstrates the importance to include production location in determining land use impacts. Though all scenarios have overlapping uncertainty ranges and therefore differences between scenarios are not significant, the assessment provide us with clear information about hotspots which need to be considered.



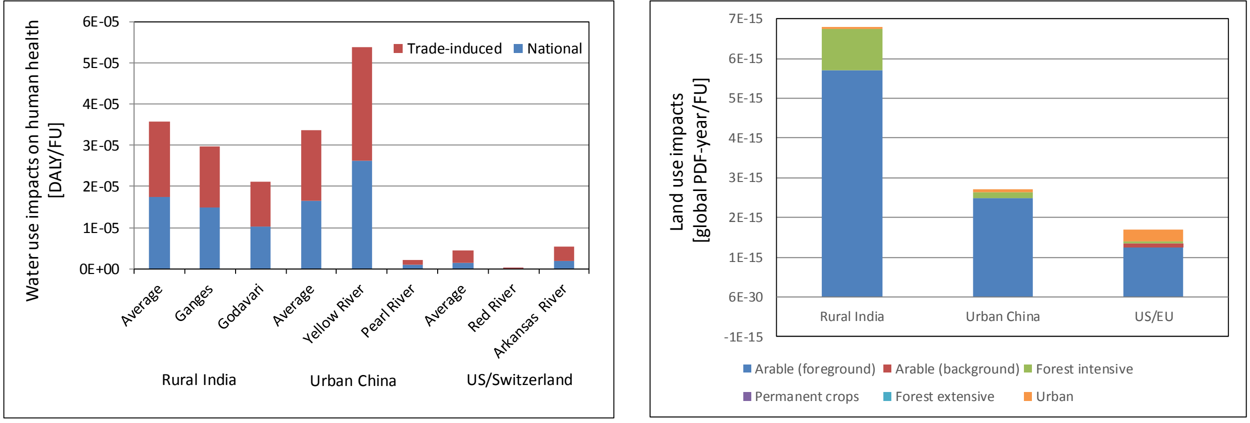
a) Climate change, shorter-term impacts based on GWP100 with climate-carbon cycle feedbacks

b) Climate change, long-term impacts based on GTP100 with climate-carbon cycle feedbacks



c) Impacts of fine particulate matter on human health based on average ERF slope

d) Water scarcity impact using AWARE



e) Impacts of water consumption on human health, accounting for national and trade effects

f) Land use impacts on global biodiversity

Fig.1 Impact scores per kg cooked white rice for the rural India, urban China and USA-Switzerland scenarios, to illustrate and test the recommended LCIA indicators for climate change, fine particulate matter impacts, water and land use impacts. These results are not meant to be representative for rice production and consumption in the covered regions.

Most of the recommended indicators cannot be easily compared nor aggregated across impact categories, as they address different damage impact categories, unless they would be normalized and weighted. The orders of magnitude of human health impacts associated with fine particulate matter (Fig. 1c: 5×10^{-6} to 3×10^{-5}DALYs/kg$_{rice}$) and with water consumption (Fig. 1e: 0.1×10^{-6} to 8×10^{-6}

DALYs/kg$_{rice}$) can however be directly compared and fall in an overlapping range, demonstrating the interest of damage oriented approaches and the importance to consider these two impact categories. Since the case study aims at offering cooked rice, it is also interesting to compare the malnutrition impacts of water consumption with the potential reduction in malnutrition impacts associated with the 3700 kcal (raw) produced per kg rice. Using the same health effect factor of 4.55×10^{-8} [DALY/kcal], this potential reduction amounts to 1.7×10^{-4} [DALY/kg$_{rice}$], and is substantially higher than the impacts of water consumption on human health.

7. Conclusions and outlook

The work and discussions before and during the Pellston Workshop^{TM} resulted in relevant recommendations in the four topical areas climate change, fine particulate matter impacts, impacts of water consumption and land use impacts, as well as on the updated LCIA framework and crosscutting issues. The recommended characterization factors and impact category indicators include latest findings of topical research and clearly go beyond current practice. The levels of recommendation show the variable maturity of the indicators and their applicability domain (Table 1). At the same time care has been taken to ensure immediate applicability in current LCA environments.

The present work was complemented by a review process in which the draft workshop report was sent to 15 qualified reviewers , who had agreed to supply comments on the topical chapter related to their area of expertise (reviewer list in section S3 of the supplementary information). Overall, the peer review comments were positive and supportive of the effort to move toward global guidance for the selected impact categories. However, some reviewers found it a bit premature for UNEP-SETAC to position and endorse many of the indicators and concepts from the workshop as global guidance. In particular, all indicators, as well as the revised framework, need to be further tested in terms of practicality and scientific rigour, by engaging various experts and practitioners. The full peer review report is available in Frischknecht and Jolliet (2016, p.157ff).

