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UNEP/SETAC Life Cycle Initiative

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Abstract

Background, Aims and Scope. Life Cycle Impact Assessment (LCIA) methods can be grouped into two families: classical methods determining impact category indicators at an intermediate position of the impact pathways (e.g. ozone depletion potentials) and damage-oriented methods aiming at more easily interpretable results in the form of damage indicators at the level of the ultimate societal concern (e.g. human health damage). The Life Cycle Initiative, a joint project between UNEP[1] and SETAC[2], proposes a comprehensive LCA framework to combine these families of methods. The new framework takes a world-wide perspective, so that LCA will progress towards a tool meeting the needs of both developing and developed countries. By a more precise and broadly agreed description of main framework elements, the Life Cycle Initiative expects to provide a common basis for the further development of mutually consistent impact assessment methods.

Main Features. Inputs to the LCIA midpoint-damage framework are results of Life Cycle Inventory analyses (LCI). Impact pathways connect the LCI results to the midpoint impact categories with the corresponding indicators, as well as to the damage categories at the level of damages to human health, natural environment, natural resources and man-made environment, via damage indicators. Midpoint impact categories simplify the quantification of these impact pathways where various types of emissions or extractions can be aggregated due to their comparable impact mechanisms. Depending on the available scientific information, impact pathways may be further described up to the level of damage categories by quantitative models, observed pathways or merely by qualitative statements. In the latter case, quantitative modelling may stop at midpoint. A given type of emission may exert damaging effects on multiple damage categories, so that a corresponding number of impact pathways is required. Correspondingly, a given damage category may be affected jointly by various types of emissions or extractions. It is therefore an important task of the Life Cycle Initiative to carefully select damage indicators. The content of the midpoint and of the damage categories is clearly defined, and proposals are made on how to express the extent of environmental damage by suitable indicator quantities.

Conclusions and Outlook. The present framework will offer the practitioner the choice to use either midpoint or damage indicators, depending on modelling uncertainty and increase in results interpretability. Due to the collaboration of acknowledged specialists in environmental processes and LCIA around the globe, it is expected that – after a few years of effort – the task forces of the Life Cycle Initiative will provide consistent and operational sets of methods and factors for LCIA in the future.

Keywords: Damage category; impact pathway; life cycle impact assessment (LCIA); Life Cycle Initiative; midpoint category; SETAC; UNEP

1 Background, Aims and Scope

Life Cycle Impact Assessment (LCIA) methods aim to connect, to the extent possible, emissions and extractions of life cycle inventories (LCI-results) on the basis of impact pathways to their potential environmental damages. Impact pathways consist of linked environmental processes, and they express the causal chain of subsequent effects originating from an emission or extraction.

According to ISO (2000), LCI results are first classified into impact categories. A category indicator, representing the amount of impact potential, can be located at any place between the LCI results and the category endpoint. Based on this format, two main schools of methods have developed:

a) Classical impact assessment methods (e.g. The Dutch Handbook: Guinée et al. 2002, EDIP: Hauschild and Wenzel 1998 and further adaptations, TRACI: Bare et al. 2003) that stop quantitative modelling before the end of the impact pathways and link LCI results to so-defined midpoint categories, e.g. ozone depletion or acidification. However, depletion of the ozone layer, as expressed by a corresponding midpoint category indicator such as ozone depletion potential, is an environmental concern in itself, but the larger concern is usually the subsequent damages to humans, animals and plants.

[1] United Nations Environment Programme
[2] Society for Environmental Toxicology and Chemistry

b) Damage oriented methods (e.g. Ecoindicator 99: Goedkoop and Spriensma 2000, EPS: Steen 1999) which aim at LCA outcomes that are more easily interpretable for further weighting, by modelling the cause-effect chain up to the environmental damages, the damages to human health, to the natural environment and to natural resources. These may be expressed for example in additional cases of human health impairment or species endangerment, enabling to reduce the number of considered endpoints in making different midpoints comparable. They can, however, lead to high uncertainties.

Although users may choose to work at either the midpoint or damage levels, a current tendency in LCIA method development aims at reconciling these two approaches. Both of them have their merits, and optimal solutions can be expected if the 'midpoint-oriented methods' and the 'damage-oriented methods' are fitted into a consistent framework (Bare et al. 2000). Certain methods of this type were recently made available (Impact 2002+: Jolliet et al. 2003a, The Japanese LIME method: Itsubo and Inaba 2003) or will soon be finalized (the Recipe project: Heijungs et al. 2003). Furthermore, the Vienna workshop 2003 of the UNEP/SETAC Life Cycle Initiative (described below) started a process amongst international LCIA specialists with the aim of consolidating this joint framework. The following questions need to be examined:

- How can midpoint-oriented approaches be combined with damage-oriented approaches in a common and consistent framework?
- How can damages be related to 'areas of protection', and their intrinsic and functional values (definitions of these terms in Chapter 8 of Udo de Haes et al. (2002))?
- What are the criteria to properly describe impact pathways?
- What are the main achievements and gaps in the different midpoint and damage categories?

The 'Life Cycle Initiative', a joint project between UNEP and SETAC, has nominated an international task force with the aim to develop answers to the aforementioned questions and determine a common framework for 'midpoint-oriented' as well as 'damage-oriented' LCIA methods. This task force takes a worldwide perspective, including all bio-geographic regions of the globe. The common framework is expected to provide assistance to LCIA method developers, because they can profit from embedding their proposals into an overarching structure that is generally accepted on all continents. While facilitating the inclusion of new impact categories that may be specific for developing countries, this framework will also provide a basis to analyse and compare existing and emerging methods, with the goal to establish recommended characterisation factors and related methodologies for different impact categories, possibly consisting of sets at midpoint and at damage level (Stewart and Jolliet 2004). To achieve this, the Life Cycle Initiative first appointed a draft author team to write an LCIA definition study (Jolliet et al. 2003b) with an extensive review process led by T. McKone and M. Hauschild. Based on this initial work the initiative has now nominated an international task force on *LCIA information system* lead by T. Gloria to further develop this framework. Written in the context of the present task force, this paper presents the main features of the framework proposed in the LCIA definition study, and develops it further to ensure a consistent description of midpoint and damage categories.

The main elements of this framework are described in the following sections, starting with the general framework description, structuring both midpoint and damage approaches of LCIA in a consistent way. Individual midpoint impact categories and damage categories are then discussed. More details on midpoint and damage categories are given in the LCIA definition study (Jolliet et al. 2003b).

