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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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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™ in January 2016 leading to the following recommendations.

Results

LCIA framework: The updated LCIA framework now distinguishes between intrinsic, instrumental and cultural values 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.

2. Introduction and goal of the harmonisation process

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

81 A series of complementary initiatives for LCIA consensus building have taken place since the early
82 1990s, striving towards providing recommendations and guidance for the development and use of
83 LCIA methods. Two rounds of SETAC working groups led to category-specific recommendations for
84 developing LCIA impact indicators (Udo de Haes et al. 2002), taking advantage of broader consensus
85 efforts, such as those led by the Intergovernmental Panel on Climate Change for climate change
86 issues. The LCIA program of the phase I and phase II of the UNEP-SETAC Life Cycle Initiative
87 developed a combined midpoint-damage framework (Jolliet et al. 2004), and provided further
88 recommendations for multiple impact categories. The UNEP-SETAC scientific consensus toxicity
89 model was then developed and endorsed to estimate ecotoxicity and human toxicity impacts in LCA
90 (Rosenbaum et al. 2008; Westh et al. 2015). In parallel, more emphasis was given to better frame
91 resource-related categories, especially for land use (Milà i Canals et al. 2007) and water use, with the
92 launch of a Water Use in LCA working group, WULCA (Köhler 2007). Since the launch of phase I of
93 the initiative and the publication of its framework, several developments have been and are being
94 carried out for developing worldwide applicable methods, with spatially differentiated impact
95 indicators, at midpoint level (Hauschild et al. 2011 and 2013) and damage level (Bulle et al. 2016;
96 Frischknecht et al. 2013; Huijbregts et al. 2014 and 2017; Itsubo and Inaba 2010). These developments
97 now need to be accounted for in a global consensus building process.

98 To answer these needs, Phase III of the UNEP-SETAC Life Cycle Initiative launched a flagship
99 project to provide global guidance and build consensus on environmental LCIA indicators. Initial

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

113   This paper presents the consensus building process and scientific approach retained, as well as the
114   indicators selected and recommendations reached for the above-described selected impact categories
115   and crosscutting issues. The first section describes the process and criteria used to select the
116   recommended indicators. The second section presents the updated LCIA framework. The next sections
117   describe the selected characterization factors and the main recommendations for each of the four
118   impact categories considered. The paper ends by applying the recommended indicators to a rice case
119   study, followed by conclusions and outlook that addresses potential concerns that such consensus
120   processes may raise (Huijbregts, 2014). A more comprehensive description of the process and its
121   outcome is further detailed in the first assessment report on LCIA guidance (Frischknecht and Jolliet
122   2016).

3. Process and recommendation criteria

124   **Process:** To achieve the goals of the LCIA harmonisation project, following open calls for interest and
125   search for category specific specialists, task forces were set up involving more than 100 world-leading
126   domain experts and LCA scientists, organized in impact category specific task forces (TFs) and
127   complemented by a TF on crosscutting issues. Multiple topical workshops and conferences were
128   organised by each individual TF to first scope the work and then develop scientifically robust state-of-
129   the-art indicators suitable for a global consensus (Boulay et al. 2015c; Cherubini et al. 2016; Curran et
130   al. 2016; Fantke et al. 2015; Hodas et al. 2016; Levasseur et al. 2016; Teixeira et al. 2016). This was
131   followed by two overarching workshops and stakeholder meetings in Basel 2014 and in Barcelona
132   2015 to address specific critical crosscutting issues and collect feedback from multiple stakeholders.
133   Section S1 of the supporting information further details the multiple workshops and communications
134   carried out in each task force. Additionally, an LCA case study on the production and consumption of
135   rice common to all TFs (Frischknecht et al. 2016) was developed to test the recommended impact
136   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™. According to the standard operating procedures for SETAC-supported Pellston Workshops™, 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

209 and/or species in a way that takes resilience, rarity and recoverability into account. It is recommended
210 that the unit at the damage level should be based on "potentially disappeared fraction (PDF) of
211 species" (e.g. global or local PDF, PDF-m2-yr or PDF-m3-yr). Any method addressing biodiversity
212 that includes units that are convertible to PDF related metrics is recommended to describe and report
213 the conversion factors. It is recommended to develop CFs at local, regional and global levels, to reflect
214 losses in local and regional ecosystem functionality and global extinction. We emphasize that impacts
215 quantified at global level (i.e. species are completely lost from the Earth) cannot be directly compared
216 with local or regional impacts (i.e. species are only extinct in a certain part of the world); thus method
217 developers need to report very explicitly at which level their model was developed.

