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LCIA OF IMPACTS ON HUMAN HEALTH AND ECOSYSTEMS

IMPACT World+: a globally regionalized life cycle impact assessment method

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Abstract

Purpose This paper addresses the need for a globally regionalized method for life cycle impact assessment (LCIA), integrating multiple state-of-the-art developments as well as damages on water and carbon areas of concern within a consistent LCIA framework. This method, named IMPACT World+, is the update of the IMPACT 2002+, LUCAS, and EDIP methods. This paper first presents the IMPACT World+ novelties and results and then analyzes the spatial variability for each regionalized impact category.

Methods With IMPACT World+, we propose a midpoint-damage framework with four distinct complementary viewpoints to present an LCIA profile: (1) midpoint impacts, (2) damage impacts, (3) damages on human health, ecosystem quality, and resources & ecosystem service areas of protection, and (4) damages on water and carbon areas of concerns. Most of the regional impact categories have been spatially resolved and all the long-term impact categories have been subdivided between shorter-term damages (over the 100 years after the emission) and long-term damages. The IMPACT World+ method integrates developments in the following categories, all structured according to fate (or competition/scarcity), exposure, exposure response, and severity: (a) Complementary to the global warming potential (GWP100), the IPCC Global Temperature Potentials (GTP100) are used as a proxy for climate change long-term impacts at midpoint. At damage level, shorter-term damages (over the first 100 years after emission) are also differentiated from long-term damages. (b) Marine acidification impact is based on the same fate model as climate change, combined with the H^+ concentration affecting 50% of the exposed species. (c) For mineral resources depletion

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impact, the material competition scarcity index is applied as a midpoint indicator. (d) Terrestrial and freshwater acidification impact assessment combines, at a resolution of 2° × 2.5° (latitude × longitude), global atmospheric source-deposition relationships with soil and water ecosystems' sensitivity. (e) Freshwater eutrophication impact is spatially assessed at a resolution grid of 0.5° × 0.5°, based on a global hydrological dataset. (f) Ecotoxicity and human toxicity impact are based on the parameterized version of USEtox for continents. We consider indoor emissions and differentiate the impacts of metals and persistent organic pollutants for the first 100 years from longer-term impacts. (g) Impacts on human health related to particulate matter formation are modeled using the USEtox regional archetypes to calculate intake fractions and epidemiologically derived exposure response factors. (h) Water consumption impacts are modeled using the consensus-based scarcity indicator AWARE as a proxy midpoint, whereas damages account for competition and adaptation capacity. (i) Impacts on ecosystem quality from land transformation and occupation are empirically characterized at the biome level.

Results and discussion We analyze the magnitude of global potential damages for each impact indicator, based on an estimation of the total annual anthropogenic emissions and extractions at the global scale (i.e., "doing the LCA of the world"). Similarly with ReCiPe and IMPACT 2002+, IMPACT World+ finds that (a) climate change and impacts of particulate matter formation have a dominant contribution to global human health impacts whereas ionizing radiation, ozone layer depletion, and photochemical oxidant formation have a low contribution and (b) climate change and land use have a dominant contribution to global ecosystem quality impact. (c) New impact indicators introduced in IMPACT World+ and not considered in ReCiPe or IMPACT 2002+, in particular water consumption impacts on human health and the long-term impacts of marine acidification on ecosystem quality, are significant contributors to the overall global potential damage. According to the areas of concern version of IMPACT World+ applied to the total annual world emissions and extractions, damages on the water area of concern, carbon area of concern, and the remaining damages (not considered in those two areas of concern) are of the same order of magnitude, highlighting the need to consider all the impact categories. The spatial variability of human health impacts related to exposure to toxic substances and particulate matter is well reflected by using outdoor rural, outdoor urban, and indoor environment archetypes. For "human toxicity cancer" impact of substances emitted to continental air, the variability between continents is of two orders of magnitude, which is substantially lower than the 13 orders of magnitude total variability across substances. For impacts of water consumption on human health, the spatial variability across extraction locations is substantially higher than the variations between different water qualities. For regionalized impact categories affecting ecosystem quality (acidification, eutrophication, and land use), the characterization factors of half of the regions (25th to 75th percentiles) are within one to two orders of magnitude and the 95th percentile within three to four orders of magnitude, which is higher than the variability between substances, highlighting the relevance of regionalizing.

Conclusions IMPACT World+ provides characterization factors within a consistent impact assessment framework for all regionalized impacts at four complementary resolutions: global default, continental, country, and native (i.e., original and non-aggregated) resolutions. IMPACT World+ enables the practitioner to parsimoniously account for spatial variability and to identify the elementary flows to be regionalized in priority to increase the discriminating power of LCA.

Keywords IMPACT World+ · Life cycle assessment · Midpoint-damage framework · Regionalized life cycle impact assessment

1 Introduction

This paper addresses the need for a regionalized life cycle impact assessment (LCIA) method covering the entire world, including addressing uncertainty related to spatial variability and implementing state-of-the-art characterization modeling approaches.

The life cycle of a product implies numerous substance emission and resource use, which LCIA methods allow translating into a limited number of environmental impact scores by the mean of characterization factors, which indicate the environmental impact per unit of emission or resource use. Numerous LCIA methods have been developed and applied in life cycle assessment (LCA) studies (Hauschild et al. 2013). Developments are typically viewed along three families: midpoint (Bare 2011; Guinée et al. 2002; Hauschild and Wenzel 1998) or damage (Goedkoop and Spriensma 2000; Steen 1999) oriented methods, and methods that attempted to combine both in a common and consistent framework (Goedkoop et al. 2009; Itsubo and Inaba 2012; Jolliet et al. 2003). These latter approaches allow LCA practitioners to calculate environmental profiles either at the midpoint or damage levels (depending on the scope of the LCA study) taking advantage of their respective merits in terms of lower model uncertainty and higher environmental relevance, respectively. The LCIA method presented here also provides characterization results at midpoint and damage levels.

Since the extensive review in 2008–2009 by Hauschild et al. (2013) identifying the best existing practices for LCIA characterization modeling, several improved models have been published

but not yet included in any LCIA method. These new developments may significantly influence the environmental performance profile of several product categories. It includes modeling of impact pathways from renewable resource use such as water consumption (Boulay et al. 2015; Kounina et al. 2013) and land use (Chaudhary et al. 2015; de Baan et al. 2013; Koellner et al. 2012). For human health and ecosystem quality areas of protection (AoPs), progress was made (a) in characterizing freshwater and terrestrial acidification, with a spatially resolved global scale atmospheric fate and receiving environment modeling (Roy et al. 2014a, 2012a, b); (b) in characterizing health impacts of particulate matter formation with new epidemiologically derived factors and indoor environments (Fantke et al. 2015; Hodas et al. 2015; Humbert et al. 2011); (c) in freshwater eutrophication characterization with a world model at 0.5° × 0.5° resolution (Helmes et al. 2012); and (d) in marine acidification with a first LCA compliant model covering this impact category (Azevedo et al. 2015). The LCA community is still struggling on how to best account for the consumption of resources. Several authors advocate the need for functional-based approaches (Boulay et al. 2011; European Commission 2010; Goedkoop and De Schryver 2008; Stewart and Weidema 2005; Van Oers et al. 2002) that assess impacts of resources based on their functional value (i.e., the loss of service) rather than on their intrinsic value (i.e., the loss of resource itself) and may provide a common ground across resource-related impact categories.

Beside using best practices for characterization modeling in LCIA, there is also a need for ensuring consistency across impact categories for all the underlying modeling assumptions and choices, such as geographical and temporal scope, avoidance of double counting, the linkage between midpoint and damage level modeling, and normalization reference. Without this effort, an LCIA method will suffer major methodological and/or operational drawbacks. As an example, the ILCD method (European Commission 2011) reflects a collection of 15 midpoint impact indicators that could hardly be integrated within a coherent midpoint-damage framework without introducing methodological bias and inconsistencies among impact categories. Each of the chosen models represents a consensus about the best practices among the experts for a specific impact category, but no harmonization effort was done across impact categories to ensure that the same environmental mechanism was modeled the same way and that the same parameterization was used across impact categories.

Moreover, an increasing interest toward carbon footprint and water footprint as separate areas of concern (AoCs), which complement AoPs, was raised recently (Jolliet et al. 2014; Ridoutt et al. 2015, 2016). The ISO 14046:2014 standard (ISO 2014) defines a water footprint as a "metric that quantifies the potential environmental impacts related to water" and specifies that a "comprehensive water footprint implies to consider all environmentally relevant attributes or aspects of natural environment, human health and resources related to water, including water availability and water degradation." No attempt has been made to integrate into an LCIA compliant framework both carbon and water together as AoCs *in a consistent approach*.

Some existing LCIA methods partially address regionalization with characterization models being representative of the region where the elementary flow takes place, but they usually only cover a specific region of the world and do not depict the spatial variability within this specific region. For example, Eco-indicator 99 (Goedkoop and Spriensma 2000), CML (Guinée et al. 2002), ReCiPe (Goedkoop et al. 2009), EDIP (Hauschild and Wenzel 1998), IMPACT 2002+ (Jolliet et al. 2003), and EPS (Steen 1999) are representative of Western European conditions, LIME 2.0 of Japan (Itsubo and Inaba 2012), TRACI of the USA (Bare 2011), and LUCAS of Canada (Toffoletto et al. 2007). Characterizing supply chains from a global economy with a European LCIA method, for example, implies the underlying assumption that all the life cycle emissions and resource consumptions occur in Europe or at least under European conditions, which is not necessarily a better assumption than applying global or site-generic characterization factors (CFs). Generic CFs of current LCIA methods generally do not, or only partially, account for the spatial variability of impacts according to the location of the elementary flow. Spatial variability is not assessed at a global level, nor quantified in terms of additional uncertainty referred to the regional scope selected in an LCIA method. Stepping toward a fine resolution scale for LCIA encompassing a global perspective represents a challenge in terms of data management and parsimony as it also affects the required resolution of the life cycle inventory (LCI). There is a need to offer a globally regionalized LCIA method, to analyze the importance of spatial variability and to account for such variability in characterization results in a parsimonious way (European Commission 2010).

The main aim of the present study is to propose a novel framework that includes recent methodological advances in multiple impact categories in a consistent way by (a) implementing the same modeling structure of fate, exposure, exposure response, and severity across ecosystem quality and human health-related impact categories, (b) adopting the consumption/competition/adaptation functionality-based assessment for all impacts on human society generated from the loss of functional value of a resource or an ecosystem service, and (c) offering the flexibility to represent impact scores at midpoint level or at damage level, with the possibility to adopt an AoP or an AoC viewpoint.

Specific objectives are to propose the first regionalized LCIA method covering the entire world at different levels of spatial resolution to analyze the magnitude of characterization results for each impact category at the global scale and to quantify the relative importance of spatial variability compared to the overall spread of characterization factors.

2 Methods

Developed as a joint major update to IMPACT 2002+ (Jolliet et al. 2003), EDIP (Hauschild and Wenzel 1998), and LUCAS (Toffoletto et al. 2007), the newly introduced IMPACT World+ addresses the need to assess regional impacts of any geo-referenced elementary flow, providing CFs at four hierarchical levels of spatial resolutions: global default (non-spatially resolved), continental, country, and native resolutions. This latter corresponds to the original level of resolution for a given impact indicator as published by the model developers.