2 General Description of the LCIA Framework

To implement the connection between LCI results and environmental[3] damages LCI results with similar impact pathways (e.g. all substance flows reducing stratospheric ozone concentration) are classified into impact categories at midpoint level, also called midpoint categories. For each LCI result, an indicator value is calculated per midpoint category, characterising the LCI result according to its specific contribution to the common impact. The term 'midpoint' expresses that this point is located on the impact pathway at an intermediate position between the LCI results and the ultimate environmental damage (often referred to as endpoints). As a consequence, an additional step may allocate these midpoint categories to one or more damage categories, the latter representing quality changes in the environment which are the ultimate object of society's concern. A damage indicator is the quantified representation of this damage. In practice, a damage indicator is always a simplified model of a very complex reality, giving only an approximation of the quality status of the damaged entity.

Fig. 1 shows the overall scheme of the proposed framework, linking all types of LCI results via the traditional midpoint categories to the damage categories. An arrow means that a 'relevant' impact pathway is currently known or assumed to exist between the two corresponding elements. The midpoint categories and arrows shown in Fig. 1 give an initial view of the relevant impacts, but this may change under the influence of additional insights. A short summary on each midpoint category is given in section 4.

[3] Environment is taken here in a broad sense, including biotic and abiotic environment, mankind and man-made environment.

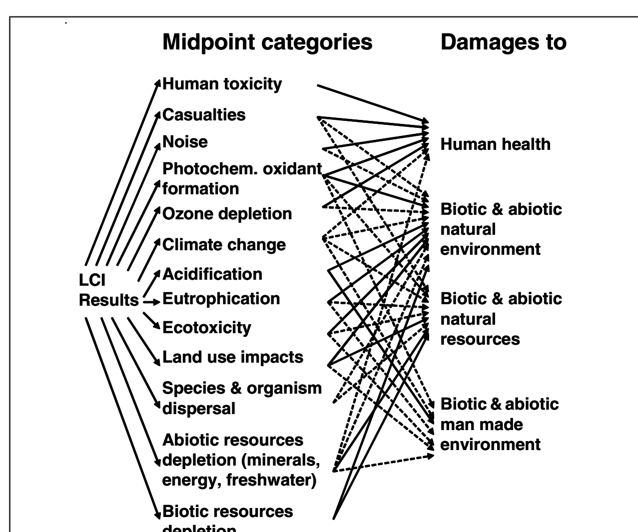

Fig. 1: General structure of the LCIA framework (adapted from Jolliet et al. 2003b). Solid arrows indicate that a quantitative model is available; dashed arrows indicate that only uncertain or qualitative relationships are known

It would be desirable to draw quantitative impact pathways up to the damage categories, connecting each type of LCI result with a relevant damage contribution to the corresponding damage categories. For the time being, this ambitious task cannot be attained for all types of impacts, mainly due to current limits of scientific knowledge. Since midpoints have often been chosen at a point where further modelling was considered to become too uncertain, currently available information on the last sections (between midpoint and damage level) of some impact pathways may be particularly uncertain or lacking agreement. This is expressed by dashed arrows in Fig. 1. Whilst modelling of quantitative impact pathways currently appears to be possible in the case of solid arrows, the implementation of the dashed arrows may consist, as a minimum, in a qualitative description of the influence of the corresponding midpoint indicator on the expected increase in damage at the level of the damage category. The LCIA framework will therefore contain a coordinated mix of a) fully quantitative links from LCI results up to damage indicators going via midpoints and b) fully quantitative links only up to midpoints, with complementary qualitative information on the expected influence of the midpoint indicators on their respective damages. This complementary qualitative information is needed for an adequate evaluation of midpoint indicator values at the level of the LCA interpretation phase.

In addition to the abovementioned midpoint categories, soil salinity, soil dessication and soil erosion are issues of high interest, especially in developing countries. These impacts are mainly linked to the types of land use and freshwater use, which can lead to increases in soil salinity. Further clarifications are required to determine the exact status of these impacts and to see if they can be addressed within the land use impact and freshwater depletion categories or if they require separate midpoint categories. It should be noted that for some midpoint categories, it may be necessary to divide the impact category into a number of subcategories, as aquatic or terrestrial eutrophication and aquatic, terrestrial or marine ecotoxicity. The exact structuring will certainly be subject to further improvement in parallel with modelling progresses. In some cases, there can be relevant interactions between different midpoints. Thus, it is very important to state whether overlaps or any links between midpoint indicators are taken into account in the modelling of pathways starting from the LCI level. Otherwise it would be necessary to introduce explicit overlapping pathways in Fig. 1 between different midpoints. If the interpretation phase of LCA has to be conducted at the level of midpoint indicators, this overlapping aspect needs to be considered to avoid double counting. If damage indicators are available for the interpretation of the results, the overlap effect must be taken into account by the model developers who design the models and links between midpoints and damages.

Traditionally, LCA was mostly limited to those environmental damages which are grouped in Fig. 1 under the damage categories: damages to human health, to biotic natural environment (occurrence of species) and to abiotic natural resources (ores, energy carriers, freshwater and soil). The framework makes it possible to include other damage categories: for this, Fig. 1 also shows the damages to man-made abiotic & biotic environment (buildings and crops), to biotic natural resources (wild animals and plants, if used by humans), as well as to the abiotic natural environment (non-resource materials, structures and non-living landscape elements). The content of each of the damage categories is discussed in more detail in Section 5. Within the Life Cycle Initiative, in order to build on the existing strengths of LCA, and particularly its basis in scientific rationality, the initial focus is on the first three traditional damage categories. For some categories such as human toxicity and ecotoxicity, the distinction between midpoint and damage is difficult to define, as there is not a clear common pathway from midpoint to endpoint. In some cases of modelling at the damage level several pathways could also be better modelled without involving indicators at the midpoint level.

Damage categories in Fig. 1 are grouped according to the different areas of protection, human health, natural environment, natural resources and man-made environment. These areas of protection, also called safeguard subjects, represent operational groups of subjects (humans, biotic, abiotic and built environment) of direct value to human society. The damage categories group damages to these areas of protection and are retained as the main basis for further classification.

