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METHODS, TOOLS, AND SOFTWARE

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LC-IMPACT: A regionalized life cycle damage assessment method

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Abstract

Life cycle impact assessment (LCIA) is a lively field of research, and data and models are continuously improved in terms of impact pathways covered, reliability, and spatial detail. However, many of these advancements are scattered throughout the scientific literature, making it difficult for practitioners to apply the new models. Here, we present the LC-IMPACT method that provides characterization factors at the damage level for 11 impact categories related to three areas of protection (human health, ecosystem quality, natural resources). Human health damage is quantified as disability adjusted life years, damage to ecosystem quality as global species extinction equivalents (based on potentially disappeared fraction of species), and damage to mineral resources as kilogram of extra ore extracted. Seven of the impact categories include spatial differentiation at various levels of spatial scale. The influence of value choices related to the time horizon and the level of scientific evidence of the impacts considered is quantified with four distinct sets of characterization factors. We demonstrate the applicability of the proposed method with an illustrative life cycle assessment example of different fuel options in Europe (petrol or biofuel). Differences between generic and regionalized impacts vary up to two orders of magnitude for some of the selected impact categories, highlighting the importance of spatial detail in LCIA. This article met the requirements for a gold – gold JIE data openness badge described at http://jie.click/badges.

KEYWORDS

disability adjusted life years, global extinction risk, industrial ecology, kilogram ore extracted, potentially disappeared fraction of species, spatial differentiation

1 | INTRODUCTION

Life cycle assessment (LCA) aims at quantifying potential environmental impacts associated with the life cycle of a product or service (Klöpffer, 1997). The desire to assess the "complete" environmental impact profile has been an important driver for developments in life cycle impact assessment (LCIA). No LCIA method is truly complete today, with missing impact categories including salinization, plastic pollution, invasive species, and others. To increase the coverage of potential environmental impacts in LCIA, there is a need to increase the number of impact pathways considered by developing new methods or improving existing methods. This can be done, for example, by improving the modeling, using better data, or adding spatial detail for impacts that have a local or regional dimension (Pfister, Koehler, & Hellweg, 2009). Regionalization can be highly relevant because environmental conditions vary greatly through space (e.g., water availability, land types, number and degree of endemism of species present, population density, and background concentration of reacting agents). Regionalization in LCIA is a topic that has been acknowledged as important and tackled before, in different ways, in LCIA methods, for example, in both the EDIP (Potting & Hauschild, 2004) and the LUCAS methodology (Toffoletto, Bulle, Godin, Reid, & Deschênes,2007). However, there is still a need for a regionalized LCIA method that covers a large number of impact categories on a global level and respects the different scales that are relevant for the specific impact categories.

When conducting an LCA, characterization factors (CFs) are used to translate the inventory results of a given case study into indicators of potential environmental impacts. Sets of CFs are typically available to practitioners in the form of LCIA methods (implemented into LCA software), which represent an effort to integrate several published characterization models into a consistent framework. Many recent methodological developments and improvements in LCIA models, in particular with regard to spatial differentiation, have however been published independently from each other and have not yet been consolidated within a consistent LCIA method. As a consequence, some of these newer, more environmentally relevant models, are less used compared to older and often less comprehensive models currently integrated in available methods. It should be noted, however, that efforts on building new LCIA methods are ongoing (apart from LC-IMPACT: also ReCiPe2016 (Huijbregts et al., 2017) and IMPACTWorld+ (Bulle et al., 2019)).

The EU-FP7-funded project "Development and application of environmental Life Cycle Impact assessment Methods for imProved sustAinability Characterisation of Technologies (LC-IMPACT)" resulted in many novel and valuable advancements in LCIA, such as new models for impact pathways (e.g., land use and resource scarcity) and greater regionalization of impact pathway models. It is our aim to combine the advancements that emerged from this project into one consistent and transparently documented LCIA method. In addition, we complemented the developments of the EU-FP7-funded project with further refinements after the end of the project, especially for impacts related to ecosystem quality. We also added extra characterization models for categories that were not covered within the project to arrive at an impact pathway coverage which is as complete as possible, given the current state of the art. Our objectives for the development of the LC-IMPACT method were to (a) collect characterization models for all available impact pathways and, where needed, develop state-of-the-art characterization models and use them to provide regionalized

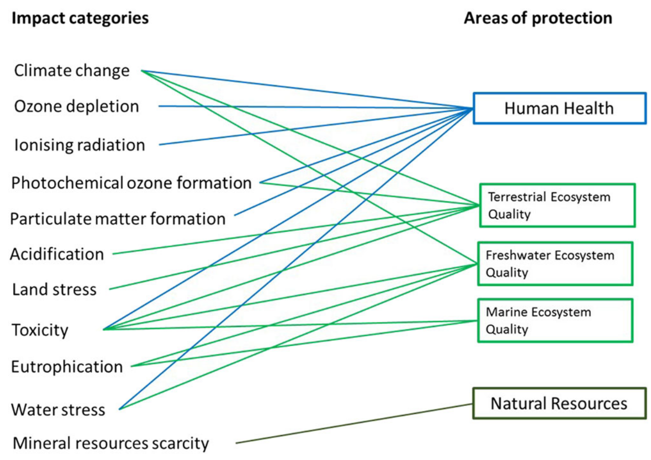

FIGURE 1 Overview of the broad impact categories and areas of protection (AoP) covered so far in LC-IMPACT. The color of the lines indicates to which AoP the impact categories are related. Within ecosystem quality, three different ecosystems types are distinguished (Verones et al., 2019)

characterization factors with global coverage at category-specific, country, continental, and global scale, (b) include aspects of species extinction vulnerabilities in the assessment of ecosystem quality, and (c) provide distinct sets of characterization factors, based on consistently implemented value choices across impact categories. We also applied LC-IMPACT to a case study on different fuel options to illustrate its application.

2 | LC-IMPACT METHOD

2.1 | Areas of protection and impact categories

Most LCIA methods cover three areas of protection (AoP), topics that are important to society and that we want to safeguard. This is also the case for LC-IMPACT, where we implemented the AoPs "human health," "ecosystem quality," and "natural resources." So far, LC-IMPACT includes 11 broad impact categories (Figure 1), all of them contributing to one or two AoPs (the impact categories climate change, photochemical ozone formation, toxicity, and water stress contribute to two AoPs each). In addition, three ecosystem types (terrestrial, freshwater, and marine) are distinguished within the "ecosystem quality" AoP. For eutrophication, LC-IMPACT covers both freshwater and marine eutrophication and for ecotoxicity, impacts on freshwater, marine and terrestrial ecosystems are included. All impacts are quantified at a damage level (see details further below).

2.2 | Spatial detail

Some impact categories cover impacts that are distributed across the world, independently from the place of emission or extraction. Therefore, they only contain global CFs. This is the case for climate change, stratospheric ozone depletion, and mineral resources extraction. Other impact categories describe impacts that are limited to the regional or local scale and thus vary widely depending on where the intervention (emission/extraction) takes place and the associated regional or local environmental conditions. These latter impact categories were modeled with spatial differentiation (Tables 1 and 2). Regionalized CFs were reported for four different spatial levels: the original "native" spatial level (Mutel et al., 2018), as determined by the method developer, as well as country averages, continental averages and a global average (the latter for application when the location of the emission/resource extraction is unknown), to facilitate the concordance with standard LCI data and the practical application. The native resolution is impact-category specific. For example, the native resolution for water stress impacts is the (sub-)watershed, while for land stress it is ecoregions with similar ecological conditions (Olson et al., 2001). Aggregation to country, continental, and global levels was done based on where emissions or resource consumption are most likely to take place (i.e., using data on spatially explicit emission data, specific for each impact category). For land use, the area shares of the ecoregions within each country or continent were used as the basis for aggregation.