2.1 General framework

IMPACT World+ relies on a midpoint-damage framework as shown in Fig. 1 providing four consistent and complementary viewpoints to express a life cycle impact assessment profile:

1. A midpoint level viewpoint
2. A damage level viewpoint
3. An AoP viewpoint at damage level, grouping the impact categories of the damage level above into three AoPs as recommended by Verones et al. (2017): human health, ecosystem quality, and resources & ecosystem services. The latter includes potential impacts on human society with no direct consequences on human health, focusing specifically on the instrumental value of resources and ecosystems, as recently recommended by the UNEP/SETAC Life Cycle Initiative (Verones et al. 2017). It is derived from the loss of the functional value of a resource or an ecosystem as an input to estimate the potential costs that society has to bear to maintain or replace the same service.
4. An AoC viewpoint at damage level, grouping and expressing damage level impact categories in terms of water-related damages, carbon-related damages, and the rest of damages on the human health and ecosystem

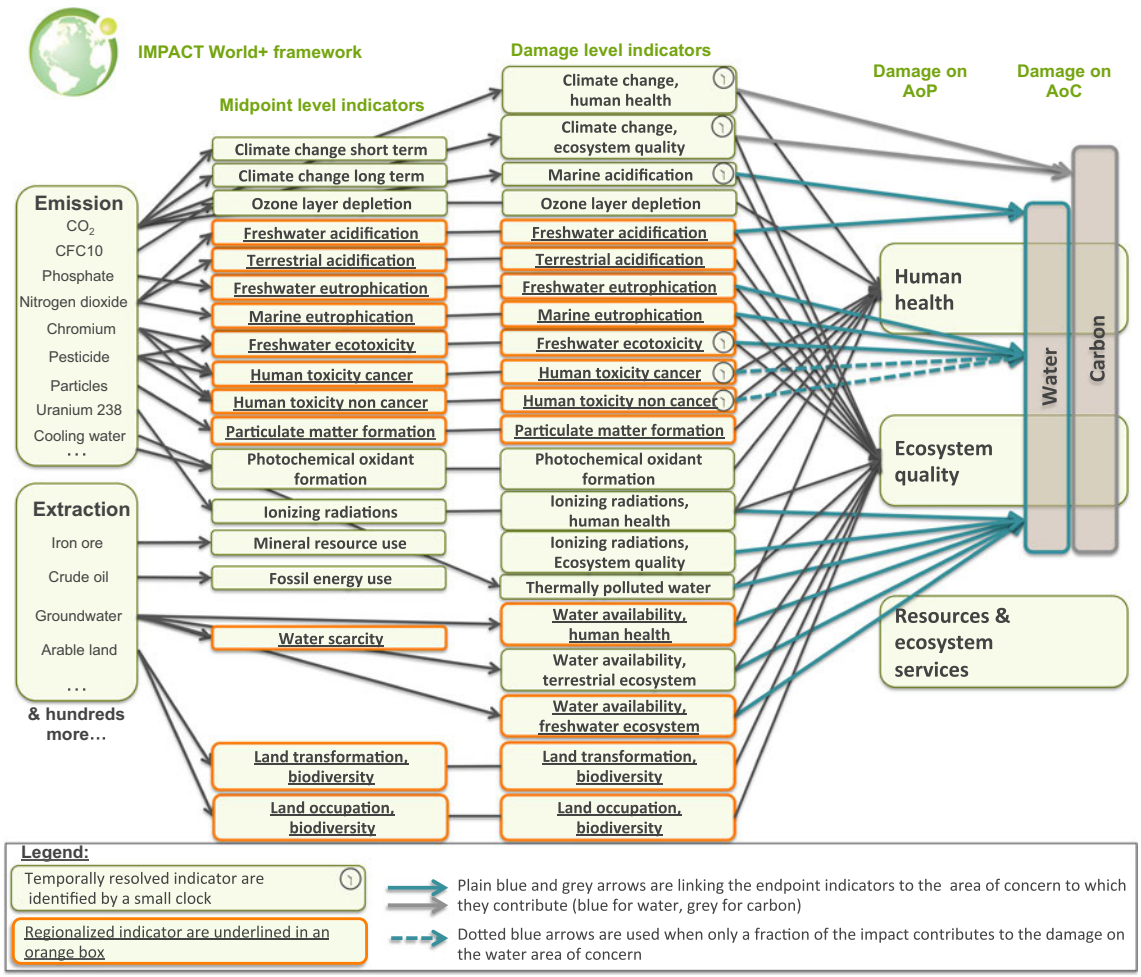

Fig. 1 IMPACT World+ LCIA framework (recommended impact categories only). Impact categories are represented by the corresponding indicators at midpoint and/or at damage level. At damage level, impact categories can be aggregated according to AoP or AoC. The comprehensive list of impact indicators within each group of impact categories at midpoint and damage levels is described in Table 1 and the detailed framework including the interim impact categories is available in supporting information, section 4

quality AoPs. This is illustrated with the overlap of the AoC and AoP boxes in Fig. 1. We thus define the following six "sub-AoCs": carbon human health, water human health, rest of human health, carbon ecosystem quality, water ecosystem quality, rest of ecosystem quality. For example, land transformation impacts on biodiversity are neither affecting the water nor the carbon AoCs, but are still considered in IMPACT World+ AoC version in the "rest of ecosystem quality." Table 1 summarizes the list of impact categories at midpoint and damage level and their contribution to the three AoPs and the six sub-AoCs.

The impact score at midpoint or damage level for impact category k in an emitting region a, I_a^k, is calculated as the sum over elementary flows and all emitting compartments of the characterization factor CF_{ai}^{sk} for the elementary flow s and the impact category k for a given emitting compartment i in a given emitting region a multiplied by the amount M_{ia}^s of elementary flow s (resource or emission) from the life cycle inventory in a given environmental compartment I in a given emitting region a (Eq. 1). The sum of I_a^k over all emitting region a provides the overall impact impact score at midpoint or damage level for impact category k. The list of symbols and indices can be found in the Electronic Supplementary Material (ESM). All details for all the equations are provided in the ESM.

$$I_a^k = \sum_s \sum_i CF_{ai}^{sk} M_{ia}^s \quad (1)$$

CF are first calculated at the native (n) higher available resolution and can then be aggregated at a regional level (a). The same structure is adopted to model the native CF throughout the causality chain at the damage level across all impact categories, with two specific structures for emission-related impact categories and resource-related impact categories. For emission-related impact categories, characterization models of the IMPACT World+ method build on the general LCIA framework proposed by the Society of Environmental Toxicology and Chemistry (SETAC) (Udo de Haes et al. 2002) and the United Nations Environmental Program (UNEP)/SETAC Life Cycle Initiative (Margni et al. 2008; Verones et al. 2017). The calculation of CF^{sk} for regionalized emission-related impact categories at the damage level is described in Eq. 2, where CF_{ni}^{sk} the element of the regionalized CF^{sk} matrix describes the characterization factor for impact category k and for an elementary flow s emitted into an environmental compartment i and an emitting native region n. It is expressed as the product of a fate factor matrix (FF), exposure factor matrix (XF), exposure-response factor matrix (ERF), and severity factor vector (SF). The equation for the calculation of CF^{sk} for non-regionalized emission-related impact categories is a simplified version of Eq. 2 and can be found in the ESM.

$$CF^{sk} = \overrightarrow{1} \cdot \overrightarrow{SF^{sk}} \cdot ERF^{sk} \cdot XF^{sk} \cdot FF^{sk} \quad (2)$$

For a given impact category k, FF_{jbni}^{sk} describes, for an elementary flow s emitted in compartment i and a native region n, the increase of mass of active substance in a receiving compartment j in a receiving region b integrated over time to the infinite (or on a specific time interval for impact categories subdivided between shorter-term and long-term impacts); XF_{pbj}^{sk} describes a change in population or ecosystem exposure via pathway p per unit of mass of active substance s in the receiving environment compartment j in the receiving region b integrated in time to the infinite (or on a specific time interval for impact categories subdivided between shorter-term and long-term impacts); ERF_{rbp}^{sk} describes the change in adverse consequences for response r due to a change in exposure pathway p of human population or ecosystems in the receiving region b; SF_r^{sk} aggregates responses r into damage level units for impact category k. Each term of Eq. 2 is further detailed into governing equations specific to each impact category in Table 2 and in the ESM, sections 2 and 3.

For resource-related impact categories (resource use, mineral, fossil, land and water use), characterization models of the IMPACT World+ method are all consistently built based on an extraction-consumption-competition-adaptation approach. The resource consumption leads to an increased competition between its different users (e.g., when water is consumed close to its renewability rate, competition for water increases). Some of those competing users may be able to adapt if they can afford it or if alternatives are available at an equivalent price to fulfill the function provided by the resource (e.g., in Spain, no one is going to suffer human health impacts from water deprivation, but people will pay to desalinate or import water). For the users that are not able to adapt, the resource deprivation may lead to direct impacts on human health—if the resource provides essential functions to human life (e.g., water for irrigation or domestic use)—and/or to the loss of resource services, expressed as a cost to society (impact on the resources & ecosystem service AoP). The same governing equations as for emission-related can be applied to resource-related impact categories, where FF is replaced by a competition scarcity index (**CSI**) that expresses the quantity of resource that is going to deprive competing users (current or future) sharing the same resource per quantity of resource used in a dissipative manner. The calculation of CF^{sk} for regionalized resource-related impact categories at the damage level is described in Eq. 3, for all the resource-related impact categories further detailed per impact category in Table 2 and in the ESM. The equation for the calculation of CF^{sk} for non-regionalized resource-related impact categories is a simplified version of Eq. 3 and can be found in the ESM.

$$CF^{sk} = \overrightarrow{1} \cdot \overrightarrow{SF^{sk}} \cdot ERF^{sk} \cdot XF^{sk} \cdot CSI^{sk} \quad (3)$$

CSI^{sk}_{ubni} describes the competition scarcity index factor for impact category k and elementary flow s in a compartment i in a native region n for a competing user u (current or future) in a region b; XF^{sk}_{pbu} describes the exposure for a user u to deprivation (or to adaptation) in the region b through the exposure pathway p; ERF^{sk}_{rbp} describes the change in adverse

Table 1 Comprehensive list of the IMPACT World+ indicators at midpoint (18 recommended, plus 1 interim) and damage level (21 recommended, plus 23 interim) and of the areas of protection (human health [HH], ecosystem quality [EQ], or resources & ecosystem services [R&ES]) and areas of concern to which they contribute. Complementary description of their spatial and temporal resolution, the corresponding number of elementary flows covered, and the references on which they are based. Midpoint level impact categories with an asterisk (*) are proxies which are not directly on the cause-effect chains leading to the damages

Shorter term impact (occuring between 0 and 100 yrs after the environmental intervention occur)
Long term impact (occuring 100 yrs after the environmental intervention)
Timely resolved impact with both shorter term (0-100 yrs) and long term impacts (more than 100 yrs)

Midpoint level impact category (*proxy midpoint)	Damage level impact category	Area of protection (AoP)	Area of concern (AoC)	Recommended (R) or *Interim (I)*	References	Native geographical resolution scale	Time resolution	Emission/consumption data or proxy used to agregate CFs at country level, continental and global scales	Number of elementary flows
Climate change, long term*				R	Levasseur et al. 2016; de Schryver et al. 2009; Joos et al. 2013; Myhre et al 2013;	Global			212
Climate change, short term*				R					
	Climate change, human health	HH	Carbon, HH	R					
	Climate change, ecosystem quality	EQ	Carbon, EQ	R					
	Climate change, ecosystem services	*R&ES*		*I*					
	Marine acidification	EQ	Water, EQ	R	Myhre et al 2013; Azevedo et al. 2015	Global			9
Ozone layer depletion	Ozone layer depletion	HH	Rest of HH	R	Margni et al. 2008; Struijs et al. 2009	Global			23
Mineral resources use	*Mineral resources use*	*R&ES*		R at midpoint *I at damage*	de Bruille 2014	Global			165
Fossil energy use	*Fossil energy use*	*R&ES*		R at midpoint *I at damage*	Fatemi 2012; Frischknecht 2003	Global			37
Terrestrial acidification	Terrestrial acidification	EQ	Rest of EQ	R	Roy et al. 2014a; Roy et al. 2012a; Roy et al. 2012b	2° x 2.5°		Acidifying subtances emissions in each 2°x2.5° cell intersection the country/ continent / globe	15
Freshwater acidification	Freshwater acidification	EQ	Water,EQ	R	Roy et al. 2012b; Roy et al. 2014b	2° x 2.5°			15
Marine eutrophication	Marine eutrophication	EQ	Water, EQ	R	Roy et al. 2012b;	2° x 2.5°		Atmospheric emissions of N containing subtances in each 2°x2.5° cell intersectiing the country/ continent / globe	16
Freshwater eutrophication	Freshwater eutrophication	EQ	Water,EQ	R	Helmes et al. 2012; Tirado-Seco 2005	0.5° x 0.5°		Population density used as a proxy of P emissions in each 0.5°x0.5° cell intersectiing the country/ continent / globe	8