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

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

227 **5. Selected indicators, characterization factors and main recommendations**

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

233   **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	Recommen-dation 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 $PM_{2.5}$ $DALY/kg_i$ $CF = iF \times ERF \times SF$	- 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

234   [1] $kg_{CO2\text{-}eq.(shorter)}$ and $_{kgCO2\text{-}eq.(long)}$ 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.

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

275   **b) Calculation method:** The GWP from the IPCC 5th Assessment Report (Myhre et al. 2013, Joos et
276   al. 2013) are produced from models that give the temporal evolution of radiative forcing in response to
277   an instantaneous emission of a climate forcer. For CO_2 the impulse response function consists of three
278   terms governed by distinct decay time constants, and one time-invariant constant term that represents a
279   variety of carbon cycle processes operating on a range of time scales (Joos et al. 2013). Simpler
280   models are used for non-CO_2 climate forcers with simple exponential decays, accounting for indirect
281   effects for CH_4 and N_2O. The GTP are obtained from models yielding the temporal evolution of
282   global-mean temperature change due to changes in radiative forcing. These models are based on a
283   short and a longer time constant that are calibrated using more complex models (Boucher and Reddy
284   2008). Further technical details can be found in Section 8.SM.11 of IPCC 5th AR, as well as in the
285   two publications of the climate change TF (Levasseur et al. 2016; Cherubini et al. 2016).

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

297

298 **Table 2** IPCC Characterization factors for selected greenhouse gases, representing shorter-term
299 (GWP100) and long-term (GTP100) climate change impacts, according to Myhre et al. (2013, Table
300 8.A.1).
301

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

302
303 CFs for Near-Term Climate Forcers and GWP20 are available for download on the UNEP-SETAC life
304 Cycle Initiative website (http://www.lifecycleinitiative.org/applying-lca/lcia-cf/) to perform the
305 recommended sensitivity studies and assess very short-term climate change effects.

306 ### 5.1.3 Recommendation and applicability

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

313 The use of two complementary climate change impact subcategories in LCA is an element of novelty
314 compared to the traditional practice, which is based on the use of a single climate change indicator
315 (usually GWP100). The proposed refinement will certainly require updates of CFs in common
316 database and software providers, and the availability of characterization factors in the IPCC 5th AR
317 can make this transition easy. Modest adaptation efforts from practitioners will ensure an important
318 step forward in the robustness and relevance of climate change impact assessment in LCA.[1] For
319 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.

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

5.2 Fine particulate matter impacts on human health

5.2.1 Background and scope

324 A number of health studies, in particular the global burden of disease (GBD) project series (Lim et al.
325 2012), reveal the significant disease burden posed by fine particulate matter ($PM_{2.5}$) exposures indoors
326 (household and occupational buildings air) and outdoors (ambient urban and rural air) to the world
327 population. However, clear guidance is currently missing on how health effects associated with $PM_{2.5}$
328 exposure can be consistently included in LCIA (Fantke et al. 2015). This section provides a consistent
329 modelling framework elaborated by multiple world experts for calculating characterization factors for
330 indoor and outdoor emission sources of primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursors.