In view of harmonising with the conceptual structure of LCIA as presented in Chapter 8 of the SETAC publication 'Life-Cycle Impact Assessment – Striving towards best practice' (Udo de Haes et al. 2002), the damage categories are structured in the upper part of **Table 1** according to:

- area of protection: human health, natural environment, natural resources and man-made environment,
- physical objects concerned: human life, biotic and abiotic environment, and
- different modes of values involved: intrinsic and functional values.

In particular, this leads to a differentiation of damages into damages related to an intrinsic part of the considered subjects (value of healthy life years as such; biotic and abiotic natural environment) and damages related to a functional part of the subjects (value of humans as an economic production factor; biotic and abiotic natural resources). Here, functionality is defined as valuable because it enables us to achieve other goals; whereas, intrinsic is considered to be valuable completely for the sake of its existence, and not for what the object or person can accomplish. It should be noted that not all area of protection can be easily labelled as either intrinsic or functional, but may serve both functions. The corresponding differentiation of damages to man-made environment would lead to further damage categories representing the intrinsic value of cultural heritage. For the sake of simplicity the latter is not included in Table 1.

In Table 1, the links between midpoints and damage categories are indicated in a more detailed manner than in Fig. 1, because of the horizontal subdivision into eight damage categories, and of the vertical split into resource types. Note that both Fig. 1 and Table 1 are edited versions of similar figures and tables included in the definition study (Jolliet et al. 2003b). This has been done to improve consistency in the midpoint and damage category description.

The lower part of Table 1 shows the midpoint categories and the relevant links to the damage categories. Links '(x)' in brackets would only become relevant if the correspond-

Table 1: Overview of damage categories, midpoint categories and their links, adapted from Jolliet et al. 2003b. '⊗' indicate relevant links that could be quantitatively modelled, 'x' other relevant links, '()' indicate that these links are only relevant if the corresponding damage category were included in LCA[a]

Subjects considered	Human life		Biotic environment			Abiotic environment		
Damages related to intrinsic values	Human health (intrinsic)		Biotic natural environment (species)			Abiotic natural env. (e.g.rapids)		
Damages related?to functional values		Human health (labour)		Biotic nat. resources (e.g. tuna)	Man-made biotic envir. (e.g. crops)		Abiotic nat. resources (e.g. water)	Man-made abiotic envir. (e.g. houses)
Midpoint categories								
Human toxicity	⊗	(x)						
Casualties	⊗	(x)	x	(x)				
Noise	⊗	(x)	x	(x)	(x)			
Photooxidant formation	⊗	(x)	⊗	(x)	(x)			
Ozone depletion	⊗	(x)	x	(x)	(x)			
Climate change	x	(x)	x	(x)	(x)			(x)
Acidification			⊗	(x)	(x)			(⊗)
Eutrophication			⊗	(x)	(x)			
Ecotoxicity			⊗	(x)	(x)			
Land use impacts			⊗	(x)	(x)	x	⊗	
Species and organism dispersal			x	(x)	(x)			
Abiotic resource depletion								
Metallic minerals .							⊗	
Other minerals							⊗	
Energy			x	(x)	(x)	x	⊗	
Freshwater	x	(x)	x	(x)	(x)	x	⊗	
Biotic resources depletion			⊗	(⊗)	(x)			

[a] The names of the damage categories have been abbreviated in Table 1. Strictly speaking, the damage categories are **damages to** human health, **to** the biotic natural environment, etc.

ing damage category were included in LCA, which is initially of lower priority within the Life Cycle Initiative. Resource types 'energy ' and 'freshwater ' may include stock resources and flow resources. In the case of flow resources, the use causes no damage to the resource itself, but other damage categories may be involved (e.g. water harnessing from rivers causing damages to aquatic species).

In the context of Table 1, the notion of 'Life Support Function' (LSF) could also be introduced as an additional concept to help understanding of the value judgement inherent in some midpoint categories. According to Udo de Haes et al. (2002), LSFs are major regulating functions within the environment that enable a life on earth that could also deserve to be protected. Particular LSFs are: climate regulation, hydrological cycles and soil fertility. For example, climate equilibrium can be considered as having an intrinsic value deserving to be protected from damage. As suggested by Heijungs et al.(2003), LSFs then play a role at midpoint level similar to areas of protection at damage level: LSFs could be considered as safeguard subjects at midpoint level, representing operational groups of items of value to human society for some midpoint categories. While the exact status and role of LSFs needs to be further clarified (for further explanations refer to Udo de Haes et al. 2002), it can presently be recognised that the LSF concept helps to make explicit the values behind some of the midpoint categories, as global warming, and therefore aids the performing of a proper weighting exercise at that level, if appropriate and desired. It can further be acknowledged that LSFs have an intermediary character compared to human health and natural environment, as damage to climate regulation, for example, could generate further damages to human and non-human life.

3 How to Describe Impact Pathways

Impact pathways connect LCI results across midpoints to one or more damage category(ies). An example for the structure of such impact pathways is shown in **Fig. 2**, linking the emission quantities of ozone depleting gases to two types of morbidities, whose severity, duration and number of cases can be quantified as a damage indicator, expressed e.g. in Disability Adjusted Life Years (DALYs), representing the intrinsic part of human health damage.

The full description of an impact pathway should contain the following main elements:

- the structure, indicating the starting link, the intermediate links and the final link(s), presented as far as possible as well defined modules,
- the indicators and corresponding units by which the input and the output of each pathway link are expressed,
- as far as possible, the marginal transfer function of each pathway link, giving the number of additional output units per one additional input under applicable background conditions,
- information on model sensitivity, on model, data and parameter uncertainties and on verification against measured data,
- information on time lags and on the relevant spatial scale,
- reference to supporting scientific documentation for the environmental process modelled.