Midpoint level impact category (*proxy midpoint)	Damage level impact category	Area of protection (AoP)	Area of concern (AoC)	Recommended (R) or *Interim (I)*	References	Native geographical resolution scale	Time resolution	Proxy or emission/consumption data used to agregate CFs at country level, continental and global scales	Number of elementary flows
Freshwater ecotoxicity	Freshwater ecotoxicity	EQ	Water, EQ	R	Hauschild et al. 2008; Rosenbaum et al. 2008; Kounina et al. 2014; Huijbregts et al. 2005; Hellweg et al. 2009; Rosenbaum et al. 2015; Wenger et al. 2012; Fantke et al. 2011; Fantke and Jolliet 2016; Fantke et al. 2012	Continent		USEtox default version used for global default CFs	2516
	Terrestrial ecotoxicity	*EQ*		*I*					
	Marine ecotoxicity	*EQ*		*I*					
Human toxicity cancer	Human toxicity cancer	HH	Water, HH Rest of HH	R		Continent + high/low population and indoor archetypes			1020
Human toxicity non-cancer	Human toxicity non-cancer	HH	Water, HH Rest of HH	R					439
Particulate matter formation	Particulate matter formation	HH	Rest of HH	R	Fantke et al. 2015; Humbert et al. 2011; Gronlund et al. 2015			Population density used as proxy of emission	5
Photochemical oxidant formation	Photochemical oxidant formation	HH	Rest of HH	R	European Commission, 2011	Not regionalized			134
Ionizing radiations	Ionizing radiation, human health	HH	Water, HH	R	Frischknecht et al. 2000; Margni et al. 2008; Garnier-Laplace et al. 2008	Not regionalized			29
	Ionizing radiation, ecosystem quality	EQ	Water, EQ	R					
Water scarcity*				R	Boulay et al. 2018 (AWARE)	Subwatershed		Water consumption in each native resolution cell included in the country / continent / Globe	1
	Water availability, human health	HH	Water, HH	R	Boulay 2011	Watershed & countries			58
	Water availability, resources & ecosystem services	*R&ES*		*I*	Boulay 2011; Cao et al. 2015	Watershed & countries			58
	Water availability, freshwater ecosystem	EQ	Water, EQ	R	Hanafiah et al. 2011	Watershed			1
	Water availability, terrestrial ecosystem	EQ	Water, EQ	R	van Zelm et al. 2011	Not regionalized			2
	Thermally polluted water	EQ	Water, EQ	R	Verones et al. 2010	Not regionalized			1
Water stream use and management	*Water stream use and management*	*EQ*		*I*	Humbert and Maendly 2009	Not regionalized			1

Table 1 (continued)

Midpoint level impact category (*proxy midpoint)	Damage level impact category	Area of protection (AoP)	Area of concern (AoC)	Recommended (R) or *Interim (I)*	References	Native geographical resolution scale	Time resolution	Proxy or emission/consumption data used to agregate CFs at country level, continental and global scales	Number of elementary flows
Land transformation, biodiversity	**Land transformation, biodiversity**	**EQ**	**Rest of EQ**	**R**	de Baan et al. 2013; Curran et al. 2010	Olson Biomes		Surface of the characterized land cover in the different sections of Olson ecoregions covering the country / continent / Globe	12
	Land transformation, mechanical filtration	*R&ES*		*I*	Cao et al. 2015; Saad et al. 2011; Curran et al. 2010	Holridge lifezones			
	Land transformation, phys.-chemical filtration	*R&ES*		*I*		Holridge lifezones			
	Land transformation, freshwater recharge	*R&ES*		*I*		Holridge lifezones			
	Land transformation, erosion resistance	*R&ES*		*I*		Holridge lifezones			
	Land transformation, biotic production	*R&ES*		*I*		JRC Climate zones			
	Land transformation, mechanical filtration	*HH*		*I*		Holridge lifezones			
	Land transformation, phys.-chemical filtration	*HH*		*I*		Holridge lifezones			
	Land transformation, freshwater recharge	*HH*		*I*		Holridge lifezones			
Land occupation, biodiversity	**Land occupation, biodiversity**	**EQ**	**Rest of EQ**	**R**	de Baan et al. 2013	Olson Biomes			6
	Land occupation, mechanical filtration	*R&ES*		*I*	Cao et al. 2015; Saad et al. 2011	Holridge lifezones			
	Land occupation, phys.-chemical filtration	*R&ES*		*I*		Holridge lifezones			
	Land occupation, freshwater recharge	*R&ES*		*I*		Holridge lifezones			
	Land occupation, erosion resistance	*R&ES*		*I*		Holridge lifezones			
	Land occupation, biotic production	*R&ES*		*I*		JRC Climate zones			
	Land occupation, mechanical filtration	*HH*		*I*		Holridge lifezones			
	Land occupation, phys.-chemical filtration	*HH*		*I*		Holridge lifezones			
	Land occupation, freshwater recharge	*HH*		*I*		Holridge lifezones			

consequences due to a change in exposure, ultimately translated into damage level units by applying a severity factor, SF_r^{sk}, both as described in emission-related framework.

The position of the midpoint indicator along the cause-effect chain is category-specific. The midpoint **CF** matrix may, therefore, include only an FF matrix (e.g., freshwater eutrophication) or additional factors up to the damage level, as shown in detailed equations available in the ESM, section 2. For instance, for the acidification impacts, the midpoint indicator only includes FF and XF. For the land occupation, biodiversity midpoint, CF midpoint includes all FF, XF, ERF, and SF matrices and therefore equals the damage level CF matrix. Table 2 uses blue highlighted cells to specify for each midpoint impact category which of the FF, XF, ERF, and SF are included in the midpoint CF.

Midpoint to damage modeling involves additional steps in the model, which may increase parameter and model-related uncertainty, in particular when regionalized parameters are needed and may have to be estimated. However, it adds relevance and representativeness for a given environmental problem to the impact indicator, reducing the uncertainty due to poorly representing the damage on the AoP. As specified by Verones et al. (2017), "It has been common to provide the linkage between combined impact categories at midpoint level and impact categories at damage level with one constant conversion factor for the whole world. However, since 2004, several impact categories have been developed that take spatial differentiation into account (e.g. land use, water use, and freshwater eutrophication). The consideration of spatial differentiation makes it difficult - or even impossible – to apply constant conversion factors, since the cause-effect model from midpoint impact indicator to damage indicator might vary spatially as well, depending on the impact category." In other words XF, ERF, and SF from Eq. 3 may all be spatially differentiated, and not only FF. Therefore, damage scores from IMPACT World+ are not necessarily proportional to the corresponding midpoint scores. This means that damage impact scores cannot be calculated from a list of midpoint indicators without going back to the life cycle inventory. For example, damage on human health due to water use is linked both to water scarcity, which is well represented by the proxy-midpoint AWARE, but also to adaptation capacity in the region affected by this scarcity. Therefore, in some cases, human health damage of water use may not be proportional to the midpoint level indicator. Another example is provided by Roy et al. (2014b) for acidification, who set the midpoint indicator at the level of a change in soil pH to reduce its uncertainty, acknowledging that the midpoint level impact score may not be proportional to the damage level impact score. The choice to calculate results either at the midpoint or damage level is then left to the user.

For impacts in a non-native resolution, IMPACT World+ allows assessing the potential regional impact of any geo-referenced elementary flow. Native resolution CF matrices can be reduced into coarser levels of national continental or global resolution matrices considering the distribution of

elementary flows occurring at each spatial unit of the native resolution (water availability impact, acidification, marine eutrophication, land use). Alternatively, the population density is used as an emission proxy in the case of freshwater

Table 2 Main-governing equations of indicators and characterization factors harmonized structure (from global to local indicators). Legend: dark gray and bold font—recommended indicator; light gray and italic font—interim indicator; blue—midpoint model; purple—damage model. A zigzag-shaped line shows the limit between midpoint and damage modeling

Midpoint level impact category (* proxy midpoint)	Midpoint level characterization factor unit	Damage level impact category	Damage level characterization factor unit	Fate Factor FF (or competition scarcity index CSI)	Exposure Factor XF	Exposure Response Factor ERF	Severity Factor SF
Climate change, long-term*	kg $CO_{2\ eq(long)}$ /$kg_{emitted}$			$\frac{\int_{t_1}^{t_2} \Delta_{\text{Mass in the atmosphere}}\, dt}{\text{Mass}_{\text{emitted}}}$	$\frac{\Delta_{\text{Temperature after 100 years}}}{\int_{t1}^{t2} \Delta_{\text{Mass in the atmosphere}}\, dt}$		
Climate change, shorter-term*	kg $CO_{2\ eq(shorter)}$ /$kg_{emitted}$				$\frac{\int_{t1}^{t2} \Delta_{\text{Radiative forcing}}\, dt}{\int_{t1}^{t2} \Delta_{\text{Mass in the atmosphere}}\, dt}$		
	-	**Climate change, HH**	DALY/$kg_{emitted}$		$\frac{\int_{t_1}^{t_2} \Delta_{\text{Temperature}} dt}{\int_{t_1}^{t_2} \Delta_{\text{Mass in the atmosphere}}\, dt}$	$\text{Case}/\int_{t_1}^{t_2} \Delta_{\text{Temperature}}\, dt$	$\text{Damage}_{\text{HH}}/\text{Case}$
		Climate change, EQ	PDF·m^2·yr/$kg_{emitted}$			$\text{Damage}_{\text{EQ}}/\int_{t_1}^{t_2} \Delta_{\text{Temperature}}\, dt$	
		Climate change, R&ES	$/$kg_{emitted}$		$\frac{\int_{t1}^{t2} \Delta_{\text{Radiative forcing}}\, dt}{\int_{t1}^{t2} \Delta_{\text{Mass in the atmosphere}}\, dt}$	$\text{Damage}_{\text{R\&ES}}/\int_{t_1}^{t_2} \Delta_{\text{Radiative forcing}}\, dt$	
	-	**Marine acidification**	PDF·m^2·yr/$kg_{emitted}$		$\frac{\int_{t_1}^{t_2} \Delta_{\text{pH}}\, dt}{\int_{t_1}^{t_2} \Delta_{\text{Mass in the atmosphere}}\, dt}$	$\text{PAF} \cdot \text{Area} \cdot \text{Time}/\int_{t_1}^{t_2} \Delta_{\text{pH}} dt$	$\text{Damage}_{\text{EQ}}/(\text{PAF} \cdot \text{Area} \cdot \text{Time})$
Ozone layer depletion	kg CFC-11_{eq}/$kg_{emitted}$	**Ozone layer depletion**	DALY/kg_{mitted}	$\frac{\int_{t_1}^{t_2} \Delta_{\text{Mass eq eff.strato.chlorine}}\, dt}{\text{Mass}_{\text{emitted}}}$	$\frac{\text{UVB}_{\text{human exposure}}}{\int_{t_1}^{t_2} \Delta_{\text{Mass eq eff.strato.chlorine}}\, dt}$	$\frac{\text{Damage}_{\text{HH}}}{\text{UVB}_{\text{human exposure}}}$	
Mineral resources use	$kg_{deprived}$/$kg_{dissipated}$	*Mineral resources use*	$/$kg_{dissipated}$	$\text{Mass}_{\text{deprived}} / \text{Mass}_{\text{dissipated}}$		$\text{Damage}_{\text{R\&ES}}/ \text{Mass}_{\text{deprived}}$	
Fossil energy use	$MJ_{deprived}$/$kg_{dissipated}$	*Fossil energy use*	$/$kg_{dissipated}$	$\text{Primary energy}_{\text{deprived}} / \text{Mass}_{\text{dissipated}}$		$\text{Damage}_{\text{R\&ES}}/ \text{Primary energy}_{\text{deprived}}$	
Terrestrial acidification	kg $SO_{2\ eq}$/$kg_{emitted}$	**Terrestrial acidification**	PDF·m^2·yr/$kg_{emitted}$	$\frac{\text{Mass}_{\text{deposited}}}{\text{Mass}_{\text{emitted}}}$	$\frac{\int_{t_1}^{t_2} \Delta_{\text{pH}}\, dt}{\text{Mass}_{\text{deposited}}}$	$\text{PAF}\cdot\text{Area}\cdot\text{Time} / \int_{t_1}^{t_2} \Delta_{\text{pH}} dt$	$\text{Damage}_{\text{EQ}}/(\text{PAF} \cdot \text{Area} \cdot \text{Time})$
Freshwater acidification	kg $SO_{2\ eq}$/$kg_{emitted}$	**Freshwater acidification**	PDF·m^2·yr/$kg_{emitted}$				
Marine eutrophication	kg N N-lim eq /$kg_{emitted}$	**Marine eutrophication**	PDF·m^2·yr/$kg_{emitted}$		$\text{PDF} \cdot \text{Area} \cdot \text{Time}/\text{Mass}_{\text{deposited}}$		$\text{Damage}_{\text{EQ}}/\text{PDF}\cdot\text{Area}\cdot\text{Time}$
Freshwater eutrophication	kg PO_4 P-lim eq /$kg_{emitted}$	**Freshwater eutrophication**	PDF·m^2·yr/$kg_{emitted}$	$\frac{\int_{t_1}^{t_2} \Delta_{\text{Mass in receiving compartment}}\, dt}{\text{Mass}_{\text{emitted}}}$	$\text{PAF} \cdot \text{Area} \cdot \text{Time}/\int_{t_1}^{t_2} \Delta_{\text{Mass in receiving compartment}} dt$		$\text{Damage}_{\text{EQ}}/\text{PAF}\cdot\text{Area}\cdot\text{Time}$