2.3 | Linear/average versus marginal characterization factors

LCIA methods generally derive their CFs following either a marginal approach or an average approach (Hauschild & Huijbregts, 2015). A marginal approach investigates the additional impact, if the pressure is increased by a very small amount, relative to the current state at a given point in time, which is the reference state, that is, it takes the derivative of the cause–effect curve. Average characterization factors use the distance between the current state and a state of zero impact to calculate the average impact per unit of intervention. In case information on the current state is lacking, a linear approach can be used instead. The linear approach, most closely connected to the average approach, is represented by the line connecting the origin (zero pressure = zero impact) with a predefined point on the response curve. In LC-IMPACT, this is always where 50% of the species in the ecosystem are potentially affected. From a conceptual perspective, the main advantage of the marginal approach is that it focuses on

TABLE 1 Overview of impact categories dealing with human health (see also section 2.4), modeling approaches taken, spatial scales and key references used in LC-IMPACT for modeling the impact pathways. For details on time horizons and covered effects see the LC-IMPACT report (Verones et al., 2019). The native scale chosen is the available scale that best represents the respective spatial relevance (Mutel et al., 2018)

Impact category	Modeling approach	Native spatial scale	Key references
Climate change	Mix marginal/average	Global	De Schryver, Brakkee, Goedkoop, and Huijbregts (2009) De Schryver et al. (2011) Joos et al. (2013) IPCC (2013)
Stratospheric ozone depletion	Linear	Global	Hayashi, Nakagawa, Itsubo, and Inaba (2006)
Ionizing radiation	Linear	Global	De Schryver et al. (2011) Frischknecht,Braunschweig, Hofstetter, and Suter (2000)
Photochemical ozone formation	Linear	56 world regions (Krol et al., 2005; Van Dingenen et al., 2018)	van Zelm, Preiss, van Goethem, Van Dingenen, and Huijbregts (2016)
Particulate matter formation	Linear	56 world regions (Krol et al., 2005; Van Dingenen et al., 2018)	van Zelm et al. (2016)
Human toxicity (carcinogenic)	Linear	16 subcontinental regions (Kounina, Margni, Shaked, Bulle, & Jolliet,,2014)	Rosenbaum et al. (2008) Rosenbaum et al. (2015) Fantke and Jolliet (2016)
Human toxicity (non-carcinogenic)	Linear	16 subcontinental regions (Kounina et al., 2014)	Rosenbaum et al. (2008) Rosenbaum et al. (2015) Fantke and Jolliet (2016)
Water stress (human health)	Average	11,050 watersheds (Alcamo et al., 2003)	Pfister et al. (2009) Pfister and Bayer (2014)

emission changes with the highest efficiency in terms of effect reduction. The average approach, on the other hand, explicitly strives to reach a state of the environment in which effect targets set by society are not exceeded (Huijbregts, Hellweg, & Hertwich,2011). For more details on differences between the approaches, see, for example, also Hauschild and Huijbregts (2015).

Where possible, sets of CFs derived from both average/linear and marginal approaches were made available in LC-IMPACT (see Tables 1 and 2). This was the case for two of the impact categories included in LC-IMPACT: land stress and water use impacts on human health. Two categories are only modeled as marginal (terrestrial acidification, water consumption for ecosystem quality), and 13 are average/linear (remaining impact categories). For those impact categories with a choice available, we recommend being as consistent as possible, when using different sets of CFs.

2.4 | Human health

The basic equation for calculating characterization factors (CFs) for human health (Hauschild & Huijbregts, 2015) is shown in Equation (1) and consists of a damage factor (DF), an effect factor (EF), a human exposure factor (XF), and a fate factor (FF).

$$CF_{\text{human health}} = DF \times EF \times XF \times FF \tag{1}$$

For human health, LC-IMPACT quantifies the well-established disability adjusted life years (DALY) per functional unit. FFs, XFs, and EFs are based on specific data and models per impact category (see Table 1 for references). The human damage factor is based on information about how many healthy years are lost due to a certain cause of premature death or a disability, as reported in the Global Burden of Disease studies from the World Health Organization and the Institute for health metrics and evaluation (e.g., Kassebaum et al. (2016)). We included seven impact categories affecting human health (Figure 1, Table 1). Four of them encompass spatial detail (water stress, human toxicity, particulate matter formation, and photochemical ozone formation), while three are calculated as global averages due to the insensitivity to the place of emission and the global consideration of the impact in underlying models (climate change, stratospheric ozone depletion), or due to the lack of spatial consideration in available models (ionizing radiation).

TABLE 2 Overview of impact categories dealing with ecosystem quality (see also section 2.5), modeling approaches taken, spatial scales , and key references used in LC-IMPACT for modeling the impact pathways. For details on time horizons and covered effects see the LC-IMPACT report (Verones et al., 2019). The native scale chosen is the available scale that best represents the respective spatial relevance (Mutel et al., 2018)

Impact category	Modeling approach	Taxonomic coverage	Native spatial scale	Key references
Climate change (terrestrial ecosystems)	Mix marginal/average	Mammals, birds, frogs, reptiles, butterflies, vascular plants	Global	Urban (2015) Joos et al. (2013) IPCC (2013)
Climate change (freshwater ecosystems)	Mix marginal/average	Fish	Global	Hanafiah,Xenopoulos, Pfister, Leuven, and Huijbregts (2011) Joos et al. (2013) IPCC (2013)
Photochemical ozone formation	Linear	Vascular plants	56 world regions (Krol et al., 2005; Van Dingenen et al., 2009)	van Zelm et al. (2016)
Terrestrial acidification	Marginal	Vascular plants	2.0° x 2.5°	Roy et al. (2014) Azevedo, Van Zelm, Hendriks, Bobbink, and Huijbregts (2013a)
Freshwater eutrophication	Linear	Fish	449 freshwater ecoregions of the world (Abell et al., 2008)	Azevedo et al. (2013b) Helmes, Huijbregts, Henderson, and Jolliet (2012) Scherer and Pfister (2015)
Marine eutrophication	Linear	Fish (bony and cartilaginous), crustaceans, molluscs, echinoderms, annelids, and cnidarians	River basins to large marine ecosystems (5,772 pairs)(Sherman, Alexander, & Gold,1993)	Cosme, Koski, and Hauschild (2015) Cosme and Hauschild (2016) Cosme and Hauschild (2017) Cosme, Mayorga, and Hauschild (2018)
Freshwater ecotoxicity	Linear	For metals: algae, crustaceans, fish; for organic chemicals: freshwater species as available in USEtox	16 subcontinental regions (Kounina et al., 2014)	Dong, Gandhi, and Hauschild (2014) Gandhi et al. (2010) Rosenbaum et al. (2008)
Marine ecotoxicity	Linear	For Be, Cs: crustaceans; for Be, Cr, Fe(II), Fe(III), Sr: crustaceans, fish; for Al, Mn: algae, crustaceans, fish	16 subcontinental regions (Kounina et al., 2014)	Dong, Rosenbaum, and Hauschild (2016)
Terrestrial ecotoxicity	Linear	For Cu, Ni: crustaceans, plants, bacteria; for Ag: crustaceans, chlorophytes, bony fish; for As(III), As(V), Hg, Sb(III), Sb(V), Se, Cr(VI), Sn, Tl, V: freshwater species as available in USEtox; for Ba, Be, Cd, Co, Mn, Pb, Zn, Al, Cr(III), Fe(II), Fe(III), Sr: algae, crustaceans, fish	16 subcontinental regions (Kounina et al., 2014)	Owsianiak et al. (2015) Owsianiak, Rosenbaum, Huijbregts, and Hauschild (2013)
Land stress	Both marginal and average	Mammals, birds, reptiles, amphibians, vascular plants	804 terrestrial ecoregions (Olson et al., 2001)	Chaudhary, Verones, De Baan, and Hellweg (2015)
Water stress (ecosystems)	Marginal	Mammals, birds, reptiles, amphibians, vascular plants	0.05° x 0.05°	Verones, Pfister, van Zelm, and Hellweg (2017a)