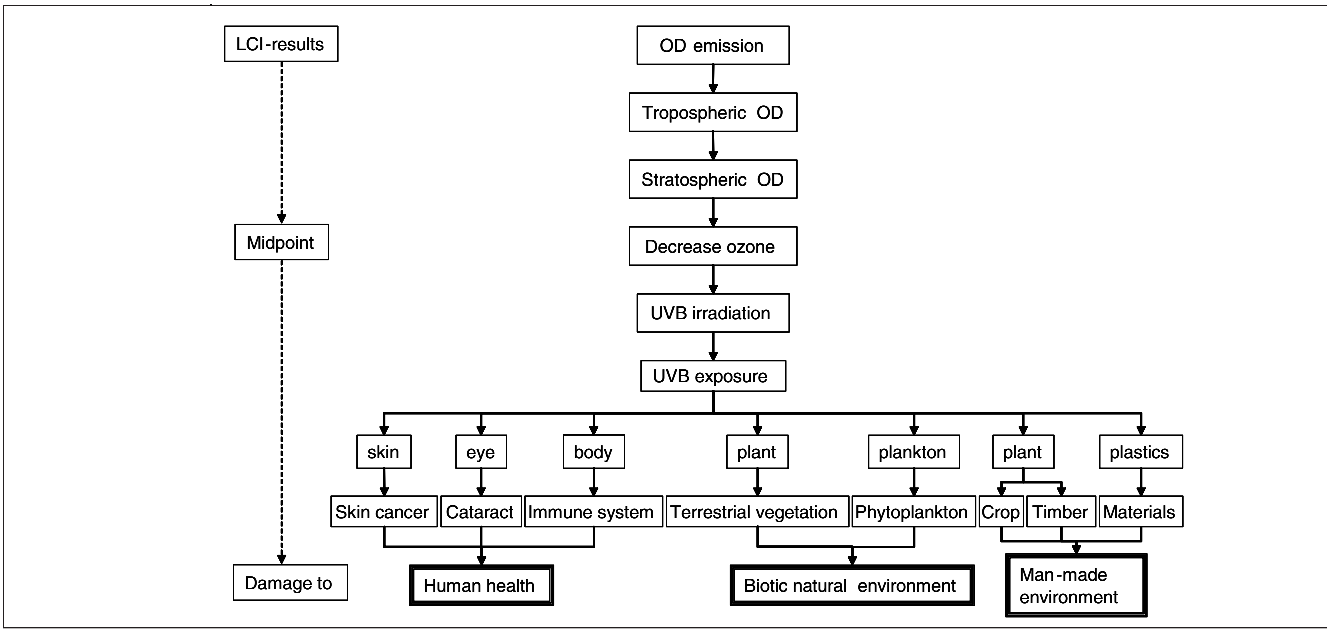

Fig. 2: Example of a pathway structure linking ozone depleting emissions to impacts on human health, biotic natural environment and man-made environment (adapted from Itsubo et al. 2004)

A preliminary checklist for impact pathway descriptions has been provided by Jolliet et al. (2003b). Depending on the current extent of knowledge, the representation of a pathway link may vary from a fully quantitative description to a short qualitative description of the expected causal impact on subsequent pathway links.

For a comprehensive environmental judgement including all damages, the decision maker may want to execute an implicit or explicit weighting of the various impacts or damages, which involves a number of value judgements: There is no scientific procedure for finding the 'right' exchange ratio between e.g. a lost year of human life and the loss of a plant species through extinction. On the one hand, providing recommended weighting factors is clearly not part of the Life Cycle Initiative project, as the UNEP policy explicitly leaves value judgments to users. On the other hand, guidance needs to be provided to users on how to derive consistent weighting procedures and sets of weighting factors for LCIA results.

4 Midpoint Categories

The 13 midpoint categories shown in Fig. 1 and Table 1 need to be addressed according to the present state of the art:

- A first group of relatively well-established midpoints based on common impact mechanisms, where there is a good level of agreement on how to determine meaningful midpoint indicators for all types of LCI results that may be linked to the respective midpoint. Midpoints of this group are: photooxidant formation, stratospheric ozone depletion, climate change, acidification and aquatic eutrophication. Here, there is a need for adapting latest knowledge from other scientific communities focusing on environmental modelling to the assessment of Life Cycle Impacts linked to functions and products. The *task force* of the Life Cycle Initiative on *transboundary impacts* will also cover terrestrial eutrophication and particles in collaboration with the toxicity task force, including the consideration of spatial aspects. The group expects to consolidate current practice as well as to contribute to further development in collaboration with experts from different fields where necessary.
- For other midpoints that often comprise different impact mechanisms, it is less clear how to define midpoint indicators and how these indicators could be determined quantitatively for the relevant types of LCI results. Partially, as a consequence, some of these midpoints have often been ignored in LCA practice. Here, the Life Cycle Initiative expects to contribute to the development of concepts and practical solutions that are supported by a reasonable degree of consensus. *The toxicity task force* of the Life Cycle Initiative has already established a matrix structure as a flexible framework for Life Cycle Toxicity Assessment. This will be the basis upon which to establish libraries of processes and matrix factors of substance data and estimation tools, and of geographic data (landscape data, etc.). Another *task force* focuses *on natural resources and land use*, and an initial workshop will be conducted at the Fourth SETAC World Congress in Portland in November 2004 in order to create the basis and initial consensus on the impact pathway framework, later leading to more defined and dedicated tasks.

For each of these midpoints, some key questions to be examined are mentioned below: This section briefly discusses the scope of each category and the main challenges to be addressed within the Life Cycle Initiative. A more detailed description is available in Jolliet et al. (2003b), where the background document III is dedicated to midpoint categories. Udo de Haes et al. (2002) and Pennington et al. (2004) also provide additional information.

Human toxicity. Three types of information are relevant when assessing toxicological impacts on human health: chemical fate (transport and transformation in the environment), human exposure, and toxicological effects (dose-response information such as those on which Lowest Observable Effect Level or Reference Doses are based on). In spite of advances in terms of accounting for differences in the emission scenarios (e.g. location, dispersion), current estimates generally provide preliminary or screening insights only, with high uncertainties. In a review workshop organised within the Life Cycle Initiative (UNEP 2003), experts have recommended a common matrix framework for fate, exposure and effect, as a foundation of a tiered modelling approach based on the development of components for a detailed model and a more simplified but compatible base model with lower data requirements, thus allowing its application to more substances. Within this flexible framework, the next steps include the development of libraries of environmental processes and matrix factors, of substance data and estimation tools, and of geographic data. Further efforts will also include a) a review of proposals on a human toxicity indicator in the base model, including dose-effect response and severity, b) improved assessment of metals, including speciation, essentiality and bioavailability, c) quantification of uncertainty (model, parameter, and scenario) associated with different estimates, d) studying the feasibility to identify morbidity endpoints for humans and to extend consequence measures, such as DALYs per incidence, to non-cancer effects, e) addressing the ability to deal with multiple effects which occur from single chemicals (e.g., the most severe effects vs. the lowest concentrations causing effects) and addressing the combined effects of various mixtures, f) the development of simplified methods that can be readily applied for screening with low quality/amounts of data, in a compatible way with more advanced models, and g) further investigation of the scope of the category regarding indoor emissions, worker health, accident statistics, ionising and non-ionising radiation.