Midpoint level impact category (* proxy midpoint)	Midpoint level characterization factor unit	Damage level impact category	Damage level characterization factor unit	Fate Factor FF (or competition scarcity index CSI)	Exposure Factor XF	Exposure Response Factor ERF	Severity Factor SF
Freshwater ecotoxicity	CTUe/$kg_{emitted}$	**Freshwater ecotoxicity**	PDF·m^2·yr/$kg_{emitted}$	$\frac{\int_{t_1}^{t_2} \Delta_{\text{Mass in receiving compartment}}\, dt}{\text{Mass}_{\text{emitted}}}$	$\frac{\text{Mass}_{\text{bioavailable}}}{\int_{t_1}^{t_2} \Delta_{\text{Mass in receiving compartment}}\, dt}$	$\frac{\text{PAF} \cdot \text{Volume} \cdot \text{Time}}{\text{Mass}_{\text{bioavailable}}}$	$\text{Damage}_{\text{EQ}}/\text{PAF}\cdot\text{Volume}\cdot\text{Time}$
	-	*Terrestrial ecotoxicity*					
		Marine ecotoxicity					
Human toxicity cancer	CTUh /$kg_{emitted}$	**Human toxicity cancer**	DALY/$kg_{emitted}$		$\frac{\text{Mass}_{\text{Intake}}}{\int_{t_1}^{t_2} \Delta_{\text{Mass in receiving compartment}}\, dt}$	$\frac{\text{Case}}{\text{Mass}_{\text{Intake}}}$	$\text{Damage}_{\text{HH}}/\text{Case}$
Human toxicity non-cancer	CTUh/$kg_{emitted}$	**Human toxicity non-cancer**					
Particulate matter formation	kg $PM2.5_{eq}$/$kg_{emitted}$	**Particulate matter formation**					
Photochemical oxidant formation	kg $NMVOC_{eq}$ /$kg_{emitted}$	**Photochemical oxidant formation**					
Ionizing radiations	Bq C-14_{eq}/$kg_{emitted}$	**Ionizing radiation, HH**					
		Ionizing radiation, EQ	PDF·m^2·yr/$kg_{emitted}$		$\frac{\text{PAF} \cdot \text{Volume} \cdot \text{Time}}{\int_{t_1}^{t_2} \Delta_{\text{Mass in receiving compartment}}\, dt}$		$\text{Damage}_{\text{EQ}}/\text{PAF}\cdot\text{Volume}\cdot\text{Time}$
Water scarcity *	$m^3_{\text{world-eq}}/m^3_{\text{consumed}}$		-	Increased relative deprivation potential/ $\text{Volume}_{\text{consumed}}$			
	-	**Water availability, HH**	DALY/m^3_{consumed}	$\text{Volume}_{\text{deprived}} / \text{Volume}_{\text{consumed}}$	$\text{Volume}_{\text{lost with no adaptation}} / \text{Volume}_{\text{deprived}}$	$\text{Damage}_{\text{HH}}/ \text{Volume}_{\text{lost with no adaptation}}$	
		Water availability, R&ES	$/$m^3_{deprived}$	$\text{Volume}_{\text{deprived}} / \text{Volume}_{\text{consumed}}$	$\text{Volume}_{\text{lost with adaptation}} / \text{Volume}_{\text{deprived}}$	$\text{Damage}_{\text{R\&ES}} / \text{Volume}_{\text{lost with adaptation}}$	
		Water availability, freshwater ecosystem	PDF·m^2·yr/$m^3_{\text{dissipated}}$	$\frac{\int_{t_1}^{t_2} \Delta_{\text{river discharge}}\, dt}{\text{Volume}_{\text{dissipated}}}$	$\text{PAF} \cdot \text{Volume} \cdot \text{Time}/\int_{t_1}^{t_2} \Delta_{\text{river discharge}} dt$		$\text{Damage}_{\text{EQ}}/\text{PAF}\cdot\text{Volume}\cdot\text{Time}$
		Water availability, terrestrial ecosystem	PDF·m^2·yr/$m^3_{\text{dissipated}}$	$\frac{\int_{t_1}^{t_2} \Delta_{\text{groundwater depth}}\, dt}{\text{Volume}_{\text{dissipated}}}$	$\frac{\int_{t_1}^{t_2} \Delta_{\text{soil moisture}}\, dt}{\int_{t_1}^{t_2} \Delta_{\text{groundwater depth}}\, dt}$	$\frac{\text{PNOF}}{\int_{t_1}^{t_2} \Delta_{\text{soil moisture}}\, dt}$	$\frac{\text{Damage}_{EQ}}{\text{PNOF}}$
	-	**Thermally polluted water**	PDF·m^2·yr /$m^3_{\text{cooling water}}$	$\frac{\int_{t_1}^{t_2} \Delta_{\text{river temperature}}\, dt}{\text{Volume}_{\text{cooling water}}}$	$\text{PDF.Volume.time}/\int_{t_1}^{t_2} \Delta_{\text{river temperature}} dt$		$\text{Damage}_{\text{EQ}}/\text{PDF}\cdot\text{volume.time}$
Water stream use and management	$m_{eq}^3 / m^3_{\text{turbined}}$	*Water stream use and management*	PDF·m^2·yr/m^3_{turbined}	$\text{Damage}_{\text{EQ}} / m^3_{\text{turbined}}$			

Table 2 (continued)

Midpoint level impact category (* proxy midpoint)	Midpoint level characterization factor unit	Damage level impact category	Damage level characterization factor unit	Fate Factor FF (or competition scarcity index CSI)	Exposure Factor XF	Exposure Response Factor ERF	Severity Factor SF
Land transformation, biodiversity	$m^2_{\text{arable land eq}}/m^2_{\text{transformed}}$	**Land transformation, biodiversity**	$PDF \cdot m^2 \cdot yr/m^2_{\text{transformed}}$	$\frac{Area_{occupied} \cdot Time}{Area_{transformed}}$	$\frac{Damage_{EQ}}{Area_{occupied} \cdot Time}$		
	-	*Land transformation, mechanical filtration, R&ES*	$\$/m^2_{\text{transformed}}$	$\frac{\int_{t_1}^{t_2} \Delta_{\text{biophysical indicator}}\, dt}{Area_{transformed}}$	$\frac{\int_{t_1}^{t_2} Service_{\text{not lost (adaptation)}}\, dt}{\int_{t_1}^{t_2} \Delta_{\text{biophysical indicator}}\, dt}$	$Damage_{R\&ES}/\int_{t_1}^{t_2} Service_{\text{not lost (adapt.)}}\, dt$	
		Land transformation, phys.-chemical filtration, R&ES					
		Land transformation, freshwater recharge, R&ES					
		Land transformation, erosion resistance, R&ES					
		Land transformation, biotic production, R&ES					
		Land transformation, mechanical filtration, HH	$DALY/m^2_{\text{transformed}}$		$\frac{\int_{t_1}^{t_2} Service_{\text{lost (no adaptation)}}\, dt}{\int_{t_1}^{t_2} \Delta_{\text{biophysical indicator}}\, dt}$	$Damage_{HH}/\int_{t_1}^{t_2} Service_{\text{lost (no adapt.)}}\, dt$	
		Land transformation, phys.-chemical filtration, HH					
		Land transformation, freshwater recharge, HH					
Land occupation, biodiversity	$m^2_{\text{arable land eq}} \cdot yr/(m^2_{occupied} \cdot yr)$	**Land occupation, biodiversity**	$PDF \cdot m^2 \cdot yr/(m^2_{occupied} \cdot yr)$	$\frac{Damage_{EQ}}{Area_{occupied} \cdot Time}$			
	-	*Land occupation, mechanical filtration, R&ES*	$\$/m^2_{\text{transformed}}$	$\frac{\int_{t_1}^{t_2} \Delta_{\text{biophysical indicator}}\, dt}{Area_{Occupied} \cdot Time}$	$\frac{\int_{t_1}^{t_2} Service_{\text{not lost (adaptation)}}\, dt}{\int_{t_1}^{t_2} \Delta_{\text{biophysical indicator}}\, dt}$	$Damage_{R\&ES}/\int_{t_1}^{t_2} Service_{\text{not lost (adapt.)}}\, dt$	
		Land occupation, phys.-chemical filtration, R&ES					
		Land occupation, freshwater recharge, R&ES					
		Land occupation, erosion resistance, R&ES					
		Land occupation, biotic production, R&ES					
		Land occupation, mechanical filtration, HH	$DALY/m^2_{\text{transformed}}$		$\frac{\int_{t_1}^{t_2} Service_{\text{lost (no adaptation)}}\, dt}{\int_{t_1}^{t_2} \Delta_{\text{biophysical indicator}}\, dt}$	$Damage_{HH}/\int_{t_1}^{t_2} Service_{\text{lost (no adapt.)}}\, dt$	
		Land occupation, phys.-chemical filtration, HH					
		Land occupation, freshwater recharge, HH					

Note that $t_1 = 0$ and $t_2 = 100$ years for shorter-term indicators; $t_1 = 100$ years and $t_2 = \infty$ (500 years for climate change) for long-term damage level indicators; $t_1 = 0$ and $t_2 = 100$ years for the two climate change midpoint indicators; and $t_1 = 0$ and $t_2 = \infty$ for all the other indicators