2.5 | Ecosystem quality

The general equation for CFs in ecosystem quality is given in Equation (2). It consists of a vulnerability factor (VF) to translate species loss from local or regional to global, an effect factor (EF), an exposure factor (XF), and a fate factor (FF). Note that the XF is equal to one for some categories (e.g., for land stress) where exposure does not have a conceptual meaning.

$$CF_{\text{ecosystem quality}} = VF \times EF \times XF \times FF \tag{2}$$

For ecosystem quality, LC-IMPACT can be used to quantify the "potentially disappeared fraction of species over time" (PDF•yr) per functional unit (Verones, Moran, Stadler, Kanemoto, & Wood, 2017b; Woods et al., 2017). CFs may or may not already contain the time dimension (e.g., PDF·yr/m^3 for water stress or PDF/m^2 for land occupation). When these CF are multiplied with the inventory flows (m^2•yr in the case of land occupation and m^3 in the case of water consumption) we achieve the same unit for the ecosystem impact scores, namely PDF•yr. In earlier approaches, different impact categories have used "disappeared fractions" at different scales, thus mixing local or regional with global levels. This is problematic because a globally lost species is gone forever, whereas a regionally lost species may be recovered through repopulation if it was not endemic. The endpoint of LC-IMPACT aims to consistently quantify *global* PDF, that is, an irreversible extinction of species on a global level. It is important to have a consistent understanding of which share of species is globally lost, due to a variation in irreversibility and magnitude of impact. If a species is extinct in a certain region, it is not automatically extinct on a global level. In addition, global species loss is irreversible, while regional loss is not (de Baan et al., 2015; Kuipers, Hellweg, & Verones, 2019). Therefore, although the numerical value for regional loss is always higher than for global loss, this does not mean that the effects are larger. Both assessments are needed, the global assessment to avoid irreversible biodiversity loss and the regional assessment to make sure that ecosystems can maintain their functions, even if they have a lower contribution to overall global species diversity. We consider the global PDF as a good indicator for the risk of extinction, that is, for the fraction of species that is committed to global extinction.

However, this does not aim to quantify the overall extinction related to the functional unit of an LCA in absolute units. For instance, the time unit here does not say that the species is lost during a certain period of time, but we simply should understand it as an indicator, where we measure global extinction risks and where we give more weight to long-lasting interventions compared to short-lasting ones. Ecosystem impacts refer to the fraction of species that is committed to become globally extinct. For instance, a PDF of 0.01 means that 1% of the global species pool is committed to go extinct if the pressure (e.g., land use) continues to happen. As there are typically lag times between the pressure and the effect, the duration of the pressure has an influence on whether the full extent of effect will happen or not. This is because there is no instant global extinction of species after a change in pressure, for example, an increase in land occupation will not immediately lead to species loss in the surrounding ecoregion, but gradually over time. For this reason, the exposure duration to the pressure is also included in the unit of ecosystem impacts (PDF yr). Hence, impact scores should be interpreted as an increase in global extinction *risk* over a certain exposure period of time and not so much as an instantaneous global species *loss*.

The EF and VF can be specific for taxonomic groups (e.g., mammals, reptiles, amphibians, and fish). If several taxonomic groups are used for calculating CFs, final CFs for representing the whole "ecosystem" are calculated as weighted averages of the taxonomic groups in PDF. In LC-IMPACT we chose that plants and animal taxa are given a 50% share each, thus giving plants and animals equal weight. Contributions of several animal taxa are included relative to their species richness, as discussed by Verones et al. (2015), in order to avoid that species-rich taxonomic groups dominate the impact assessment. The underlying assumption is that diversity of taxa represents ecosystem functioning better than diversity of species in the same taxon. In addition, whenever possible, we included a vulnerability factor, in order to take into account that not all taxonomic groups show the same vulnerability to environmental pressures. This factor is based on information from IUCN (2013) for both current red list status and geographical range areas of species. The procedure and details for calculating taxon-specific and global vulnerability factors are described in Verones et al. (2019) and Verones et al. (2017a).

In the AoP "Ecosystem quality" we ultimately covered seven broad impact categories (Figure 1, Table 2). All, except for climate change, include spatial differentiation. Note that we named the climate change approach a mix between marginal and average. For reasons of feasibility, the step from emission to temperature increase was modeled in a marginal way, while expected impacts on humans and ecosystems caused by temperature increase were modeled via an average approach. Terrestrial ecosystems are covered in five categories (climate change, photochemical ozone formation, terrestrial acidification, terrestrial ecotoxicity, and land stress). Impacts on freshwater ecosystems are represented in four impact categories (climate change, water stress, freshwater ecotoxicity, freshwater eutrophication), while the marine ecosystem is covered in two categories (marine eutrophication and marine ecotoxicity). Impacts of marine, freshwater, and terrestrial ecosystems, in terms of PDF•yr, can be directly added under the assumption that these ecosystems are equally important. The question of how important marine, freshwater, and terrestrial ecosystems are compared to each other should, however, be preferably answered in the weighting step of the LCIA phase. We therefore recommend reporting impact scores for each ecosystem separately, since no generally accepted weighting scheme between the three ecosystem types exists yet.

2.6 | Mineral resources

The endpoint indicator of mineral resource scarcity, is surplus ore potential ($kg_{ore}/kg_{mineral}$), which is reflecting the additional amount of ore that needs to be extracted in the future for generating a unit of a specific mineral that is extracted at present. More ore will need to be extracted, as ore grades will decline due to mining higher-ore grades (Mudd, 2007; Prior, Giurco, Mudd, Mason, & Behrish, 2012). Global endpoint factors are available for 70 minerals (Vieira, Ponsioen, Goedkoop, & Huijbregts, 2016; Vieira, 2018).

2.7 | Value choices

In LC-IMPACT, CFs are provided for four sets, using insights from cultural perspective theory (e.g., Goedkoop et al. (2009)). Two key aspects were specifically addressed: the time horizon and the level of evidence of impacts. Depending on the goal and scope of the LCA, the LCA practitioner can choose between a set of CFs considering 100 years of impacts or longer-term impacts and between "impacts with a high degree of scientific confidence only" (i.e., certain impacts) or "all impacts included." This results in four possible combinations (see also Table 3). The level of evidence depends on expert judgment (of the model developer and scientific literature) within each impact category and thus inevitably will contain some form of subjectivity. We chose 100 years as the "shorter-term" time horizon, since this is in line with current LCA practice. We believe that this makes application of CFs more transparent, since they are not restricted to predefined perspectives and refer explicitly to key value choices, illustrating the consequences of these choices in the outcomes of the study.