Casualties. So far, very few LCAs have considered accidents by physical impacts. However, neglecting damages to human health due to accidents over the life cycle of a product could lead to biased decisions, if no other tools are applied in parallel (e.g. risk assessments) Accidents can be described, for example, by an extent and a probability distribution. A possible way to deal with accidents in LCA is to split the events contained in the extent-probability distribution into two domains. On the one hand, accidents causing restricted damages (e.g. some accidents associated with transports), normally accompanied by higher probabilities, should be recorded in LCI based on accident statistics and could eventually be directly taken into account at damage level. A special form of these accidents are the occupational accidents causing direct injury or death to workers operating in certain processes in the life cycle. On the other hand, for the rare accidents causing extensive damages, it no longer makes sense to assume the LCA-typical linear relationship between emission and impacts and these may give rise to supplementary impact categories. The current challenge is to agree on the inclusion of accidents in general in LCA vs. dealing with accidents in parallel via other tools and approaches, based on consistent criteria for inclusion or non-inclusion of accident types in LCA. It is also interesting to explore whether it is feasible and practical to define a corresponding midpoint with its indicator, or if it is preferable to model a direct link from LCI results to the damage categories (essentially human health).

Noise. Traffic noise also affects human health (Mueller-Wenk 2002). The current challenge is to develop, on the basis of available knowledge, quantitative impact pathways to a possible midpoint or directly to the human health damage. Inventories so far do not contain data on noise emissions, proposals for the format of noise-relevant data in LCI need to be prepared.

Photochemical oxidant formation. Photochemical smog is caused by the reaction of volatile organic compounds (VOCs) and NO_x in the troposphere, both natural and man-made, with reactive oxygen forms, particularly hydroxyl radicals, which are formed in the presence of sunlight. Ozone (an important component of smog) is a toxic gas which has been shown to cause respiratory distress in people and other mammals, as well as causing reduction in the primary production rates of plants. Two types of models have mostly been used to analyse midpoint indicators for smog. The Northern European model is based on the calculated photochemical ozone creation potential (POCP), and measured in ethylene units. The model used in the United States is based on the Maximum Incremental Reactivity (MIR), and is measured in units of O_3. Care should be taken to include the impact of NO_x appropriately. Attention should be paid to ensure consistent approaches between this impact category and the human toxicity and ecotoxicity categories. These methods should be evaluated regarding specific LCIA requirements, leading to recommendations eventually dependent on generic situations and data availability.

Ozone depletion. Several dozen, mostly man-made, compounds released to the air have a known effect of reducing stratospheric ozone concentrations (see Fig. 2 for the impact pathway of ozone depleting substances on humans). The consequence is an increase of solar radiation, particularly UVB, on the earth's surface. We note here that LCIA for ozone depletion must build on the expertise from other scientific fields. Therefore, the challenge here, as well as in other categories, is to learn how to extract the information that is relevant and informative for LCIA from complex assessments in other fields.

Climate change. The impact pathways of greenhouse gases include temperature rise, changes in precipitation, sea level rise, change of ocean currents, storms, hurricanes and possibly others, eventually leading to impacts on human health and biotic natural environment and resources. All of these types of impacts depend on changes in radiative forcing in the atmosphere (expressed as Wm^{-2}). This category offers the opportunity for a science-based midpoint indicator, related to the well-known Global Warming Potential (GWP). Climate equilibrium can be considered as a life support function to be protected as such: the capacity of the environment to provide the conditions for a long-term stability of climate on earth. This could help making explicit the values behind such a midpoint indicator, if interpretation and weighting is performed at a midpoint level. Alternatively, an important activity is to model or at least describe the related damages on ultimate areas of protection. Here, inputs from IPCC (Intergovernmental Panel on Climate Change) could be highly relevant as well as developments from the Japanese national LCA project to help interpreting the resulting damages. There are a number of climate change models that characterise what we in LCA call damage, IPCC recommending a multiple-model approach due to high uncertainties. In addition to the choice of a time horizon, an important challenge here is how to best use existing models for LCIA.

Acidification. Through oxidation and hydrolysis, a number of atmospheric gases as sulphur dioxide and nitrogen are transformed to acidifying substances. These acids can be deposited as dust (dry deposition) or dissolved in precipitation (wet deposition) and may cause undesirable effects on terrestrial and aquatic ecosystems (decrease of pH, detrophication of soils), man-made resources and even human health. For this category as well as for other transboundary impacts, it is of high importance to rely on the expertise and timely contribution of various experts from different fields. Present methods take advantage of models as RAINS (Regional Acidification Information and Simulation) and underlying models and data from EMEP (Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air pollutants in Europe) for Europe and NAPAP (National Acid Precipitation Assessment Program) for North America to develop acidification fate and transport. When developing the link between midpoints and damages it is the ambition to further establish contacts with related scientific communities working e.g. on Integrated Assessment Models (IAM), and with experts of the scientific network under the UNECE convention on Long-Range Transboundary Air Pollution (United Nations Economic Commission for Europe). The primary aim is to get external input towards recommended practice, but a secondary interest is to further explore the interfaces between LC(I)A and integrated models.

Eutrophication. Nitrogen and phosphorus are essential nutrients required for life, but, in excess, these substances cause eutrophication. It is necessary to subdivide the impact category into aquatic and terrestrial eutrophication. The increase of these nutrients in water areas contributes to the increased growth of phytoplankton, and may cause algae blooms. Reduced oxygen availability and decreased transparency of the water causes reduction of fish populations. Attention should be paid to the potential of three groups of modelling methodologies (simple aquatic biomass growth, aquatic biomass growth combined with fate models, or damage modelling) to deliver outcomes desired for this impact category. Only one of the two nutrients will normally be limiting in a given water body, typically phosphor in fresh waters and nitrogen in marine water. The larger part of airborne emissions will be deposited on land where basically only nitrogen contributes to terrestrial eutrophication, since natural land is typically not limited by phosphor. The present attitude is therefore to explicitly consider them as two separate impact subcategories. Attention should be paid to ensure consistent approaches between eutrophication and the acidification and ecotoxicity impact categories.