HH human health, *EC* ecosystem quality, *R&ES* resources & ecosystem services

eutrophication as no spatially resolved emission inventory of eutrophying elementary flows is available. Equation 4 describes how to aggregate native resolution matrices into regional lower resolution matrices by weighting all native CF^{sk}_{ni} for region n intersecting the aggregating region a by its spatial proportionality factor SPF^{sk}_{ni} which equation is described in the ESM. By using such an aggregation approach, we make the underlying assumption that an elementary flow occurring in an unspecified location in a country, a continent, or the globe has more chances to occur where most of the similar emissions or extractions occur in this region. The emission or extraction data or proxy used to aggregate native resolution CFs at a less refined resolution scale (country, continent, globe) are described in Table 1 and their values are available in the database (ESM, section 5).

$$CF^{sk}_{ai} = \sum_n CF^{sk}_{ni} \times SPF^{sk}_{ni} \tag{4}$$

Midpoint impact indicators can be reported and interpreted separately, offering a first viewpoint. At the damage level, three additional and complementary viewpoints are available: (1) impact categories can be kept separated, which allows putting in perspective the relative importance of each impact category as a contributor to the overall damage on one AoP with consistent units; (2) the resulting impact scores can be summed up to express the overall damage on the AoPs considering all the different impact categories at damage level—i.e., the "end" of different cause-effect chains—affecting the same AoP p as defined in Table 1 (Eq. 5):

$$S^{AOP} = \sum_{k \in AOP} I^k \tag{5}$$

(3) Alternatively, impact scores across impact categories can be summed up within each of the six sub-AoCs (i.e., carbon human health, water human health, rest of human health, carbon ecosystem quality, water ecosystem quality, rest of ecosystem quality) for all impact categories at damage level contributing to the same sub-AoC c as defined in Table 1 and allowing to sum up within one AoC such as carbon or water (Eq. 6):

$$S^{AOC} = \sum_{k \in AOC} I^k \tag{6}$$

2.2 Impact categories

IMPACT World+ provides CFs for 21 recommended damage level indicators, plus 23 interim damage level indicators (Table 1). Interim indicators are the one considered as not mature enough to be included in the default version, but bringing useful information for sensitivity analysis rather than just assuming zero impact from these pathways. Figure 1 shows this overall structure of the methodology with the different viewpoints: midpoint impact categories, damage level impact categories, AoP, and AoC. Only the recommended impact categories are shown, and the complete framework including all the interim impact categories can be found in the ESM, section 4. The indicators including long-term effects (climate change, marine acidification, toxicity cancer, toxicity non-cancer, and freshwater, terrestrial, and marine ecotoxicity) are subdivided to differentiate shorter-term from long-term impacts. This is done using a dynamic modeling of the impact, differentiating between shorter-term impacts—taking place within the first 100 years after the emission (named "shorter-term" impacts in the present paper)—and long-term impacts—occurring beyond 100 years after the emission, up to the infinite (or up to 500 years for climate change and marine acidification, for which a full recovery will never be reached—or reached after several millennia—and for which integrating the impact in time up to the infinite would lead to an almost infinite impact), named "long-term" impacts in the present paper.

At the midpoint level, considering that some midpoint indicators are on the impact pathway leading to several damage level indicators, efforts were made to limit the number of individual indicators. Therefore, only 18 recommended plus one interim midpoint indicators are considered in IMPACT World+, using the following principles to reduce the number of indicators:

1. Midpoint indicators all represent integrated impacts over an infinite time horizon. Temporal resolution (i.e., integration over defined time horizons) is considered at damage level only. Climate change is an exception as, at midpoint level, both shorter-term indicator (GWP100) and long-term indicator (GTP100) are considered in order to follow the UNEP/SETAC life cycle initiative consensual recommendations. This allows to adequately assess the contribution of greenhouse gases to both the rate of temperature change (shorter-term climate change) and the long-term temperature increase (long-term climate change) (Levasseur et al. 2016; UNEP 2016). As a side note, GTP100 is an instantaneous indicator and not a time-integrated indicator as currently used in LCIA, but it has been recommended as an appropriate proxy to replace GWP for longer time horizon since the IPCC does not recommend modeling over such long-time horizons because of high uncertainty (Levasseur et al. 2016; UNEP 2016).
2. Some midpoint indicators are considered a reasonable proxy for other midpoints. Climate change long-term midpoint GTP100 is indeed used as a proxy midpoint for marine acidification, recognizing that only CO_2—one of the main climate change contributors remaining in the atmosphere after 100 years—contributes to marine acidification. The AWARE indicator aims to cover water use impacts on scarcity for both freshwater ecosystems and human health. This indicator is not directly on any of the cause-effect chains leading to these damages, but it has been developed with the purpose of being an acceptable common proxy to assess water scarcity at midpoint level for all the water use-related damages (acknowledging the absence of any shared midpoint on these cause-effect chains) (Boulay et al. 2018; Verones et al. 2017). Freshwater ecotoxicity is used as a proxy at the midpoint level for both marine and terrestrial ecotoxicity as the same substances may appear as very toxic, no matter the receiving ecosystem. However, it is still an imperfect proxy as the fate to freshwater, marine water, and soil compartment for the same elementary flow and the same emission compartment may differ a lot. Land occupation and land transformation impacts on terrestrial biodiversity are considered as an acceptable proxy for all the land use impacts on ecosystem services.

Table 2 describes the governing equations linking elementary flows to midpoint and damage indicators for all impact categories. Blue and purple colors distinguish the boundaries between midpoint and damage characterization modeling. The position of the midpoint indicator along the cause-effect chain is category-specific and is chosen based on expert judgment to ensure robustness and minimize model uncertainty. To our knowledge, the only example of midpoint indicator choice based on the quantified increase of uncertainty is the work by Roy et al. for acidification (Roy et al. 2014b).

Even when choosing to communicate results at the midpoint level, a midpoint-damage framework is helpful to interpret the environmental relevance of different midpoint indicators using midpoint-damage models based on physical, biological, and chemical principles. Doing so the aggregation of impacts from midpoint impact categories pertaining to a common AoP rely on natural science principles, limiting value judgments on the aggregation of AoP into a single value. Allowing normalization at midpoint level, further aggregation could only occur through a value-based weighting step. Therefore, IMPACT World+ only provides normalization factors at damage level, as we consider a midpoint-damage modeling based on natural science a more robust approach to put in perspective the relative importance of the different midpoint indicators affecting the same AoP than any normalization/weighting scheme.

Table 1 provides the number of elementary flows covered, the spatial and temporal resolution scale of each impact category. For the former, numbers do not account for regionalization, and the same elementary flow emitted in different compartments is considered as being a single elementary flow even if it has several CFs. For each regionalized impact category, the native spatial resolution corresponds to the scale at which the most influent modeling parameters vary geographically (i.e., the scale at which the CF can be considered as uniform within the spatial unit) or, more pragmatically, to a scale where sufficient input data for the parametrization of the characterization are still available. This choice relies on the judgment of the model developer of each specific impact category.

In the ESM (section 3), we describe each impact category focusing on the models used for the different indicators in each category, their original features, and the adaptations made to ensure consistency across indicators (see also the ESM section 6 for a summary of the main consistency features). The reader is invited to refer to the original references for further details on the models, which are all listed in Table 1. As a brief overview of the main new features in IMPACT World+ impact categories: (a) In complement to GWP100, the IPCC Global Temperature change Potentials (GTP100) are used as a proxy for climate change longer-term impacts at midpoint. At damage level, shorter-term damages (over the first 100 years after emission) are also differentiated from longer-term damages. (b) Marine acidification impact is based on the same fate model as climate change, combined with the H^+ concentration affecting 50% of the exposed species. (c) The material competition scarcity index is applied as a midpoint indicator for mineral resource depletion impact. (d) Terrestrial and freshwater acidification impact assessment combines global atmospheric source-deposition relationships with soil and water ecosystem sensitivity at a resolution of 2° × 2.5° (latitude × longitude). (e) Freshwater eutrophication impact is spatially assessed based on a global hydrological dataset at a resolution grid of 0.5° × 0.5°. (f) Ecotoxicity and human toxicity impacts are based on the parameterized version of USEtox for continents. We consider indoor emissions and differentiate the impacts of metals and persistent organic pollutants for the first 100 years from longer-term impacts. (g) Particulate matter formation-related impacts on human health are modeled using the USEtox population density archetypes for urban and rural emissions to calculate intake fractions and epidemiologically derived exposure response factors. (h) Water consumption impacts are modeled using the consensus-based scarcity indicator AWARE as a proxy midpoint, whereas damages account for competition and adaptation capacity. (i) Impacts on ecosystem quality from land transformation and occupation are empirically characterized at the biome level.

Interim indicators are further described in the ESM, section 3. A systematic comparison of IMPACT World+ models with the other state-of-the-art LCIA methods is available for each impact category (Rosenbaum 2018).

2.3 Areas of concerns—carbon and water

In addition to AoPs, the concept of environmental AoC, defined as an area of particular interest to stakeholders or society, has been introduced through recent work on life cycle-based footprints (Ridoutt et al. 2015, 2016). In general, an AoC may align or not with existing LCA inventory flows or impact categories and may explicitly allow double counting of impacts, particularly when reporting several footprints. Impact World+ aims to avoid such double counting by proposing an LCA-compliant way of grouping impact scores of recommended damage categories by AoC within each AoP:

- The water AoC includes all damage level indicators related to water consumption and degradation on aquatic ecosystems ("marine acidification," "freshwater acidification," "freshwater eutrophication," "marine eutrophication," "freshwater ecotoxicity," "ionizing radiation, ecosystem quality," "thermally polluted water," "water availability, terrestrial ecosystem," "water availability, freshwater ecosystem") and on human health ("human toxicity cancer," "human toxicity non-cancer," "ionizing radiation, human health," "water availability, human health") in compliance with the "comprehensive water footprint" definition of the ISO 14046 standard. It includes water-related impacts associated with a reduction in both water quantity and quality. It considers water-related impacts from a receptor perspective (corresponding to subscript j in Eq. 3). Thus, for human toxicity cancer and human toxicity non-cancer, only the damage on human health through water and fish ingestion (the "water intake") is considered as contributing to the water AoC. Impacts of and other pathways, e.g., impacts via volatilization and inhalation of substances, initially emitted to water are considered in "rest of human health" damages.
- The carbon AoC includes all the shorter-term and long-term damages due to climate change on both human health and ecosystem quality. It cannot be called a "carbon footprint" as it does not correspond to the carbon footprint accounting methodology proposed by the ISO/TS 14067:2018: this standard recommends the use of GWP100, which corresponds to the IMPACT World+ "climate change, shorter-term" midpoint level indicator. ISO/TS 14067:2018 allows also to consider GTP100 (which corresponds to the IMPACT World+ "Climate change, long term" midpoint level indicator) as a complementary indicator when doing carbon footprint.

The IMPACT World+ AoC version therefore allows the following: (i) to sum up the contribution of damage indicators pertaining to water or carbon AoC within a given AoP and (ii) to compare resulting water and carbon impact scores on a common scale, i.e., in DALY and PDF m^2 year within the human health and ecosystem quality AoP, respectively. Damage indicators not pertaining to water or carbon AoC are grouped into the so-called rest of human health and rest of ecosystem quality categories.

This allows, for example, to compare the carbon AoC-related damages on human health ("climate change, human health") to the water AoC-related damages on human health (sum of "human toxicity cancer," "human toxicity non-cancer," "ionizing radiation, human health," and "water availability, human health") and at the same time inform the practitioner about the magnitude of impact scores of a comprehensive LCA that does not fall within the area of concern of interest. The IMPACT World+ AoC is therefore aligned with LCA inventory flows and impact categories, avoids any double counting of impacts, builds on consistent models and units, and does not require any normalization. This AoC approach includes only the recommended impact categories at damage level.

2.4 IMPACT World+ evaluation: global scores and spatialized analyses

2.4.1 Global world inventory flows and normalization factors

We first evaluated IMPACT World+ by determining and comparing the contribution of each damage level indicator to the overall global damage on human health and ecosystem quality AoPs (i.e., performing the world's LCA).