Seven out of 21 impact pathways so far included in LC-IMPACT provide the option to choose which potential effects to include (certain impacts vs. all impacts, see Table 3). For 14 impact pathways, the considered time frame can be selected (see Table 3). Low level of evidence in the expected impacts or uncertainties and lack of robustness in models may be reasons for excluding some potential impacts from the "certain impacts" values. It is for example uncertain whether cataract occurrences are caused by stratospheric ozone depletion (Struijs et al., 2010), therefore this disease is only included in the "all impacts" factor, but not in the "certain impacts" value. Another example is impacts from groundwater consumption on ecosystems, which are more uncertain than impacts from surface water consumption due to significantly lower data availability (Fantke et al., 2018). Therefore, the set of "certain impacts" characterization factors is a set of factors with comparably low model and parameter uncertainty but neglecting impacts that are considered relatively uncertain (see also Table 3 for included effects). The set of "all impacts" characterization factors contains all possible impacts that were quantifiable, including impact pathways with lower levels of evidence, which follows a more precautionary line of reasoning.

The two extreme scenarios are "long term impacts with all levels of evidence" (i.e., all impacts, long term) and "short term impacts with high level of evidence" (i.e., certain impacts, 100-year time horizon). These two scenarios are recommended as a minimum to be included in an LCA study. The other two scenarios are added for completeness and as courtesy to practitioners to provide further freedom in the application of LC-IMPACT.

2.8 | Characterization factors

Figure 2 provides maps for a few example impact categories. Note that, depending on the chosen native scale, the size of the individual regions varies. For particulate matter (PM) emissions, characterization factors are high for regions with high population densities and consequently indicate higher damage per emission unit. Impacts of water consumption on human health (Figure 2b) are high in regions where water is scarce, population density is high, and possibilities to offset impacts (e.g., by importing food) are small. High CFs for land occupation are found on islands (high species endemism, thus vulnerable regions) and in tropical regions (high species richness). Some regions with high species richness and vulnerability correlate as well with the water consumption impacts on ecosystem quality (e.g., Australia), while in general, the impacts of water consumption are dominated by the density of wetlands included in the model (e.g., high in the United States).

3 | APPLICATION EXAMPLE

3.1 | Description

As an illustrative case study, we compared the impacts from different fuel options. The functional unit was defined as driving one passenger kilometer in a Euro 5 car in Europe, fueled with petrol or biofuel. We compare the following options: low sulfur petrol in Europe, E85 fuel with bioethanol from sugarcane produced in Brazil, and E85 fuel with bioethanol produced from maize in the United States. Transport of the bioethanol from United States and Brazil to Europe was assumed to take place via truck, then ship, and truck again. Petrol is taken directly from the ecoinvent activity "transport of petrol, low-sulfur" and includes transport inputs via ships, pipeline, train, and truck. We assumed that ethanol substitutes 1:1 for petrol on an energetic basis in modern, fuel-injected cars (1J equals 1J) (Strogen, Souza, & Lidicker, 2014; Yan, Inderwildi, King, & Boies, 2013). However, due to the lower energy density of ethanol compared to petrol, 1 kg of petrol is equivalent to 1.46 kg of ethanol. Emissions from the combustion of bioethanol differ from low-sulfur petrol. However, this difference was difficult to summarize, as it depends on, among other things, engine type,

TABLE 3 Included value choices per impact category. If time horizons were not relevant (short-term impacts), this is indicated with "not relevant," meaning that this is not considered relevant for cumulative exposure over a period of at least 100 years. If two or more sets of CFs have the same values for different value choice categories, this is indicated with merged cells

Impact category	All impacts, long term	All impacts, 100 years	Certain impacts, long term	Certain impacts, 100 years
Climate change (human health)	**Time horizon**: 1000 years **Included effects**: diarrhea, malaria, coastal flooding, malnutrition, cardiovascular diseases, inland flooding	**Time horizon**: 100 years **Included effects**: diarrhea, malaria, coastal flooding, malnutrition, cardiovascular diseases, inland flooding	**Time horizon**: 1000 years **Included effects**: diarrhea, malaria, coastal flooding	**Time horizon**: 100 years **Included effects**: diarrhea, malaria, coastal flooding
Climate change (terrestrial ecosystems)	**Time horizon**: 1000 years **Included effects**: all species included	**Time horizon**: 100 years **Included effects**: all species included	**Time horizon**: 1000 years **Included effects**: all species included	**Time horizon**: 100 years **Included effects**: all species included
Climate change (freshwater ecosystems)	**Time horizon**: 1000 years **Included effects**: impacts on fish below 42° latitude	**Time horizon**: 100 years **Included effects**: impacts on fish below 42° latitude	**Time horizon**: – **Included effects**: not considered due to uncertainty	**Time horizon**: – **Included effects**: not considered due to uncertainty
Stratospheric ozone depletion	**Time horizon**: infinite **Included effects**: cataract, skin cancer	**Time horizon**: 100 years **Included effects**: cataract, skin cancer	**Time horizon**: infinite **Included effects**: skin cancer	**Time horizon**: 100 years **Included effects**: skin cancer
Ionizing radiation	**Time horizon**: 100,000 years **Included effects**: Cancers: thyroid, bone marrow, lung, breast, bladder, colon, ovary, skin, liver, esophagus, stomach, bone surface, and remaining cancer. Hereditary disease	**Time horizon**: 100 years **Included effects**: Cancers: thyroid, bone marrow, lung, breast, bladder, colon, ovary, skin, liver, esophagus, stomach, bone surface, and remaining cancer. Hereditary disease	**Time horizon**: 100,000 years **Included effects**: Cancers: thyroid, bone marrow, lung, and breast. Hereditary disease	**Time horizon**: 100 years **Included effects**: Cancers: thyroid, bone marrow, lung, and breast. Hereditary disease
Photochemical ozone formation (human health)	**Time horizon**: not relevant **Included effects**: respiratory mortality			
Photochemical ozone formation (terrestrial ecosystems)	**Time horizon**: not relevant **Included effects**: loss of productivity for forest and grassland plant species			
Particulate matter formation	**Time horizon**: not relevant **Included effects**: cardiopulmonary and lung cancer mortality due to primary PM2.5 and secondary aerosols from SO_2, NH_3, and NO_x		**Time horizon**: not relevant **Included effects**: cardiopulmonary and lung cancer mortality due to primary PM2.5	
Terrestrial acidification	**Time horizon**: not relevant **Included effects**: reduction of plant species richness due to NO_x, NH_3, and SO_x emissions to air			

(Continues)

TABLE 3 (Continued)