Such tests are also an important step to address potential concerns that such consensus processes may raise, regarding the possibility to block scientific progress, hide uncertainty, or lead to recommendation of immature methods, without enough contact with domain experts outside the LCA community (Huijbregts, 2014). The present consensus building effort was therefore organized to stimulate the involvement of experts outside the LXA community, with e.g. close to half of the climate change TF composed of climate scientists or authors of the IPCC 5th assessment report who were not directly involved in LCA. For aa categories, involvement of well-recognized experts was secured via targeted workshops (see e.g. Fantke et al. 2014 for the human health impacts of fine particulate matter). The process has stimulated progress for LCA practice, e.g. with the development of the new water scarcity index AWARE, making data at watershed and monthly levels available for practitioners. It has also facilitated the inclusion of human health effect of PM by making assessment factors available, and discussing their variations between global, continental and city specific levels.

The present recommendations will also contribute to address the role of value choices and associated uncertainties, e.g. by providing a long-term perspective with the GTP factors complementary to the commonly used shorter-term GWP. It is also important to qualify the level of maturity of such recommendations and limit their domain of applicability accordingly. For example, the land use interim recommended CFs are suitable for hotspot analyses, but not for comparative assertions. Caution is also required when applying the characterization factors for human health impacts of water consumption to food-producing systems, the produced food having the potential to offset the calculated impacts due to malnutrition.

Given the dynamics in the LCIA research area, it is also essential to see the present recommendations as part of a continuous process, in which the recommended characterization factors should not be seen as given and static but rather evolutionary. While framework and methods are expected to be stable, periodic updates of characterization factor are to be expected and are welcomed to further help improving both robustness, topical coverage and applicability of the environmental impact indicators recommended today. Several follow-up efforts are already made in this sense. First, the proposed indicators are not intended and should not be considered as covering a comprehensive or sufficient list of environmental impact categories. They will therefore benefit to be incorporated into full LCIA methods, providing a more complete set of environmental impacts and trade-offs. Several of these indicators are already foreseen as part of methods in final development such as IMPACT World+ (for GWP/GTP 100 and AWARE – Bulle et al. 2017), or the LC-Impact method (for land use indicator – Verones et al. 2016). Second, the Pellston Workshop^{TM} successfully proved the willingness of co-operation in the field of LCIA research and development, and the already strong momentum reached in the different TFs should be maintained and further increased. A second consensus finding process has therefore been launched for a second set of environmental impact indicators, i.e. for acidification & eutrophication, human toxicity and eco-toxicity, mineral resource depletion and ecosystem services. Third, it is recommended that the Life Cycle Initiative establishes a process and community of LCIA researchers, to care for the stewardship of these indicators and ensure the long term recommendation of LCIA characterization factors. Fourth, there is a need for further defining the indicators uncertainty and applicability, in particular how to link to inventory, how to better define criteria when to select non-linear marginal vs. average dose-response slopes, and how to systematically provide uncertainty ranges as a function of the level of resolution of the applied CFs.

Finally, the United Nations’ Sustainable Development Goals and the concept of planetary boundaries may profit from the work performed in this flagship project. The recommended environmental indicators may be used to quantify and monitor progress towards sustainable production and consumption, in particular for SDG 2 (zero hunger – impacts of water consumption on malnutrition/human health), SDG7/SDG11 (affordable and clean energy/ sustainable cities and communities – shorter and long-term climate change impacts/Human health impacts of PM), SDG 14 (life below water – water scarcity impacts), and SDG 15 (life on land – land use impacts on biodiversity).

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9. Supporting documents

The full report and list of characterization factors is available for download on the UNEP-SETAC life Cycle Initiative website: http://www.lifecycleinitiative.org/applying-lca/lcia-cf/

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Fig.1 Impact scores per kg cooked white rice for the rural India, urban China and USA-Switzerland scenarios, to illustrate and test the recommended LCIA indicators for climate change, fine particulate matter impacts, water and land use impacts. These results are not meant to be representative for rice production and consumption in the covered regions

a) Climate change, shorter-term impacts based on GWP100 with climate-carbon cycle feedbacks

b) Climate change, long-term impacts based on GTP100 with climate-carbon cycle feedbacks

c) Impacts of fine particulate matter on human health based on average ERF slope

d) Water scarcity impact using AWARE

e) Impacts of water consumption on human health, accounting for national and trade effects

f) Land use impacts on global biodiversity