5.2.2 Description of selected indicators

332 **a) Selected framework and indicators (Table 1b):** The general framework extends earlier work
333 from the UNEP-SETAC life cycle initiative on the health effects from $PM_{2.5}$ exposure (Humbert et al.
334 2011, Humbert et al. 2015) and includes the combination of three factors and metrics, characterizing
335 *exposure*, health *response* and *severity*:

336 *Exposure:* The intake fraction iF [$kg_{inhaled}/kg_{emitted}$], expressed as the fraction of an emitted mass of
337 $PM_{2.5}$ or precursor ultimately taken in as $PM_{2.5}$ by the total exposed population (Bennett et al. 2002),
338 was selected as the exposure metric for both indoor and outdoor primary $PM_{2.5}$ and secondary $PM_{2.5}$
339 precursor emissions. Emission source types indoors and outdoors can be associated with a specific iF.
340 Such an iF is easier to interface and combine at the level of human exposure than a field of indoor or
341 ambient concentrations over a certain distance around the considered emission sources.

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

349 *Severity*: The severity factor, SF [DALYs/death], represents the change in human health damage
350 expressed as disability-adjusted life years per death, as summarized in the GBD (Lim et al. 2012;
351 Forouzanfar et al. 2015). The health metric chosen for exposure to $PM_{2.5}$ indoors and outdoors is the
352 Disability-Adjusted Life Year (DALY) without age weighting and without discounting (see Section
353 4.2), summing up Years of Life Lost (YLL) and Years Lived with Disability (YLD). The latter
354 includes a weighting factor describing the quality of life during the period of disability (Murray 1994).

355   The resulting characterization factors, CF [DALY/kg_emitted], are then determined as the product of these
356   three metrics:

357    $CF = iF \times ERF \times SF$ (1)

358   **b) Calculation method - spatial/temporal differentiation:** Data for calculating the *intake fraction* iF
359   are mainly based on Apte et al. (2012) for outdoor urban environments and on Brauer et al. (2016) for
360   outdoor rural environments. These outdoor urban and rural/remote area archetypes are further
361   disaggregated to account for ground level, low stack, high stack, and very high stack emissions. We
362   distinguish outdoor archetypes at three levels of detail (Fantke et al. 2017): At generic level 1, default
363   iF values are calculated reflecting a population weighted average intake fraction. At intermediary level
364   2, iF are provided for continent-specific average cities, to represent urban areas for a continental and
365   sub-continental regions. The characteristics of each of the 3646 cities with more than 100000
366   inhabitants are used in the detailed level 3 iF calculation. The basic ground work for calculating iF for
367   different indoor source environments is provided by Hodas et al. (2015). The considered archetypes
368   differentiate high, medium and low ventilation rates, further subdivided into with and without $PM_{2.5}$
369   filtration, and into indoor spaces with high, medium and low occupancy. The coupled indoor-outdoor
370   emission-to-exposure framework is available as a spreadsheet and fully described in Fantke et al.
371   (2017).

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

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

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

384

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 m²-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 [m²]) 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:

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

Where $AMD_{world\ average} = 0.0136$ and $1/AMD_i$ 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

440 value 0.1 (<1% of watersheds). This normative choice aims to avoid that an even infinitesimal water
441 consumption in an area with AMD_i close to zero, could entirely dominates the water scarcity score. As
442 further discussed by Boulay et al. (2017) "such normative choices are often unavoidable when
443 modeling impacts in LCA, but they should be transparent and relevant to best of the available
444 knowledge", as tested in the present case via multiple case studies.

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

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

457 **Table 4** Average water scarcity characterization factors for agricultural, non-agricultural (i.e. power
458 production, industrial and domestic use) and unknown water consumptions (based on all water use) in
459 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

460

461 ### 5.3.3 Recommendation and applicability

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

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

474 The method was tested on 10 case studies (see WULCA webpage), including sensitivity analyses
475 using other conceptually different methods, uncertainties on EWR (EWR ranges) and analysis of the
476 consequences of the maximum cut-off (10 to 1000). The studies revealed general agreement of trends
477 but also highlighted differences, which are judged to be reasonable with no major discrepancy. The
478 provided characterization factors are recommended for applications to marginal water consumption
479 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