To achieve this, the annual inventory of man-made emissions and extractions at the global scale for 2000 from Wegener Sleeswijk et al. (2008) is used (which is not regionalized) as the inventory flows m_i^s in Eq. 1, for all damage level categories with available data. This covers the following impact indicators: climate change, marine acidification, freshwater eutrophication, marine eutrophication (only via emissions to water), freshwater ecotoxicity, human toxicity cancer, human toxicity non-cancer, particulate matter formation, photochemical oxidant formation, ionizing radiations, and ozone layer depletion. This inventory is then complemented with (i) the annual water consumption for non-agricultural purposes as quantified by the WaterGap model (Flörke et al. 2013) for "water availability impacts, human health" impact and the total water consumption (including agricultural use) for "water availability, freshwater ecosystem" impact, (ii) land use data from the FAO map providing the different land covers around the world in each biome for land use impact indicators, and (iii) regionalized emission data for the acidifying substances available in the GEOSchem model (GEOSchem n.d.) for terrestrial and freshwater acidification as well as for marine eutrophication due to atmospheric emissions. No data could be retrieved for land transformation values, for the share of deep and shallow groundwater use, or for thermal emission at the global scale; hence, it was impossible to calculate an impact score for "land transformation, ecosystem," "water availability, terrestrial ecosystem," and "thermally polluted water" impact indicators. The overall global inventory is characterized by a mix of reference years within the period 2000 and 2010.

The global impacts of IMPACT World+ are then compared to the ones calculated applying ReCiPe and IMPACT 2002+ to the same global inventory.

Applying Eq. 7 to sum up the world annual impact scores for each category k ($I^k_{world\ annual}$) related to each AoP and dividing them by the world population ($N_{\text{world pop}}$) provides the three normalization factors (NF^{AOP}) of IMPACT World+, one per AoP:

$$NF^{AOP} = \frac{\sum_{k \in AOP} I^k_{world\ annual}}{N_{\text{world pop}}} = \frac{S^{AOP}_{world\ annual}}{N_{\text{world pop}}} \quad (7)$$

2.4.2 Spatial variability of characterization factors

Spatial variability is analyzed at each coarser level of spatial resolution, accounting for the additional uncertainty related to the less precise information about where the emission occurs. For each regionalized impact category, we analyze the global spatial variability by giving the minimum, maximum, mean, quartiles, 2.5th, and 97.5th percentiles of the native emission flows (weighted percentile by emission level in each spatial unit, e.g., an urban spatial unit represents a higher percentile of emission than a remote location with little emissions) and compare these to the overall spread of the elementary flows characterized within this impact category.

3 Results and discussion

3.1 General framework and impact categories

Characterization factors at midpoint and damage level are available in a database in the ESM, section 5. The latest information on the method updates, the maps, and the files to import IMPACT World+ in LCA software can be found on the IMPACT World+ website http://www.impactworldplus.org/.

3.2 Global normalization factors and impact contributions

Figure 2a, b shows the contribution by damage level impact indicators of global worldwide emissions to both

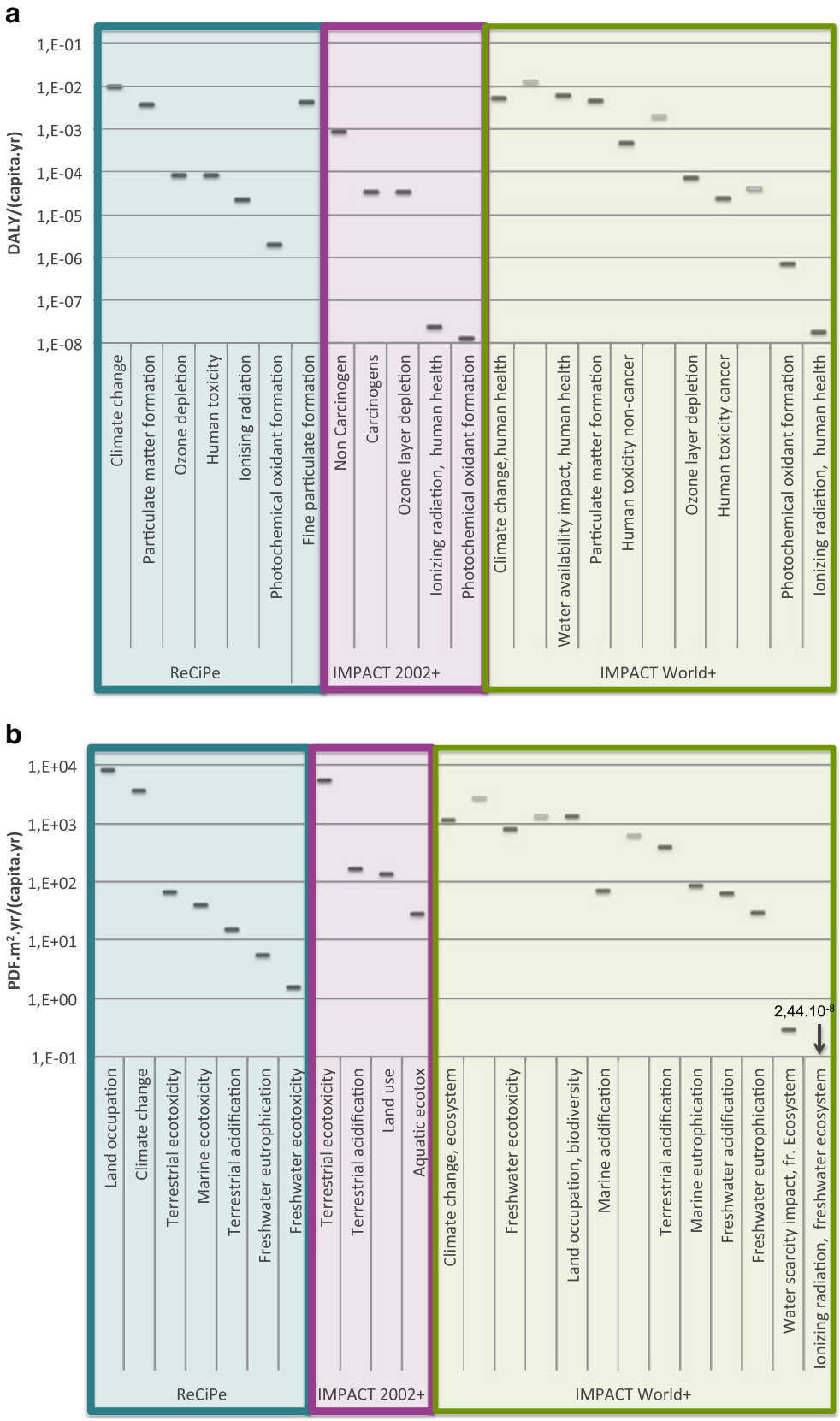

Fig. 2 Contribution by recommended damage level impact indicators of global emissions and extractions to both **a** human health and **b** ecosystem quality AoPs as assessed by ReCiPe, IMPACT 2002+, and IMPACT World+ methods. Shorter-term impacts appear in black and long-term impacts in gray. Note that the "land transformation, ecosystem," "water availability, terrestrial ecosystem," and "thermally polluted water" impact indicators are not represented on this figure, as no global inventory data was available to generate an impact score for such indicators

human health and ecosystem quality AoPs as assessed by IMPACT Word+, ReCiPe, and IMPACT 2002+. Results are plotted on a log scale to account for the high variability of impact scores at damage level and impact categories are ranked for each LCIA method in decreasing order of environmental relevance.

Normalization factors building on the global inventory for the areas of protection for human health and ecosystem quality were calculated as being 3. 10^{-2}DALY/capita/year and 9. 10^4 PDF m^2 year/capita/year respectively, including all the shorter-term and long-term IMPACT World+ indicators presented in Fig. 2a, b.

In agreement with ReCiPe and IMPACT 2002+, IMPACT World+ finds dominant contributions of climate change and particulate matter formation to human health impacts (Fig. 2a) and negligible contributions from ionizing radiation, ozone depletion, and photochemical oxidant formation. IMPACT World+ has introduced new impact indicators at the damage level, which results in important differences when compared to IMPACT 2002+ and ReCiPe, in particular for the water availability impacts on human health (second highest contributor). Similar to IMPACT 2002+ and ReCiPe, toxic impacts (cancer and non-cancer) are smaller than particulate matter formation impacts, which is in agreement with results from the WHO's Global Burden of Disease study series that identified ambient particular matter pollution as the major environmental risk factor for human health (Mathers et al. 2008).

For the damages to ecosystem quality, IMPACT World+ also provides a picture similar to ReCiPe and IMPACT 2002+, with climate change, land use, freshwater ecotoxicity, and terrestrial acidification being the most contributing impact indicators. However, additional categories introduced in IMPACT World+, such as the long-term impacts of marine acidification and eutrophication, also turn out to be relevant (Fig. 2b). Freshwater ecotoxicity normalization factors vary significantly from one method to another (around three orders of magnitude). It is the third highest contributor on ecosystem quality AoP of IMPACT World+. Such discrepancies between the different ecotoxicological models, as used in IMPACT 2002+ and ReCiPe, were at the origin of the work of the UNEP/SETAC life cycle initiative leading to the creation of the USEtox model, which is integrated into IMPACT World+. Like for damages to human health, impacts of ionizing radiation on ecosystems are orders of magnitude lower than the other impact categories.

The damages on the water and carbon AoCs are of the same order of magnitude for both human health and ecosystem quality AoPs, with a higher contribution of damages on carbon AoC to both AoPs (Fig. 3a, b). The global damages on water AoC generate 22% of impacts on human health and 35% of those on ecosystem quality, whereas the damages on carbon AoC contribute to 60.5% and 45%, respectively. "Rest of human health" and "rest of ecosystem quality" impact categories are not negligible: they contribute 17% and 20% to human health and ecosystem quality, respectively. When focusing on shorter-term impact only, damages on water AoC contribute to 39% of impacts on human health and 27% of those on ecosystem quality, whereas damages on carbon AoC contribute to 31% and 28% respectively. "Rest of human health" contribute to 30% of human health impacts and "rest of ecosystem quality" is dominating the ecosystem quality impacts with 44% of the shorter-term impacts.

3.3 Spatial variability of characterization factors

This section analyzes and discusses the spatial variability of CFs for regional impact categories: toxic impacts, water availability impacts on human health, particulate formation impacts, freshwater and terrestrial acidification, marine and freshwater eutrophication, and land occupation.

3.3.1 Impacts on human health

Figure 4 shows the spatial variability of CFs for (a) human toxicity cancer, (b) water availability impacts on human health, and (c) particulate matter formation.