Ecotoxicity. It is generally accepted that populations of non-human life may be substantially threatened by chemical emissions, although the toxicological knowledge is much more fragmentary than in the case of human toxicity, due to the enormous diversity of animals and plants. In many respects, ecotoxicity is treated similarly to human toxicity, and a common matrix framework can be retained. There are, however, some differences. The level of concentration for ecotoxicity is often taken as an interface between fate and effect. In general, exposure is implicitly taken into account in the effect factor, whereas intake through food needs to be better adressed. Expert workshops carried out in collaboration with the Life Cycle Initiative have led to several recommendations (UNEP 2003: Ligthart et al. 2004): As LCA is used for comparative rather than predictive purposes or determination of absolute risk, it is appropriate to use robust measures of toxicity rather than the lowest measures of toxicity, which are generally interpolated rather than directly measured. On this basis, the characterisation factor is recommended to be chosen at the HC50[4] (geometric mean of EC50[5]) level rather than at the HC5[6] or the NOEC[7] level. Specific recommendations on how to account for metal speciation, bioavailability and essentiality of metals were made available in the Apeldoorn declaration (Ligthart et al. 2004). Another challenge is to agree on a suitable damage indicator at the level of 'biotic natural environment' at which the impact pathway ends. It may be necessary to divide the impact category into a number of subcategories, like aquatic, terrestrial or marine ecotoxicity.

Land use impacts. Usage of land surfaces for anthropogenic processes is recognised to be a primordial threat to species and ecosystems, and generic inventory data bases have begun to register information on land use. A great challenge is the location dependency of the damaging effects of a given type of land use. In spite of many proposals, there is no agreed model of land use impacts available. However, the availability of high resolution satellite based data (AVHRR: Advanced Very High Resolution Radiometer) on the earth's land cover seems to offer a reasonable basis for the development of a globally applicable, location-oriented assessment model for the most significant land use types. Such a model may either yield indicator values at midpoint level, or may directly express effects at the level of the damage category 'biotic natural environment'. According to Fig. 1 and Table 1, land use also has a relevant damaging impact on 'abiotic natural resources' (soil, water) and 'abiotic natural environment' (landscape structure), which needs to be substantiated. In addition, the type of land use is of significance specifically in developing countries, in addition the assessment of impacts on soil salinisation, dessication and erosion.

Species and organism dispersal. The dispersal of invasive species due to anthropogenic processes may result in substantial changes in animal and plant populations in the invaded region. The impact is to some extent similar to (but less controllable than) the effects of agricultural land use: New species occupy locations that were previously occupied by other species. The resulting direct impact (midpoint category) is an altered species composition. So far, the main challenge is to find a sound basis for determining under what circumstances it is a relevant damage in the damage category 'biotic natural environment' if the pre-existing pattern of species is substituted by newcomers as a result of human activities. If considered relevant, the dispersal of genes introduced via genetically modified organisms can be modelled in the same way as dispersal of natural species.

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[4] HC50: Hazardous concentration affecting 50% of the species over their chronic EC50

[5] EC50: Effect concentration affecting 50% of tested individuals

[6] HC5: Hazardous concentration corresponding to the 5th percentile of the cumulative frequency distribution of chronic NOECs

[7] NOEC: No Observable Effect Concentration

Abiotic resource depletion. Use of abiotic natural resources (mainly metallic and non-metallic ores/minerals, energy, freshwater) is seen as an environmental damage because the exploited resource generally leaves the system of anthropogenic processes in a degraded form, so that the resource loses its potential to deliver the functionality for which it is desired. The corresponding threat to future humans is more serious where the available stock of virgin, non-degraded resource is comparatively small (relative scarcity) and where non-reversible effects are observed. This concept places the emphasis for the definition of this impact category on the ultimate form of the resource leaving the system and its remaining potential to deliver the functionality for which it is desired; as opposed to focussing on resource extraction. The applicability of these concepts to LCIA need to be verified and compared to previous methods, and the manner in which resource use is quantified in the inventory needs to be better defined in most cases. One of the current challenges is to describe the impact pathway from resource use at LCI results level up to the damage category of 'abiotic natural resources' in such a way that agreement can be reached in principle, even if undiscovered stocks and future technologies are not fully known. Specific problems of the resource types of freshwater and soil are connected with the fact that their geographical location on the earth's surface is an important descriptor of their quality: Freshwater in Iceland is not the same as freshwater in Saudi Arabia, and soil in the US Midwest is not the same as soil in the Mississippi delta. The resource impact category is especially crucial for developing countries, where a large part of resource extraction takes place. Developing the assessment of related impacts on soil quality such as salinisation, dessication and erosion is essential to contribute to avoiding relevant impacts in these countries.

According to Table 1, abiotic resource depletion also has impact links to 'human health', 'biotic natural environment' and 'abiotic natural environment', this being particularly relevant in the case of freshwater extraction from rivers. It is a significant challenge to agree on the modelling of the respective impact pathways in quantitative or qualitative form.

Biotic resource depletion. Many wild plants and animals are hunted and used by humans for various purposes, and at least certain edible marine fish species and precious woods can be seriously endangered because their reproduction rates cannot cope with the annual extractions. At this stage, it is intended as a first step to identify the impact pathways originating from biotic resource use.

5 Damage Categories and Damage Indicators

The core idea of the presented LCIA framework is to assess the LCI results with respect to quality changes caused at midpoint level and/or at damage level. It offers the practitioner the choice to use either midpoint or damage indicators, depending also on modelling uncertainty and avoidance of uncertainty linked to interpretation and weighting (if weighting is desired and appropriate for the specific study). For the sake of consistency, it is important to properly select and define the damage indicators for each damage category, so that the modelling of the various impact pathways in different midpoint categories can be oriented towards common damages. Traditionally, LCA was mainly oriented towards damages referring to human health, biotic natural environment and abiotic natural resources. Though probably not a priority at the present stage of the Life Cycle Initiative, other damage categories are also mentioned in Table 1 and discussed in this section. The damage categories are described in more detail, as less information has been published for damage than for midpoint categories in the LCA literature.

5.1 Damage to human health

Definition and review of potential damage indicators. Environmental damages to the human population could be expressed in several ways: Diminution of joy of life, loss of the production factor 'labour', cost of medical interventions, diminution of the population size, etc. However, there is a reasonable agreement that the environmental damage to humans is essentially represented by the observable or expected damage to individual human health (intrinsic value), hereby including all individuals of the present generation as well as future generations. Table 1 further exhibits the functional value of healthy humans as a separate damage category (labour as a production factor), though this is presently not to be treated in priority for LCA. Individual human health may be impaired either by a reduction of the number of life years of an individual, compared to some standard life expectancy, or by the deterioration of the years lived, due to diseases or accidents.