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

5.4.2   Description of selected indicators

491 **a) Selected indicators (Table 1c):** Building on earlier work from Pfister et al. (2009), Boulay et al.
492 (2011) and Motoshita et al. (2014), the following indicator has been retained for agriculture water
493 deprivation caused by any water consumption:

494
$$CF_{agri} = \frac{HWC_{total}}{AMC} \times \frac{HWC_{agri}}{HWC_{total}} \times SEE_{malnutrition} \qquad (3)$$

495 Where:

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

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

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

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

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

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

518   The effect of international trade is also taken into account, based on the fraction of food exports and
519   imports, as well as on the trade adaptation capacity. Countries with a high trade adaptation capacity
520   can reduce food exports or increase imports when their domestic food production decreases due to
521   reduced water availability, which may reduce food availability in other countries (Motoshita et al.
522   2014).

523   **c) Characterization factors:** Two types of characterization factors are provided for agricultural water
524   consumption and of non-agricultural water consumption (Table 5), with usually higher CFs for
525   agricultural water consumption since scarcity is usually higher during periods with high irrigation
526   requirements. Damages per m^3 range from 0 to $4.4 \cdot 10^{-5}$, with monthly variation ranging from 0.15 to
527   3.46 of the annual average. Table 5 presents representative CFs for United Arab Emirates as an
528   example of a developed economy, with no national damage but high trade-induced damage. Tunisia
529   has intermediary impacts for both national and trade-induced damage. Nepal is an example for
530   developing countries with highest impacts for both national and trade-induced damage.

531

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

		CFs for agricultural water consumption [DALY/m³]		CFs for non-agricultural water consumption [DALY/m³]	
		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

563 terms of three levels (genes, species, ecosystems) and three attributes (composition, function,
564 structure), species richness was discerned as practical proxy and good starting point for assessing
565 biodiversity loss. However, complementary metrics need to be considered in modelling, such as
566 habitat configuration, inclusion of fragmentation and vulnerability (Teixeira et al. 2016).

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

574

575 ### 5.5.2 Description of selected indicators

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

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

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

599 taxon in that ecoregion. This vulnerability score is based on the proportion of endemic species in an
600 ecoregion and the threat level assigned by the IUCN red list.

601 The current approach to determine the impacts of land transformation is to take the regeneration time
602 of each land use type to return to the reference state into account, following Curran et al. (2014) and to
603 multiply the occupation impact by half of the reference time, as suggested in Milà i Canals et al.
604 (2007). Land transformation CFs are therefore also provided ad interim as the land occupation CFs
605 multiplied by the half of the estimated years for the ecosystem to regenerate without human
606 interference, based on a recent study from Curran et al. (2014). This approach is simplistic as linear
607 recovery is assumed and refinement would be beneficial and might be problematic in case of global
608 species disappearance. The reference state used in the model is referred to as natural undisturbed
609 habitat, which could be seen as synonymous with potential natural vegetation PNV. This is the mature
610 state of vegetation in the absence of human interventions (Chiarucci et al. 2010), which at times might
611 be challenging to identify. Using the PNV as a reference is better adapted to support decisions
612 considering long-term effects of land use policies, rather than shorter-term effects (Antón et al. 2016).

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

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

Land use type	occupation average regional [PDF/m²]	transformation average regional [PDF year/m²]	occupation average global [PDF$_{global}$/m²]	transformation average global [PDF$_{global}$ year/m²]
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}

621 **5.5.3 Recommendation and applicability**

622 The selected model and indicator builds on species richness, incorporates the local effect of different
623 land uses on biodiversity, links land use to species loss, includes the relative scarcity of affected
624 ecosystems, and includes the threat level of species. Global average characterization factors (CFs) are
625 interim recommended to quantify potential species loss (PSL) from land use and land use change,
626 suitable for hotspot analysis in LCA. It is strongly recommended not to use these CFs for comparative
627 assertions. Practitioner also need to be careful when using PSL and comparing it with other impact
628 categories in which the regional species loss is quantified without vulnerability score. A conversion

629 factor might have to be applied to the other impact categories for comparison with PSL, e.g. as
630 suggested by Chaudhary et al. (2006, Eq. 11.17).