Human toxicity Human toxicity cancer CFs for an emission to air are shown in $\log_{10}$ scale in Fig. 4a), differentiating minimum, maximum values across continents. The maximum spatial variability between continents is two orders of magnitude, which is significantly lower than the total variability between toxicity cancer indicator contributing elementary flows, approximately 13 orders of magnitude. Therefore, information about the chemical composition and the exact quantities of toxic emissions allows higher discrimination than knowing the continent of emission. In USEtox, the intra-continental variability is considered for air emissions via archetypes (indoor-urban-rural continental archetypes) with a typical variation of 1.5 in average and up to a factor 127 between impacts from urban vs. rural archetype emissions. The indoor archetypes were added in Fig. 4a—USEtox CFs for industrial settings and household, using the OECD countries' average archetype—with median factors of 142 and 5 times higher than the rural continental factors. The ESM, section 7 shows how the corresponding intake fractions vary as a function of the residence time of the elementary flow in the air. The influence of these archetypes is therefore as important as the variations between continental default CFs, supporting the idea that the archetype approach is a pragmatic solution to reflect variability and connect with available inventory databases such as ecoinvent. It is only at high spatial resolution, in the order of 10 km × 10 km grid, that proximity between emission sources and population density (i.e., urban vs. rural) can be detected by a spatial model (van Zelm et al. 2008). The archetype approach is, therefore, more accurate and can be further

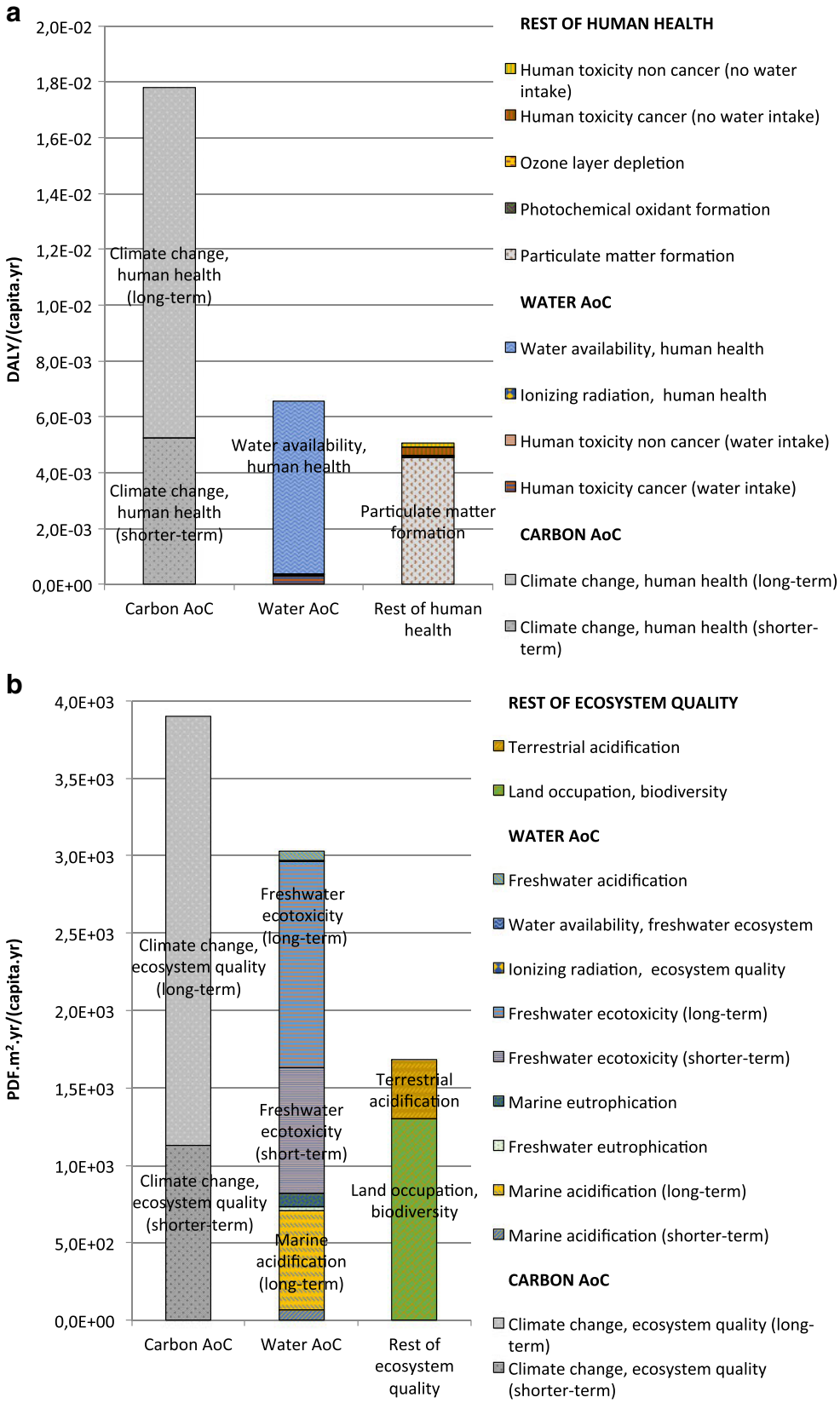

Fig. 3 Impacts aggregated in terms of AoC using the AoC version of IMPACT World+ for human health (**a**) and ecosystem quality (**b**) AoPs

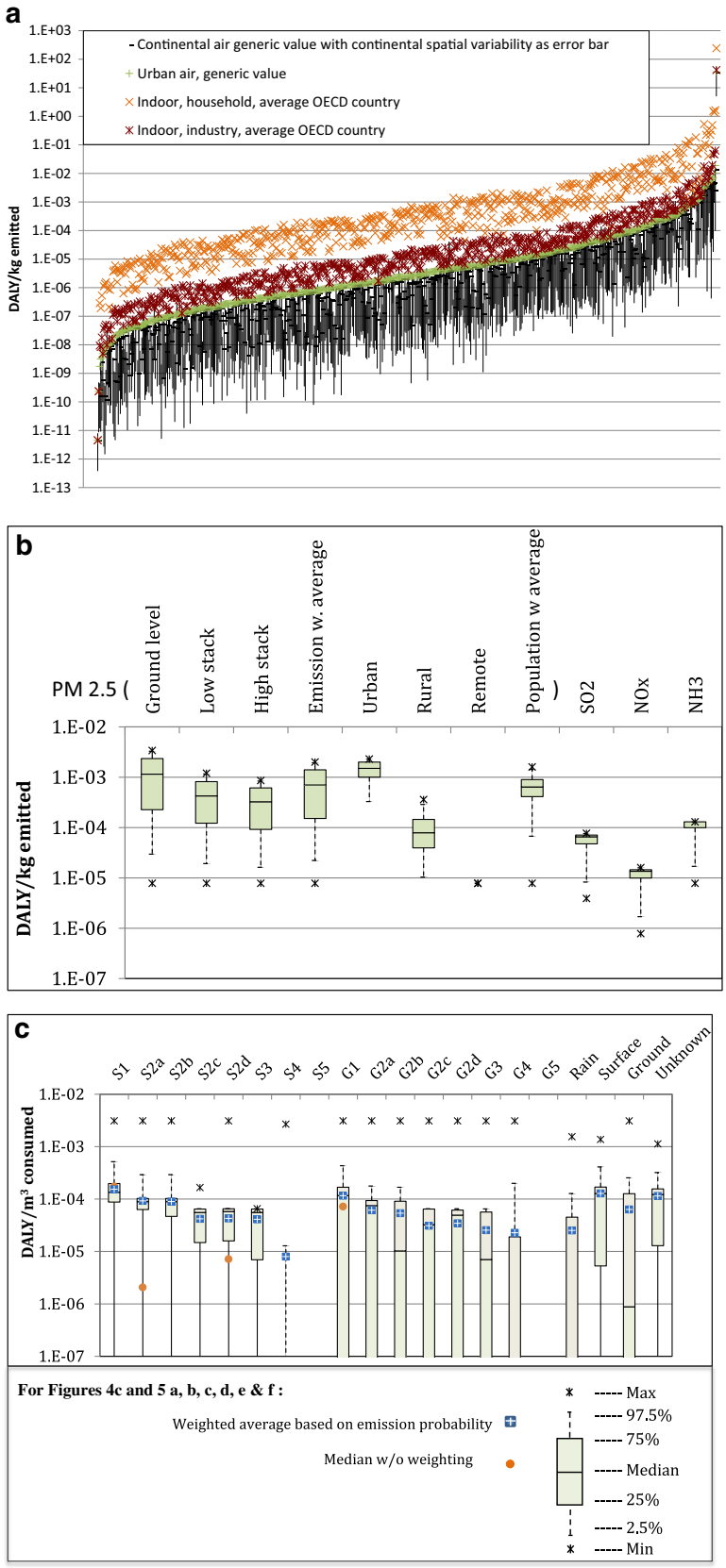

Fig. 4 Spatial variability of impact indicators contributing to human health AoP. **a** Toxicity cancer outdoor and indoor. **b** Particulate matter formation. **c** Water availability impacts (for various types of surface (S) and groundwater (G) quality—1 being the best and 5 the worst water quality). Details on all the acronyms used for water quality are defined in the supporting information, section 3

extended at city-specific level (Apte et al. 2012). Results for toxicity non-cancer impacts of air emissions and for (eco)toxicity impact categories associated with other compartments are similar to toxicity cancer impacts for air emissions as shown in the ESM, section 8.

Particulate matter formation Figure 4b presents the spatial variability of $PM_{2.5}$ impacts across continents for different emission archetypes (emission height, urban vs. rural). On the one hand, the spatial variability of $PM_{2.5}$ across continents is larger than the variability between the emission height of the source (high stack, low stack, ground level, or emission-weighted average). On the other hand, the variability between urban, rural, and remote archetypes is higher than the variability across continents. The impacts per kg $PM_{2.5}$ emitted or formed in an urban environment are a factor 30 higher than for rural areas, similarly to human toxicity impacts. It is, therefore, more important to know whether the emission occurs in a highly populated vs. rural area rather than in which continent it occurs. For the considered $PM_{2.5}$ precursor elementary flows (SO_2, NO_x, and NH_3), the variability between elementary flows is as important as the continent of emission.

Water availability impacts on human health Figure 4c presents the spatial variability of water availability impacts across the 808 spatial units obtained by overlapping water basins and countries worldwide. As a general rule, the impact on human health per m^3 consumed decreases as water quality decreases, with typically one order of magnitude difference between the highest S1 and the second lowest quality S4. The variability across extraction locations spans several orders of magnitude and is substantially higher than the variations between different water qualities, except for the lowest water quality level (types S5 and G5), for which the location does not matter as both CFs equal 0, no matter the location. Therefore, it is essential to regionalize this impact category.

Regionalized impacts on ecosystem quality Figure 5 shows the spatial variability of impact characterization factors on ecosystem quality, for (a) freshwater acidification, (b) terrestrial acidification, (c) marine eutrophication, (d) freshwater eutrophication, and (e) land occupation (which as exactly the same pattern as land transformation). For each of these impact indicators except land occupation, the spatial variability of a given elementary flow is much higher than the variability between elementary flows, which is typically less than one order of magnitude, highlighting that it may be more important to know where an emission occur than what is emitted. For land use impacts, both the type of land cover and the biome seem equally important to know.

In most of these impact categories, the characterization factors of half of the regions (25th to 75th percentiles) are within one to maximum two orders of magnitude and the 95th percentile within three to four orders of magnitude. The spatial variability of land occupation impact on ecosystem quality is especially high with 95th confidence intervals typically covering four orders of magnitude with outliers up to seven orders of magnitude. This range is much higher than the variability between land cover types (approximately one order of magnitude) showing here again the importance of regionalizing.

Across all the regionalized impact indicators (Figs. 4 and 5), the weighted average—that accounts for the probability of emission in the different spatial units—and the median do not correspond. The approach to aggregate the native resolution CFs into a coarser scale is, therefore, an influential choice that has to be documented and justified.

The spatial variability of Figs. 4 and 5 corresponds to the spatial variability at the global scale. Of course, uncertainty related to spatial variability decreases when using CFs regionalized at a more specific level, as illustrated in Fig. 6 with the example of the terrestrial acidification characterization factor of sulfur dioxide at different resolutions. The spatial variability for each of the regionalized CFs at each of the available regionalization scales (country, continent, globe) is available in the database in the ESM, section 5. The LCA practitioner has then the choice to use the global default characterization factors of IMPACT World+ as any other conventional, non-regionalized LCIA method. Alternatively, when needed, IMPACT World+ gives the opportunity to replace the global default CFs associated with the important contributors of an LCA impact score with more accurate, spatially explicit CFs, with a reduced uncertainty. The works from Patouillard et al. (2016) and Hernández-Padilla et al. (2017) show how to operationalize regionalization by applying the IMPACT World+ method.

To characterize non-spatially explicit elementary flows (as it is the case in current life cycle inventory databases), IMPACT World+ provides global default characterization factors to be used in conventional LCA software. In addition, for each regionalized impact category, IMPACT World+ provides two additional sets of characterization factors: at the continental level (6 CFs per elementary flow for an emitting compartment) and at the country level (197 CFs per elementary flow for an emitting compartment). Many unit processes are already country specific in inventory databases such as ecoinvent and some related elementary flows, such as water resource use, are also spatially explicit at the country level. The third set of CFs is also available at the native resolution scale, but not directly implemented in LCA software. They may be useful to characterize a handful of foreground elementary flows or when iteratively collecting additional relevant background data that needs to be regionalized to improve decision-making. Their numbers vary depending on the impact category and they are provided in the database available in the ESM, section 5.