Attempts have been made to express the status of health of a human population in a more aggregated manner.

The World Health Organization (WHO 2000) uses two types of health metrics in order to express the national and global health status, taking into account the life years lost as well as life years lived with a disability: DALY (disability adjusted life years) and HALE (healthy years life expectancy), both of which aggregate the severity of different non-lethal disease stages by assigning disability weights. DALY refers to the intrinsic value of humans, that is to say, humans and their health are seen as a value in itself. There are also a large number of proposals to express the intrinsic or functional (as a production factor of the economic system) value of healthy life (and, as a consequence, the negative value of life years lost or lived with disability) in the form of monetary units.

Initial proposal for damage indicator. The definition study has reemphasized the importance to document very well the objective (natural science based) and subjective (social science and value based) choices within the methods applied. As far as feasible in a reliable way, it is therefore proposed to report, per death cause and per non-lethal disease/accident type involved, the number of premature deaths per age bracket and the number of disease/accident cases with their mean duration; whereby the medical conditions of the disease/accident should be described in the form of a generally known system. In addition, it is proposed to express damages to human health in the form of DALY units as damage indicator. This provides the advantages of being coordinated with the WHO data bases. It will be necessary to analyze to which extent certain damage modelling and the use of disability weights are compatible with the present constraints of ISO 14042 for comparative assertions disclosed to the public, whereas summing up scores at midpoint level can also embed implicit equal social weighting.

Challenges, further investigation required and proposed actions. A coordination mechanism with WHO regarding the health metrics system to be preferred in the future has to be planned. As the link from exposure to disease or diminished health is complicated by many other factors, a comparison of the different existing health metrics will be performed to elucidate the model-based uncertainties introduced by the choice of health metrics, analysing how far it is feasible to assess damages beyond affected target organs. There is also a need to examine how the population age structure and life expectancy influence the metrics of different impacts, in order to elucidate the consequences of spatial differentiation in the damage modelling of human health impacts.

5.2 Damage to the biotic natural environment (wild plants and animals, ecosystems)

Definition and review of potential indicators. There is broad agreement that the variety of species and their ecosystems should be maintained or, at the least, not be rapidly reduced. This means that a damage indicator for the biotic natural environment should measure how far the anthropogenic processes affect the natural development of the occurrence of species within their habitats. Whilst in the case of human health, each individual's health matters, the focus with respect to animals and plants is rather on the species population dynamics and not on the well-being of a single individual. The occurrence of species, as a damage indicator, may include the global population status of a species, as well as its geographic dispersion. Growth of populations is generally seen as a benefit in the case of species with a historical trend towards extinction, whilst growth of invasive, ubiquitous species can be seen as a damage.

Initial proposal for damage indicator. Finding a suitable damage indicator for the biotic natural environment is more difficult than in the case of human health, and an agreed solution is not yet available. In a first phase, different options for damage indicators are evaluated, bearing in mind that such a category indicator should be usable for all of the impact pathways connected to this damage category. A simplified damage indicator can possibly be elaborated on the basis of data such as those supplied by national databases and the 'UNEP-WCMC'[8] species data base' containing the occurrence per region or country of 70,000 animals and 140,000 plant species, together with an indicator of endangerment, representing low or sharply decreasing population density of a species as a coarse indication of its current population dynamics. The 'archetypical' conditions concept could be used to arrive at a practical approach based on a variety of situations. In ecotoxicology, indicators such as the PAF (Potentially Affected Fraction of species) or PDF (Potentially Disappeared Fraction of species) are currently used. It needs to be clarified if these types of indicators can also be used with other impact pathways affecting the biotic natural environment, e.g. land use. Additionally, the relationship between PAF and PDF need to be further explored and demonstrated.

Challenges, further investigation required and proposed actions. Coordination with UNEP-WCMC and other experts will be sought in order to ensure compatibility between the damage indicator selected and indications of pressure and state regarding plants and animals. Furthermore, the relationship between toxicological indicators and biodiversity data needs to be studied in detail.

[8] of the UNEP World Conservation Monitoring Centre

5.3 Damage to the abiotic natural environment (occurrence of natural materials and structures of the non-resource type)

Definition and review of potential indicators. Anthropogenic processes may exert a degrading influence on non-living natural materials and structures, as geological structures and landscape forms, glaciers, crystal holes, waterfalls. If such elements of nature are not used as resources, the damage consists in a loss of intrinsic value related to aesthetics.

Inclusion of such damages in the LCA structure could be difficult. However, a coarse damage indicator expressing the loss of intrinsic values of non-living natural materials and structures could eventually be built up on the fraction of non-affected surface units in a region. If the area of a region is subdivided into surface units of equal size, the decrease of the total number of 'un-touched' unit areas could be a reasonable representation of the decrease of abiotic naturalness of this region. A different approach would be to assume that a certain degree of correlation exists between the quality of the non-living part of the natural environment and the quality of its living part, because the two components are interlinked by ecosystems. If natural surfaces are homogenised for facilitating the use of agricultural machinery, if coral reef structures are demolished, if river floodplains are cut off by river embankments, this also means that species diversity inside the corresponding perimeter is reduced. As a consequence, the damage indicator for biotic natural environment could be taken as a proxy for the damage on the abiotic natural environment. As a further alternative, the economical literature proposes methods for monetarisation of intrinsic values.

Initial proposal for damage indicator. No specific indicator proposed to date. The damage indicator for biotic natural environment could possibly act as a proxy.

Challenges, further investigation required and proposed actions. The problem of environmental damage to abiotic natural materials and structures is a serious issue that has not received adequate attention so far in LCA. As a consequence, further investigations are needed with respect to developing and proposing a corresponding damage indicator.

5.4 Damage to biotic natural resources (wild plants and animals used by humans)

Definition and review of potential indicators. It is imaginable that any of the wild species could sooner or later be used by humans as a resource. However, an element of nature is only considered here to be a resource if the use of this resource use has actually occurred in the past or at present. Elements of nature that are natural resources are simultaneously parts of the biotic natural environment. However, their specific value as a resource requires a separate damage indicator, based on the importance of this resource to human users, because the damage indicator for 'biotic natural environment' does not include this functional aspect.

Initial proposal for damage indicator. No specific proposal exists. It appears adequate to define a damage indicator for biotic natural resources only after agreeing on the damage indicator for biotic natural environment and abiotic natural resources. This helps to avoid double-counting, or gaps, between the two.