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

637 ## 6. Application to a rice case study

638 A rice production and consumption LCA case study was developed and its inventory described in
639 detail by Frischknecht et al. (2016) to illustrate and test the applicability and practicality of the
640 recommended life cycle impact category indicators. It is not meant to be fully representative for rice
641 production and consumption in the regions covered. The life cycle inventory was established for three
642 distinctly different scenarios of producing and cooking rice, corresponding to three different regions:
643 1) Rural India - rice production of 3500 kg/ha consuming 0.826 m^3_{water}/kg$_{rice}$, processing, distribution
644 and three stone open cooking with firewood, all in rural India; 2) Urban China - rice production of
645 6450 kg/ha consuming 0.487 m^3_{water}/kg$_{rice}$ and processing in rural China, distribution and cooking in
646 electric rice cooker in urban China; 3) USA-Switzerland - rice production of 7452 kg/ha consuming
647 0.835 m^3_{water}/kg$_{rice}$ and processing in the USA, distribution and cooking in a gas stove in Switzerland.

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

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

661 *For impacts of fine particulate matter on human health*, figure 1c demonstrates the importance of also
662 including indoor sources of PM$_{2.5}$ and related health impacts in addition to outdoor-related impacts.
663 Indoor cooking with wood stoves (solid fuel combustion) makes the rural India scenario having by far

664 the highest impacts. Gas stove-related indoor air emissions have a much smaller but still important
665 contribution for the USA-Switzerland scenario. This calls for including relevant indoor emissions in
666 LCA case studies, which is further substantiated by Fantke et al. (2017). Outdoor related impacts are
667 mainly due to primary $PM_{2.5}$ and secondary $PM_{2.5}$ precursor emissions from rice production, thus the
668 importance to distinguish between rural and urban outdoor archetypes. These archetypes are able to
669 capture important variabilities in exposure between urban and rural areas, compared to currently
670 available spatial modelling approaches that lack a sufficiently high spatial resolution to capture these
671 differences at the global scale.