Impact category	All impacts, long term	All impacts, 100 years	Certain impacts, long term	Certain impacts, 100 years
Freshwater eutrophication	**Time horizon**: not relevant **Included effects**: reduction of fish species richness due to P emissions to water			
Marine eutrophication	**Time horizon**: not relevant **Included effects**: hypoxia-driven reduction of marine animal species richness due to dissolved inorganic nitrogen (DIN) emissions			
Human toxicity (carcinogenic)	**Time horizon**: infinite **Included effects**: via inhalation and ingestion exposure, all potentially carcinogenic substances from IARC	**Time horizon**: 100 years (relevant for metals) **Included effects**: via inhalation and ingestion exposure, all potentially carcinogenic substances from IARC	**Time horizon**: infinite **Included effects**: via inhalation and ingestion exposure, only substances with strong evidence for carcinogenicity (IARC-category 1, 2A, and 2B)	**Time horizon**: 100 years (relevant for metals) **Included effects**: via inhalation and ingestion exposure, only substances with strong evidence for carcinogenicity (IARC-category 1, 2A, and 2B)
Human toxicity (non-carcinogenic)	**Time horizon**: infinite (relevant for metals) **Included effects**: via inhalation and ingestion exposure	**Time horizon**: 100 years **Included effects**: via inhalation and ingestion exposure	**Time horizon**: infinite (relevant for metals) **Included effects**: via inhalation and ingestion exposure	**Time horizon**: 100 years **Included effects**: via inhalation and ingestion exposure
Freshwater ecotoxicity	**Time horizon**: infinite **Included effects**: affected fractions via exposure to toxic chemicals in freshwater	**Time horizon**: 100 years (relevant for metals) **Included effects**: affected fractions via exposure to toxic chemicals in freshwater	**Time horizon**: infinite **Included effects**: affected fractions via exposure to toxic chemicals in freshwater	**Time horizon**: 100 years (relevant for metals) **Included effects**: affected fractions via exposure to toxic chemicals in freshwater
Marine ecotoxicity	**Time horizon**: infinite (relevant for metals) **Included effects**: affected fractions via exposure to toxic chemicals in seawater	**Time horizon**: 100 years **Included effects**: affected fractions via exposure to toxic chemicals in seawater	**Time horizon**: infinite (relevant for metals) **Included effects**: affected fractions via exposure to toxic chemicals in seawater	**Time horizon**: 100 years **Included effects**: affected fractions via exposure to toxic chemicals in seawater

(Continues)

TABLE 3 (Continued)

Impact category	All impacts, long term	All impacts, 100 years	Certain impacts, long term	Certain impacts, 100 years
Terrestrial ecotoxicity	**Time horizon**: infinite (relevant for metals) **Included effects**: affected fractions via exposure to toxic chemicals in soil	**Time horizon**: 100 years **Included effects**: affected fractions via exposure to toxic chemicals in soil	**Time horizon**: infinite (relevant for metals) **Included effects**: affected fractions via exposure to toxic chemicals in soil	**Time horizon**: 100 years **Included effects**: affected fractions via exposure to toxic chemicals in soil
Land stress (occupation)	**Time horizon**: not relevant **Included effects**: occupation of six land use types			
Land stress (transformation)	**Time horizon**: total recovery times (up to 1,200 years, depending on ecosystem) **Included effects**: transformation of six land use types	**Time horizon**: 100 years **Included effects**: transformation of six land use types	**Time horizon**: total recovery times (up to 1,200 years, depending on ecosystem) **Included effects**: transformation of six land use types	**Time horizon**: 100 years **Included effects**: transformation of six land use types
Water stress (ecosystems)	**Time horizon**: not relevant **Included effects**: surface water and groundwater consumption impacts on wetlands	**Time horizon**: not relevant **Included effects**: surface water and groundwater consumption impacts on wetlands	**Time horizon**: not relevant **Included effects**: only surface water consumption impacts on wetlands	**Time horizon**: not relevant **Included effects**: only surface water consumption impacts on wetlands
Water stress (human health)	**Time horizon**: not relevant **Included effects**: malnutrition			
Mineral resources extraction	**Time horizon**: not used **Included effects**: uses "ultimately extractable reserves"	**Time horizon**: not used **Included effects**: uses (economic) "reserves"	**Time horizon**: not used **Included effects**: uses "ultimately extractable reserves"	**Time horizon**: not used **Included effects**: uses (economic) "reserves"

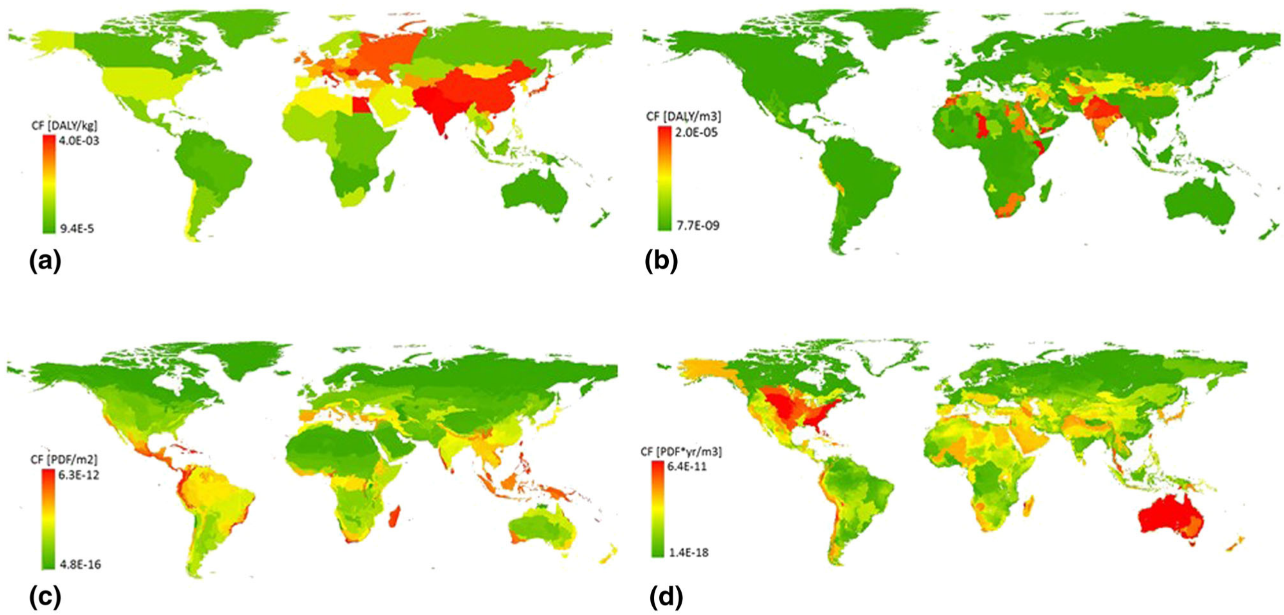

FIGURE 2 Example maps for characterization factors (CF) for (a) human health impacts of particulate matter (PM2.5) emissions (DALY/kg), (b) human health impacts of water consumption (DALY/m^3), (c) impacts on ecosystem quality from land occupation by annual crops (PDF/m^2), and (d) impacts on ecosystem quality from water consumption (PDF yr/m^3)
Underlying data used to create this figure are the characterization factors which are available in the Supporting Information
Note: DALY = disability adjusted life years; PDF = potentially disappeared fraction

driving patterns, and climate. Given this uncertainty, we made the rough assumption that bioethanol contains effectively no sulfur (no SO_2 emission) (Masum et al., 2013; Pelkmans, Lenaers, Bruyninx, Scheepers, & Vlieger, 2011; Sadeghinezhad et al., 2014). We neglected differences in price of fuels and resulting changes in consumption, as well as differences in evaporative emissions between petrol and ethanol. We also did not consider that the 15% conventional petrol in E85 would cause changes in refinery operation, as petrol could be of lower quality (have lower octane level) and thus be cheaper and avoid production of special octane-increasing additives.

Information on the yield, production areas, and irrigation for maize and sugarcane was taken from Monfreda, Ramankutty, and Foley (2008) and Pfister, Bayer, Koehler, and Hellweg (2011).