3.4 Weighting

IMPACT World+ does not provide recommended weighting factors. Nevertheless, LCA practitioners might apply public available weighting approaches, such as the STEPWISE factors proposed by Weidema et al. (2006) which are compatible with IMPACT World+ and can optionally be used to obtain a single monetized score.

3.5 Inherent limitations of the method

Several limitations of IMPACT World+ must be mentioned. While 21 midpoint impact indicators were integrated into the LCIA method, another 23 impact indicators were considered still immature and were provided as interim for sensitivity analysis only. Other impact categories were not considered at all, such as the impacts of photochemical oxidants on

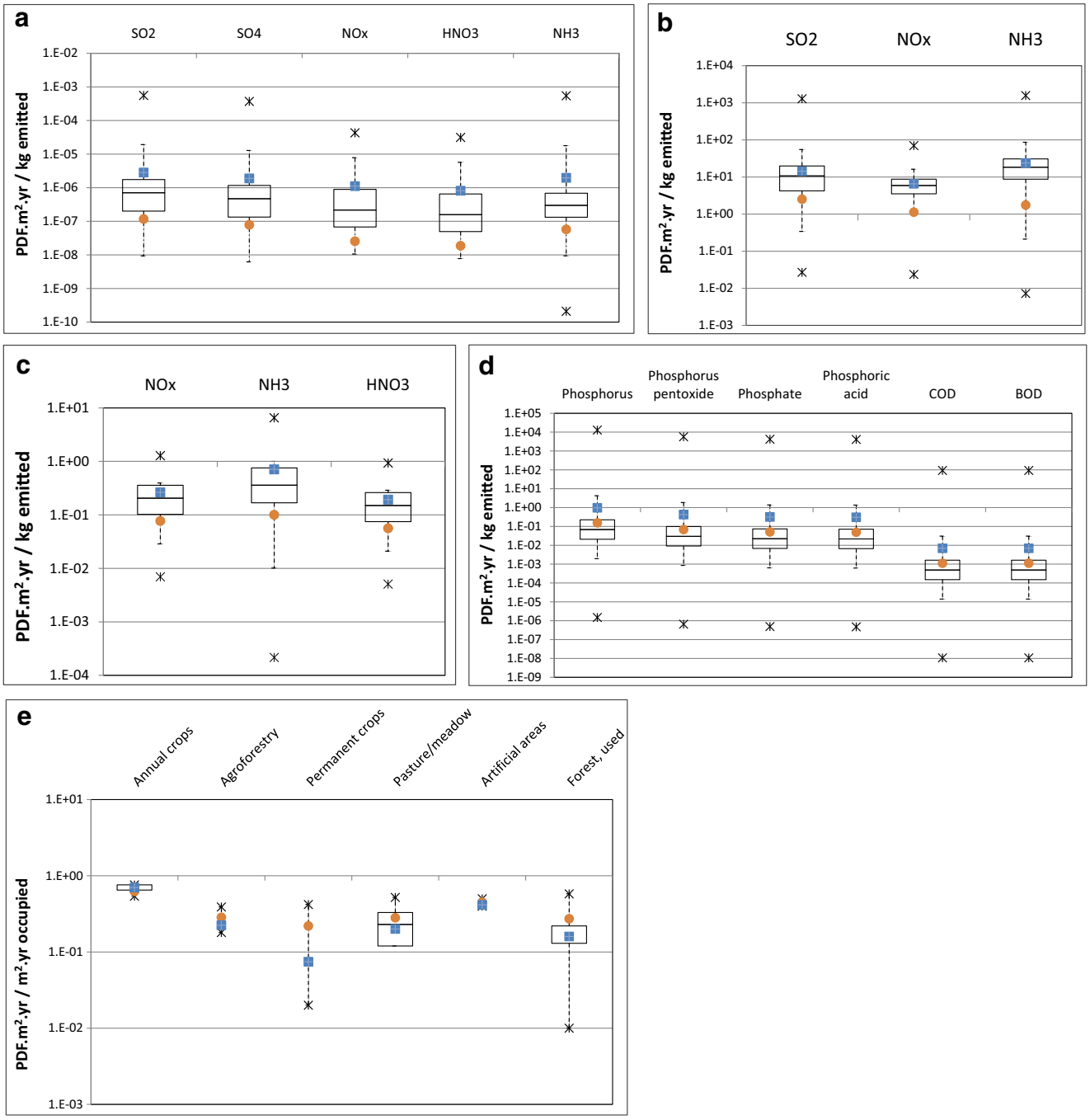

Fig. 5 Spatial variability of impact indicators contributing to the ecosystem quality AoP. **a** Freshwater acidification. **b** Terrestrial acidification. **c** Marine eutrophication. **d** Freshwater eutrophication. **e** Land occupation on ecosystem quality

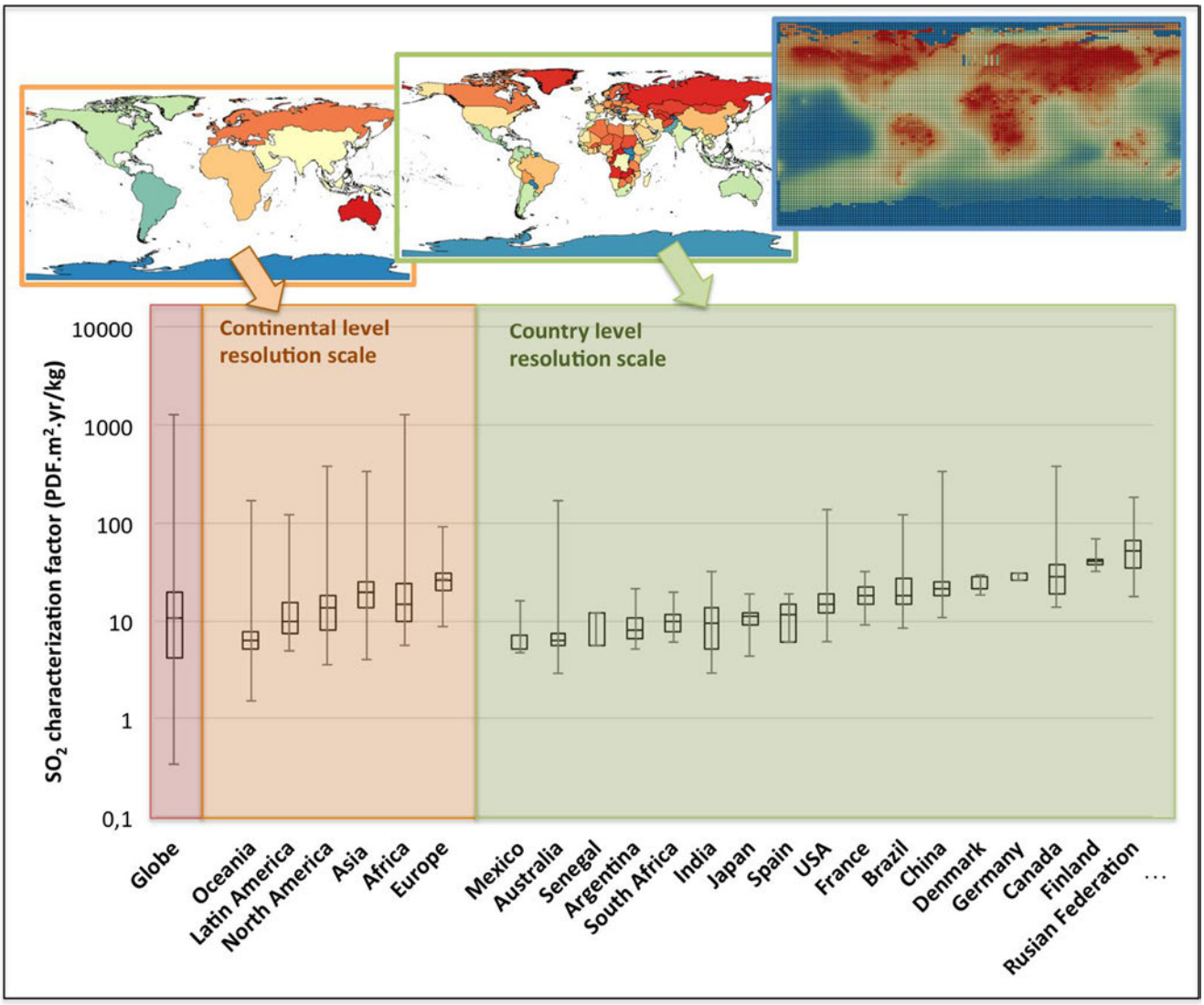

Fig. 6 Influence of the level of aggregation on uncertainty related to spatial variability. Example of the terrestrial acidification characterization factor of sulfur dioxide (SO_2) at the global, continental, and country level resolution scale with box plots representing 5th, 25th, 75th, and 95th percentiles and the median in each region. The maps represent the terrestrial acidification characterization factor of SO_2 at the continental/country/native resolution scales respectively from the left to the right

vegetation, the noise, and the biotic resources use (overfishing, unsustainable wood exploitation). They should be the focus for further research. Finally, IMPACT World+, like all other LCIA methods, inherits a number of assumptions and simplified representation of environmental mechanisms from the characterization models it builds upon. Last but not the least, IMPACT World+ builds on a set of modeling choices that represent the perspective of their developers. Therefore, while representing the current state of knowledge in environmental sciences, this implies that IMPACT World+ is a simplified and incomplete representation of the environment that we want to protect. Hence, results need to be interpreted with care, acknowledging the underlying modeling choices, hypothesis, and limitations.

4 Conclusions

The IMPACT World+ method builds on a midpoint-damage LCIA framework that ensures consistency of modeling assumptions and choices across impact categories. It allows assessing emissions and resource consumption from any location worldwide through characterization factors at four hierarchical levels of resolution: global default, continental default, country default, and native resolutions for all regional impact indicators with the associated uncertainty due to spatial variability. We demonstrated that for most of impact indicators, spatial variability of elementary flow-specific CFs is larger than the variability among elementary flows. IMPACT World+ therefore has the potential to guide an efficient

regionalization effort for LCA practitioners, identifying the most contributing elementary flows that need to be regionalized to reduce the uncertainty due to spatial variability and increase the discriminating power of LCA.

Normalization factors were obtained accounting for regional elementary flows and characterization factors. Results show the dominance of climate change and particulate matter formation impacts on human health damages, the dominance of climate change and land use on ecosystem quality damages, but also the importance of impact categories such as water availability impacts on human health (second highest contributor) or marine acidification and freshwater ecotoxicity to ecosystem quality AoP (highest contributors after climate change and land use).

The uncertainty related to the spatial variability of all the regionalized CFs has been assessed, which is only a partial assessment of the overall uncertainty on CFs. Further work is ongoing to fully document the overall uncertainty of the IMPACT World+ method in a consistent way across all the impact categories.

Four distinct, consistent, and complementary viewpoints to express an LCIA profile are offered: a midpoint level, a damage level, an AoP damage level encompassing three AoPs, and a novel AoC damage level encompassing six sub-AoCs, structured according to the respective contributions associated with the AoCs water and carbon as well as "rest of the impacts" on both human health and ecosystem impact AoPs. Both damages on AoCs computed from a global emission inventory are comparable within a factor of 2 but provide opposite conclusions when considering shorter-term or long-term impacts, damages on water AoC being more important at a shorter term. Rest of the impacts are far from being negligible, highlighting the importance of quantifying also other impact categories (in particular land use and particulate matter formation) when doing carbon footprint and/or water footprint to avoid potential burden shifting.

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