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

687 For impacts of land use, figure 1f shows that impacts are driven by agricultural land use, and to a
688 lesser extent by forest land use when fuelwood is used, and by urban land use in the US/EU scenario.
689 Higher impacts for rural India are not only due to low yield ratios but also to specific characteristics of
690 ecoregions. Therefore, the variation between scenarios also demonstrates the importance to include
691 production location in determining land use impacts. Though all scenarios have overlapping
692 uncertainty ranges and therefore differences between scenarios are not significant, the assessment
693 provide us with clear information about hotspots which need to be considered.
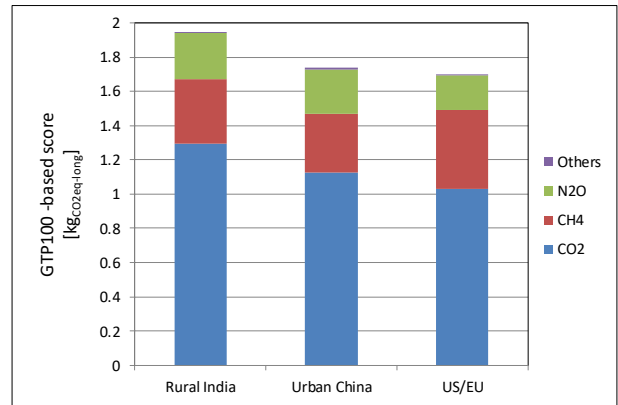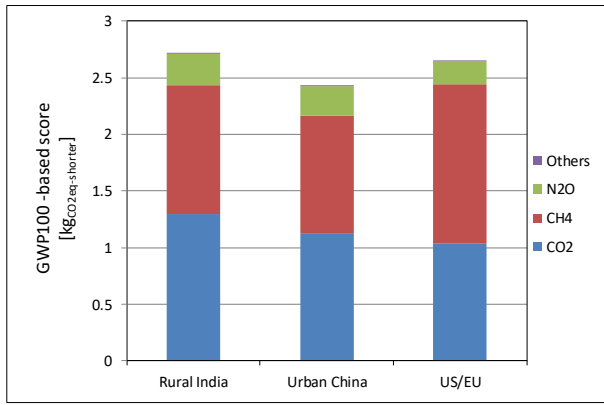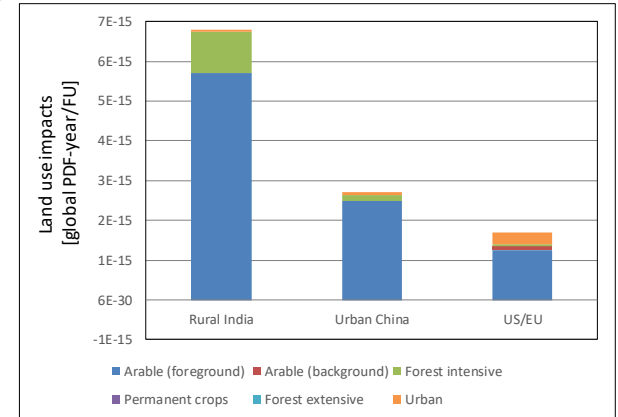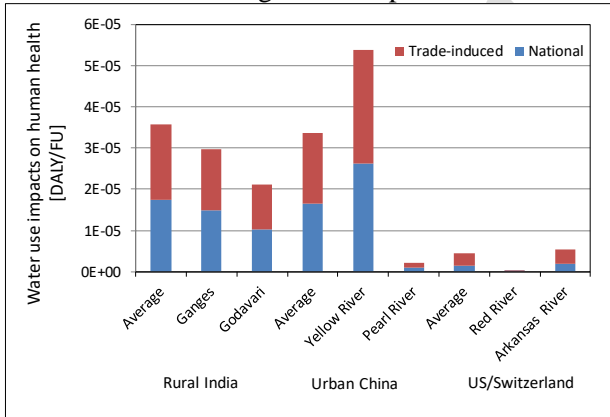
a) Climate change, shorter-term impacts based on GWP100 with climate-carbon cycle feedbacks

b) Climate change, long-term impacts based on GTP100 with climate-carbon cycle feedbacks
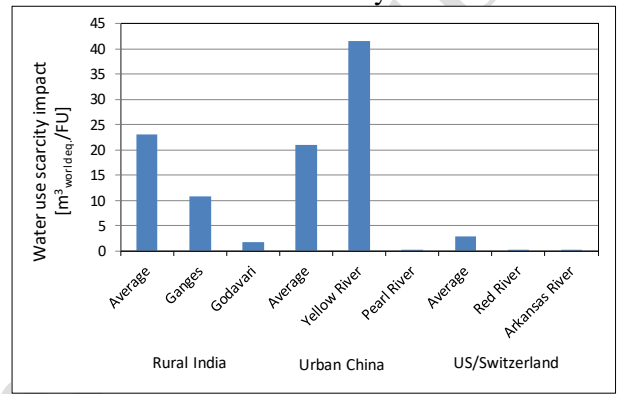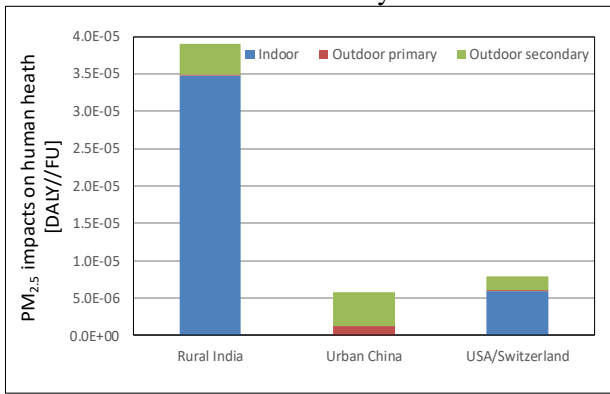
c) Impacts of fine particulate matter on human health based on average ERF slope

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.