5.5 Damage to abiotic natural resources

Definition and review of potential indicators. Depletion of non-renewable abiotic natural resources, due to human use, with the resulting destruction or dissipation of the material, is generally considered as a damage to be treated in LCA. The damage consists of the reduced availability of the corresponding type of resource to future generations. Whilst most resource geologists indicate that the total quantity of resources accessible for humans is extremely high for most of the abiotic resources, others consider the current reduction of the easily usable part of certain natural resources as not negligible. A damage indicator for such depletable abiotic resources should therefore express the quantities as well as the degree of accessibility/usability per type of resource. Various proposals have been made, but agreement on such a damage indicator has not yet been reached. Further research is required in order to supply geological data and a scientific background for such an agreement.

Initial proposal for damage indicator. As a provisional starting point, the increase of energy requirements for future procurement of the currently used quantities per type of abiotic resource can be taken as damage indicator. Surplus energy is used here as a proxy for the 'effort' needed to extract lower grade or lower quality resources. This energy requirement needs to be articulated in the context of the functionality required for each class of abiotic resources and as a function of technological evolution.

Challenges, further investigation required and proposed actions. Again, further research is needed to create a scientific basis for a future agreement on damage indicators for natural resources. This research should be based on existing LCIA work on this impact category, paying due attention to the fact that it is not the extraction of a resource which poses a problem in term of resource availability, but rather a dissipative use and/or disposal.

5.6 Damage to the man-made biotic environment (crops and animal cultures)

Definition and review of potential indicators. The quality status of agricultural and silvicultural crops, domestic animals, aqua-cultures and similar man-controlled living objects can be adversely influenced by environmental impacts, for instance, by acidifying emissions. Unlike the case of wild animals and plants, the development of the population size of a species would not be an adequate damage indicator, because human activities (as artificial reproduction, feeding and medical assistance) are able to control population size. Considering that the quantities of man-controlled crops and animals will always be adapted to meet market demands, the indicator to represent environmental damage is money, spent by the owners of the man-controlled cultures, in order to maintain the marketable output in spite of unfavourable environmental impacts. For example, if fish production in aquaculture is adversely influenced by water quality, this may be compensated by spending additional money in the form of increased input of young fish from hatcheries or in the form of medical ingredients in the feed.

Initial proposal for damage indicator. The current trend is not to represent environmental damages to man-controlled crops and animals in LCA. In case of a reversal of this position, the proposal would be to use the cost in monetary units for damage prevention activities as an initial damage indicator, or to take the damages on the biotic natural environment as a proxy.

Challenges, further investigation required and proposed actions. It is desirable to further investigate the consequences of an inclusion into LCA of environmental damages on man-controlled crops and animals. Other challenges include efforts to investigate methods for expressing the degree of well-being of cultivated animals and plants. Further, research into non-monetary indicators that reflect (environmental) sustainability of the animal/plant population is justified: Money often buys only temporary solutions that do not prevent an ultimate collapse of the population (vaccines and fertilizers can both function this way).

5.7 Damage to man-made abiotic environment (buildings and other structures)

Definition and review of potential indicators. Man-made objects in the abiotic environment are: buildings, equipment, traffic structures, mines, modifications of land surfaces for human purposes, etc. 'Man-made' hereby means that materials, land areas and other objects of nature are transformed by man into artefacts, which nevertheless may maintain some content of naturalness. As a consequence, there may be cases where it is debatable whether an object belongs to the natural environment or the man-made environment. The quality status of non-living man-made objects can be adversely influenced by environmental impacts. Buildings, for instance, are damaged by acidifying emissions. The damage consists of a physical destruction or impairment of the object, with the consequence of a loss of market value in the case of marketable objects. In the case of non-marketable goods like historical sites, the impairment reduces their intrinsic values.

It is important to note that man-made objects or structures may be impaired not only by the impacts of environmental emissions, but also by a discontinuation of certain types of intensive land use. An arable land area, being the result of land use activities like deforestation and shrub-removal, drainage, grading and fertilisation, is physically impaired with respect to its man-made properties as soon as the land use type is changed to extensive grazing or allowed to lie fallow. In such situations, a quality decrease of the man-made structure goes in parallel with a quality increase (negative environmental damage = environmental benefit) of the same object as a part of nature. If overlooked, this could cause serious inconsistencies in LCA practice.

If a man-made object is physically damaged, it is normally possible to repair it by an additional human intervention, although even technically perfect reconstructions may be considered as problematic in the case of objects of the cultural heritage. In general, however, the economic cost of the repair work is a practicable damage indicator for environmental damages to man-made objects.

Initial proposal for damage indicator. If it came to an agreement to represent environmental damages to nonliving manmade objects in LCA, the cost in money units for the repair work appears to be an adequate damage indicator. In case a repair is not possible or rejected for emotional reasons, the loss in monetary units might be found by the use of monetarisation methods.

Challenges, further investigation required and proposed actions. It is desirable to further investigate the consequences of an inclusion into LCA of environmental damages on man-made or man-transformed, non-living objects and structures, and to specify how to handle situations where a damage to the natural environment is accompanied by an improvement in the man-made environment.

6 Conclusions and Outlook

The present paper sets the basis for a widely acceptable and globally applicable LCA framework that should be further developed in the frame of the UNEP/SETAC Life Cycle Initiative and completed within the next years. It draws on the possibility to combine midpoint-oriented and damage-oriented approaches in a common and consistent framework. It also helps in clarifying the intrinsic and functional values behind the different damage categories and proposes criteria for properly describing impact pathways. Although the present framework incorporates and intends to stimulate developments both for midpoint and damage modelling, users may choose to stop at any intermediary level, as a function of model uncertainty and easiness for further interpretation and possibly weighting (if desired and appropriate).

The main progress that can be expected by these future developments in comparison to present practice includes:

- Integration of midpoint and damage approaches in a consistent system.
- Agreement on (an) indicator(s) for damage to 'biotic natural environment' and 'abiotic natural resources'.
- Proposing impact pathways from land use to 'biotic natural environment' and 'abiotic natural resources'.
- Expanding the techniques to leverage the expertise and data from the fields of environmental impact assessment and toxicology.
- Analyzing what are the best solutions for damage interpretation between keeping a large number of endpoints separate, embedding implicit equal social weighting or using weighting schemes.

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