We chose the CFs for climate change, land occupation, water stress, and particulate matter formation as impact categories for the illustrative purpose of the case study. We used marginal and “all effects” for the CFs in all categories. Time horizon was not relevant for land occupation, water stress, and particulate matter, but was relevant and included for climate change. A distinction between “certain effects” and “all effects” was possible for climate change (except for freshwater ecosystems, which are only included when “all effects” are used) and particulate matter formation. All CFs except climate change provided both site-generic and regionalized CFs. The CF values used were downloaded from www.lc-impact.eu in August 2018. We used ecoinvent 3.5 (Wernet et al., 2016) with the cutoff allocation approach as a background database. Calculations for the case study were done in the LCA software Brightway 2 (Mutel, 2017). A supporting zip-file provides the notebooks for running the calculations.

3.2 | Application example results

Figure 3a and Figure 4a show the human health impacts for the three fuel options. Climate change is the dominating impact. There is up to a factor 4 difference between the three fuel options. Differences between site-dependent and site-generic impacts are small (see Supporting Information). Contributions between the two extreme scenarios (“all effects and infinite time horizon” vs. “certain effects and 100 years time horizon”) vary, without changing the order of importance.

For impacts on terrestrial ecosystem quality (Figure 3a and Figure 4b) climate change is also an important contributor to the impact. In site-dependent assessments, land occupation increases in relevance. Between impacts of site-dependent versus site-generic land occupation there is up to a factor 80 difference in the results (sugarcane). Contributions between the two extreme scenarios (“all effects and infinite time horizon” vs. “certain effects and 100 years time horizon”) vary, without changing the order of importance.

For freshwater ecosystem quality (Figure 4c and Figure 3c), impacts from water consumption only have a difference of maximum a factor of 3 between site-generic and site-dependent assessment. Climate change remains an important contributor, but less so than for the other two AoPs (and no CFs exist for “certain effects” here). The reason for maize having dominant water impacts as opposed to land stress is that a large share

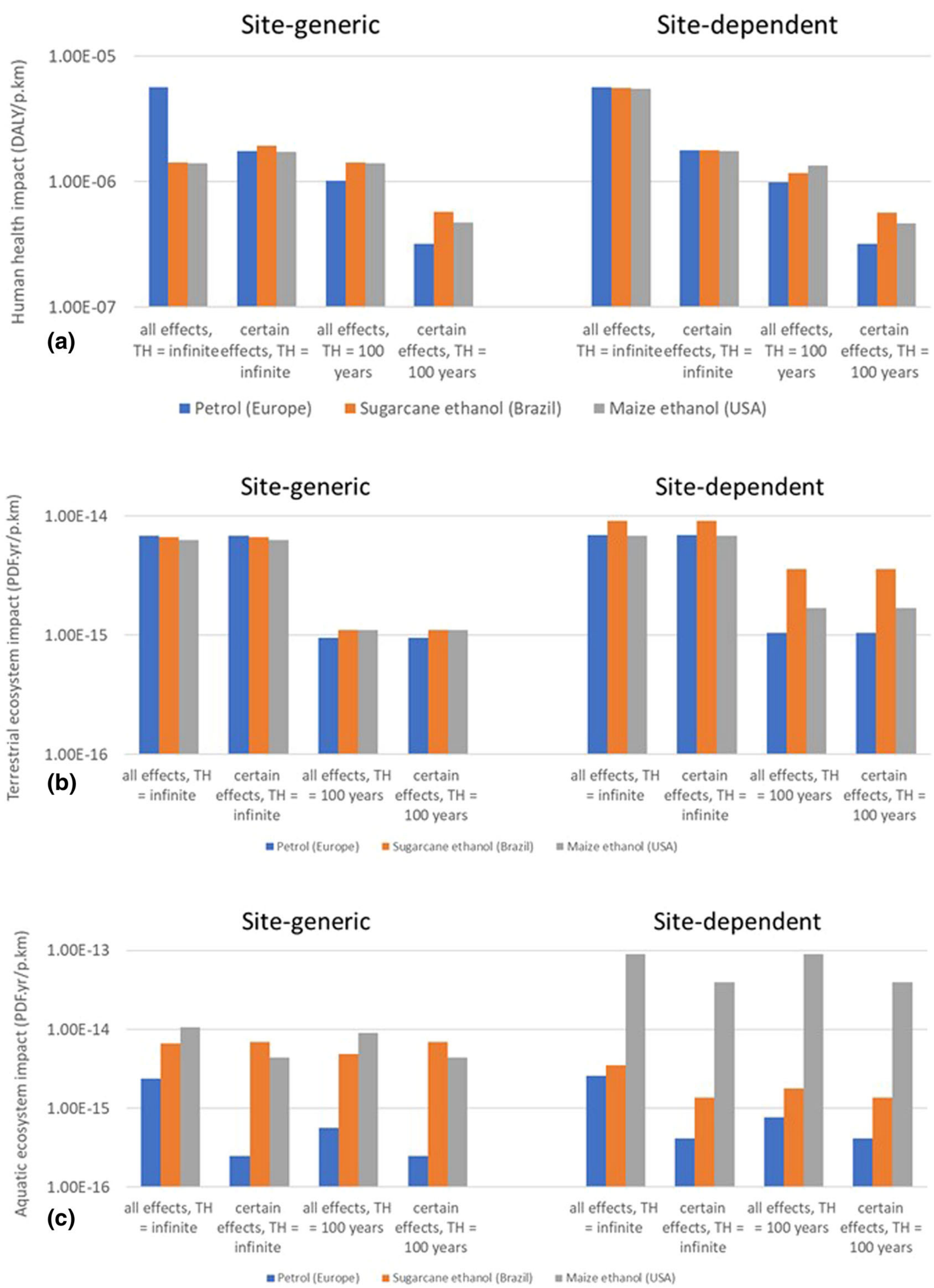

FIGURE 3 Results of the illustrative case study for the different areas of protection and sets of CFs: (a) Human health, (b) terrestrial ecosystems, and (c) aquatic ecosystems. For more information and the exact numbers, see Supporting Information. Human health results in DALY, ecosystem quality results in PDF•yr. Time horizons are only relevant for climate change in the included collection of CFs
Underlying data used to create this figure can be found in the Supporting Information S1 (see tabs HH, TE, and AE in the spreadsheet)
Note: DALY = disability adjusted life years; PDF = potentially disappeared fraction of species; TH = time horizon