694 Most of the recommended indicators cannot be easily compared nor aggregated across impact

695 categories, as they address different damage impact categories, unless they would be normalized and

696 weighted. The orders of magnitude of human health impacts associated with fine particulate matter

697 (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}

698 DALYs/kg$_{rice}$) can however be directly compared and fall in an overlapping range, demonstrating the

699 interest of damage oriented approaches and the importance to consider these two impact categories.

700 Since the case study aims at offering cooked rice, it is also interesting to compare the malnutrition

701 impacts of water consumption with the potential reduction in malnutrition impacts associated with the

702 3700 kcal (raw) produced per kg rice. Using the same health effect factor of 4.55×10^{-8} [DALY/kcal],

703 this potential reduction amounts to 1.7×10^{-4} [DALY/kg$_{rice}$], and is substantially higher than the impacts

704 of water consumption on human health.

7. Conclusions and outlook

706 The work and discussions before and during the Pellston Workshop^{TM} resulted in relevant

707 recommendations in the four topical areas climate change, fine particulate matter impacts, impacts of

708 water consumption and land use impacts, as well as on the updated LCIA framework and crosscutting

709 issues. The recommended characterization factors and impact category indicators include latest

710 findings of topical research and clearly go beyond current practice. The levels of recommendation

711 show the variable maturity of the indicators and their applicability domain (Table 1). At the same time

712 care has been taken to ensure immediate applicability in current LCA environments.

713 The present work was complemented by a review process in which the draft workshop report was sent

714 to 15 qualified reviewers , who had agreed to supply comments on the topical chapter related to their

715 area of expertise (reviewer list in section S3 of the supplementary information). Overall, the peer

716 review comments were positive and supportive of the effort to move toward global guidance for the

717 selected impact categories. However, some reviewers found it a bit premature for UNEP-SETAC to

718 position and endorse many of the indicators and concepts from the workshop as global guidance. In

719 particular, all indicators, as well as the revised framework, need to be further tested in terms of

720 practicality and scientific rigour, by engaging various experts and practitioners. The full peer review

721 report is available in Frischknecht and Jolliet (2016, p.157ff).

722 Such tests are also an important step to address potential concerns that such consensus processes may

723 raise, regarding the possibility to block scientific progress, hide uncertainty, or lead to

724 recommendation of immature methods, without enough contact with domain experts outside the LCA

725 community (Huijbregts, 2014). The present consensus building effort was therefore organized to

726 stimulate the involvement of experts outside the LXA community, with e.g. close to half of the climate

727 change TF composed of climate scientists or authors of the IPCC 5th assessment report who were not

728 directly involved in LCA. For aa categories, involvement of well-recognized experts was secured via

729 targeted workshops (see e.g. Fantke et al. 2014 for the human health impacts of fine particulate

730 matter). The process has stimulated progress for LCA practice, e.g. with the development of the new

731 water scarcity index AWARE, making data at watershed and monthly levels available for

732 practitioners. It has also facilitated the inclusion of human health effect of PM by making assessment

733 factors available, and discussing their variations between global, continental and city specific levels.

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

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

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

770 (life below water – water scarcity impacts), and SDG 15 (life on land – land use impacts on
771 biodiversity).

772 **8. Acknowledgements**

799

800 **9. Supporting documents**

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

803

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1010 **Fig.1** Impact scores per kg cooked white rice for the rural India, urban China and USA-Switzerland
1011 scenarios, to illustrate and test the recommended LCIA indicators for climate change, fine particulate
1012 matter impacts, water and land use impacts. These results are not meant to be representative for rice
1013 production and consumption in the covered regions

1014 a) Climate change, shorter-term impacts based on GWP100 with climate-carbon cycle feedbacks

1015 b) Climate change, long-term impacts based on GTP100 with climate-carbon cycle feedbacks

1016 c) Impacts of fine particulate matter on human health based on average ERF slope

1017 d) Water scarcity impact using AWARE

1018 e) Impacts of water consumption on human health, accounting for national and trade effects

1019 f) Land use impacts on global biodiversity