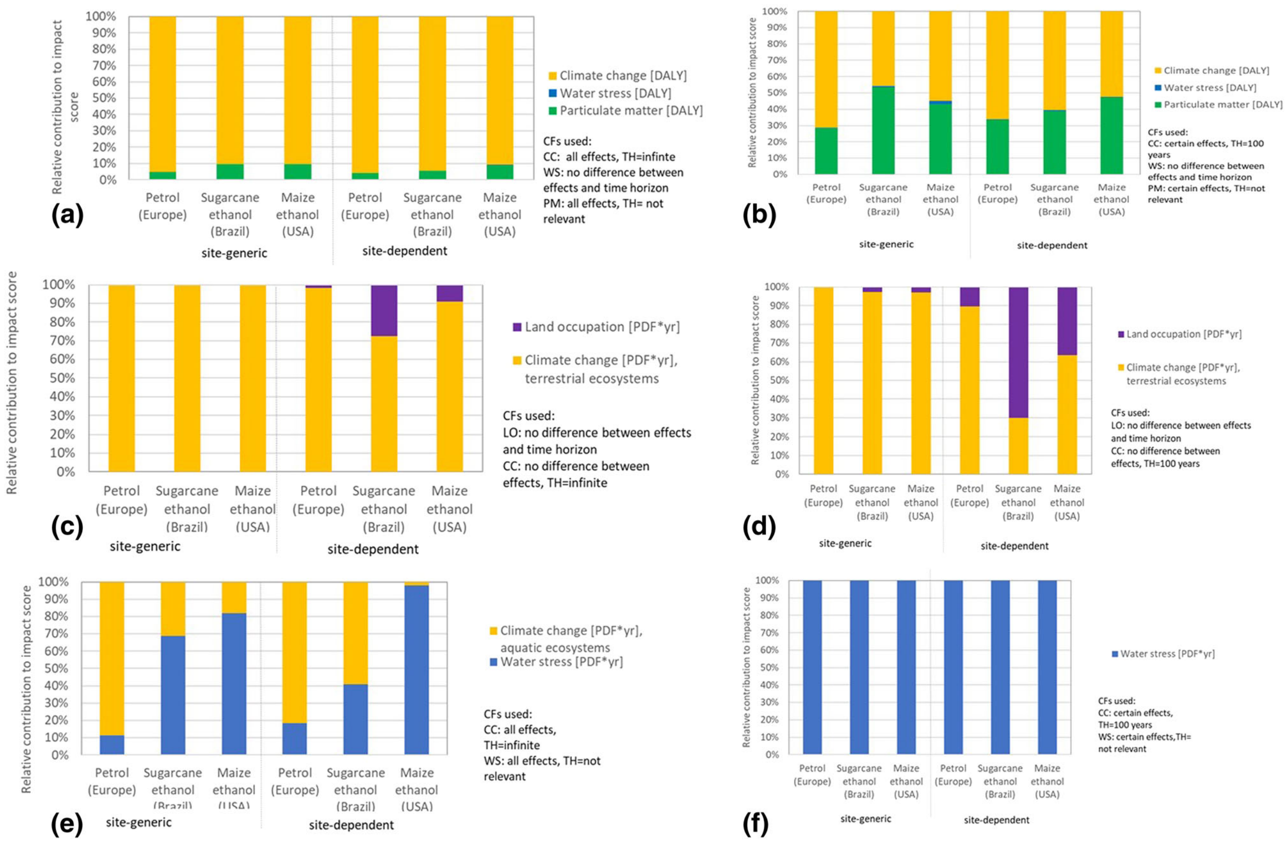

FIGURE 4 Comparison between the relative contributions of impacts of driving a car in Europe for 1 km with different fuel options for the two extreme scenarios of the selected impact categories: (a) for human health impacts ("all impacts, TH = infinite"), (b) for human health impacts ("certain impacts, TH = 100 years"), (c) for terrestrial ecosystem quality impacts ("all impacts, TH = infinite"), (d) for terrestrial ecosystem quality impacts ("certain effects, TH = 100 years), (e) for aquatic ecosystem impacts ("all effects, TH = infinite"), (f) for aquatic ecosystem impacts ("certain impacts, TH = 100 years"). Note that TH can be "not relevant" for categories and that climate change does not have spatially differentiated CFs and that there is no climate change impact for "certain impacts" for aquatic ecosystems (see Table 3)
For more detailed results and the underlying data for this figure, see Supporting Information S1
Note: CF = characterization factor; TH = time horizon; CC = climate change; WS = water stress; PM = particulate matter; LO = land occupation

of maize production in the United States is taking place in comparably dry regions with high irrigation needs (in analogy to also Henderson et al. (2017)) and high related CFs, while the respective land use CFs are smaller in the United States.

Differences between "certain effects" and "all effects" are most pronounced for climate change impacts on aquatic ecosystems (see Supporting Information and Figure 4), since no CFs exist for the "certain effects" set, due to the low level of evidence of the underlying models. CFs for climate change impacts are global and site generic. However, the rank order of the most relevant inventory values changes between site-generic and site-dependent assessment, also causing a difference in climate-change-related impacts.

As mentioned, differences between site-generic and site-dependent scores are most important for land stress (see Supporting Information S1), followed by water stress, while they are less pronounced for particulate matter formation (Figure 4a). This is because for particulate matter impacts, the scale of regionalization is coarser (see Tables 1 and 2) than for water and land stress and larger than individual countries. This means that the global average is more similar to the regionalized values than for impact categories with finer spatial scales. For water and land stress, native regions for the site-dependent values (terrestrial ecoregions and watersheds, see Table 2) are in most cases smaller than countries and thus influence the country and global averages more strongly.

Examples for regionalized results for maize and sugarcane production across several terrestrial ecoregions or watersheds, respectively, are shown in Figure 5 (i.e., an overlay of the multiplication of the regionalized inventory and the regionalized CF). The contribution of impact between the terrestrial ecoregions (Figure 5a,c) varies both because of differences in the LCI and the LCIA model, since the area used for growing sugarcane and maize and the harvested yield differs within Brazil and the United States (data from Monfreda et al. (2008)). The developed CFs vary as well between the ecoregions, due to differences in land use shares, species richness, and the rarity and threat level of species. The same is true for impacts from water consumption (Figure 5b,d), where differences in irrigation intensity, as well as differences between CFs drive the results. To get from regionalized results per ecoregion to one value (as presented in Figure 4), the impacts of each ecoregion or watershed are summed.

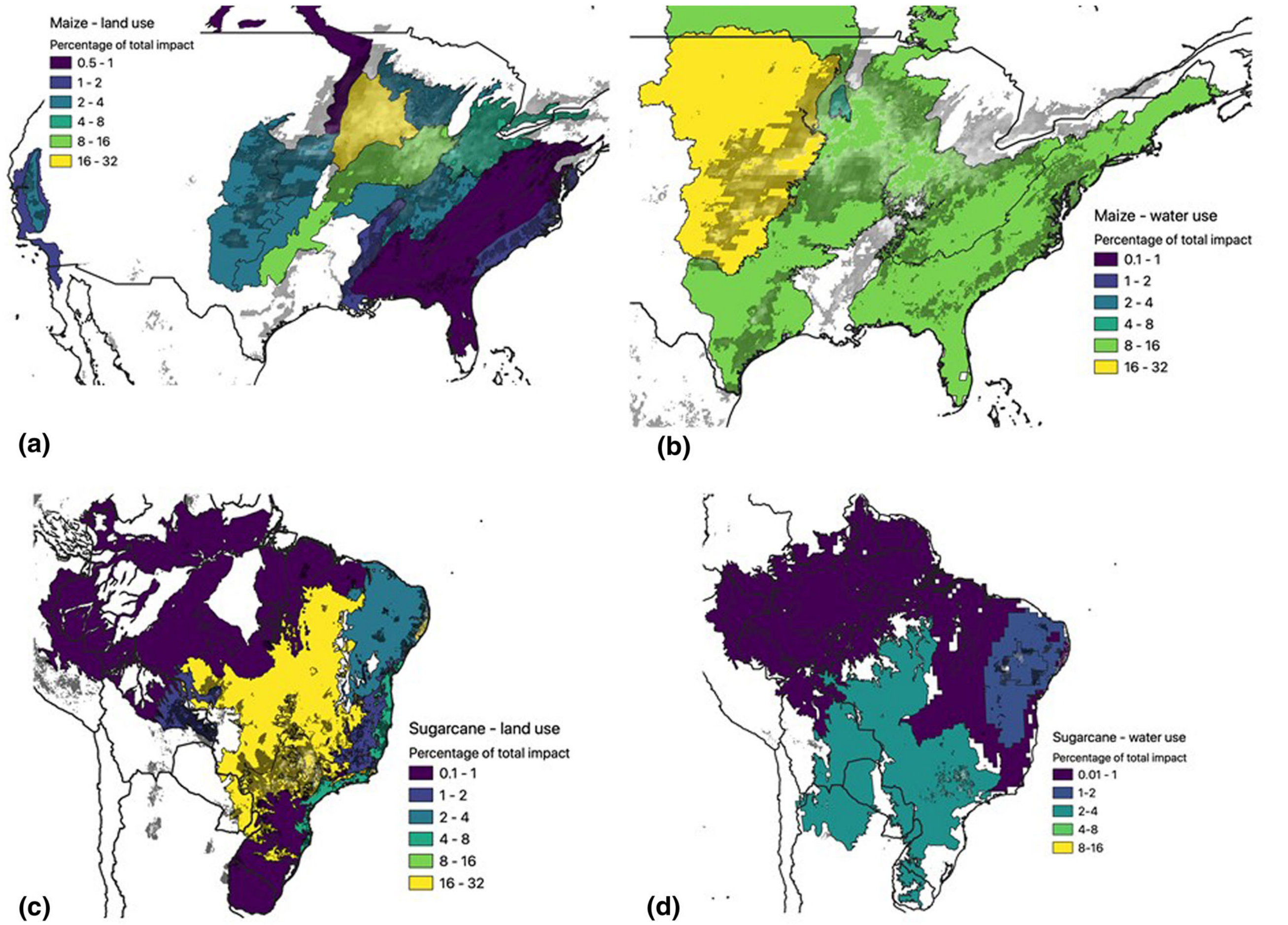

FIGURE 5 Examples of contributions of different spatial components to impacts of terrestrial ecosystem quality: (a) contribution to land occupation impacts from maize production in the United States, (b) contribution to water consumption impacts of maize production in the United States, (c) contribution to land occupation impacts from sugarcane production in Brazil, (d) contribution to water consumption impacts from sugarcane production in Brazil. Each impact is shown on a terrestrial ecoregion or watershed level (native scale for land stress and water consumption impacts). The black/white raster underlying the maps shows the land use intensity and irrigation intensity, respectively, from Monfreda et al. (2008) and Pfister et al. (2011) and are found in the Supporting Information.

When changing from site-generic to site-dependent impacts, there might also be a change in the process contributing most to the impact and the contributing share of each process (see Supporting Information S1, Excel file for case study). This is, for example, the case for sugarcane ethanol production contributing to impacts from fine particulate matter formation, which switches from clear-cutting of primary forest to electricity production from coal as the dominant impact. For land occupation impacts on ecosystems from maize-based ethanol, for example, maize grain production is contributing most to the site-dependent impact (78%). If a site-generic assessment is used, the same process is responsible for 85% of the impacts.

Overall, the conclusions based on either regionalized or generic assessments might differ. Of the four sets each of regionalized versus generic results for human health, terrestrial ecosystems, and aquatic ecosystems (see Figure 3), one to the two sets each would lead to a different conclusion in terms of the rank order of these overall impacts.

4 | DISCUSSION

4.1 | Practical aspects of using LC-IMPACT

All LC-IMPACT impact categories, except for climate change, ionizing radiation, and stratospheric ozone depletion, provide CFs with spatial detail. As illustrated in the case study, these spatial aspects can indeed be relevant. However, most of today's commercially used LCA software tools and life cycle inventory databases do not handle spatially differentiated data well, being mostly restricted to country scales. This hampers the broader applicability of LC-IMPACT, at least for use in background systems. We provide shape and raster files, as well as GoogleEarth layers for all regionalized impact categories on www.lc-impact.eu. It is thus possible to extract the relevant regionalized CFs from these layers for a foreground system. However, in future, LCA software tools will be able to incorporate the aggregated country, continental, and global values for easier use in background systems. One software system that is able to handle the fully spatially differentiated CFs, and has incorporated them for the use in the case study here, is Brightway 2 (Mutel, 2017).

Albeit optional, one commonly used step of the LCIA phase is normalization, which in the case of external normalization, requires normalization references, preferably global in their scope (Pizzol et al., 2017). For LC-IMPACT, as well as for all regionalized LCIA methodologies, the determination of external normalization references adds some challenges because inventory data at native scales should ideally be used to determine accurate normalization references. Such data are however largely lacking worldwide. For some impact categories associated with a few well-monitored substances, like NO_x, So_x, and NH_3 for terrestrial acidification, data are readily available and global normalization references can thus be computed with relative ease and good accuracy (Crenna, Secchi, Benini, & Sala, 2019). For other impact categories, like the toxicity-related impacts, which stem from thousands of substances that are poorly monitored in most countries, the building of a comprehensive global emission inventory includes major uncertainties due to data gaps and extrapolation needs (Leclerc, Sala, Secchi, & Laurent, 2019). Research is therefore needed to tackle those issues.

Uncertainty aspects are also important to include in LCIA models. Many impact categories, such as climate change, are based on data from existing scientific literature. Depending on how data was reported in these original sources, quantitative uncertainties can only be reported to a limited extent. In LC-IMPACT, uncertainty is therefore discussed in a qualitative way for all impact categories (see LC-IMPACT report for more details, www.lc-impact.eu). Aspects contributing to uncertainties include limited knowledge of the exact impact mechanism (e.g., for the number of species or river discharge change related to climate change alone), aspects related to population levels and susceptibility (e.g., human health impacts from ozone depleting substances vary according to melatonin content of the skin), or limited number of compartments for fate modeling (e.g., for toxicity or ionizing radiation). Land stress includes an additional quantitative uncertainty assessment.

4.2 | Qualitative comparison with ReCiPe 2016 and ImpactWorld+

LC-IMPACT has 11 broad impact categories, some of which further distinguish between, for example, different ecosystem types for impacts (e.g., toxicity). All of them are on endpoint level only. In terms of coverage of endpoint categories, LC-IMPACT and ReCiPe 2016 (Huijbregts et al., 2017) share the same categories for impacts on human health and ecosystem quality, in some cases with the same underlying models and assumptions (e.g., climate change). ReCiPe 2016 covers both fossil and mineral resources in the resources section and uses the metric “surplus cost potential” (as opposed to the surplus ore potential used in LC-IMPACT). LC-IMPACT and ImpactWorld+ (Bulle et al., 2019) share 17 common endpoint categories (“recommended” in ImpactWorld+; note that the underlying models in each category might be different though). Four categories that are covered in LC-IMPACT are either not covered or covered with an “interim” method in ImpactWorld+ (photochemical ozone formation on terrestrial ecosystems, marine and terrestrial ecotoxicity, and mineral resources extraction). On the other hand, ImpactWorld+ has four “recommended” endpoint categories that are not covered in LC-IMPACT (marine and freshwater acidification, thermally polluted water, and impacts of ionizing radiation on ecosystem quality).

One of the largest conceptual differences between LC-IMPACT versus ReCiPe2016 and ImpactWorld+ is the use of vulnerability factors to consistently address the global extinction of species. In terms of damage metrics, LC-IMPACT uses the global PDFs as metric for biodiversity impacts, thus number of species committed to global extinction, relative to the total. By contrast, ReCiPe2016 combines absolute species loss at the local, regional, and global scale, using species.yr. In addition, we do not use the cultural perspectives used in ReCiPe in LC-IMPACT, but instead provide four sets (depending on the impact category) of characterization factors, distinguishing between time horizons and different effects. This makes value choices more explicit and allows, but does not prescribe, a mix of value choices. Finally, LC-IMPACT does not provide midpoint characterization factors, contrary to ReCiPe 2016 and ImpactWorld+, since midpoint factors are not available yet in a consistent way across all included impact categories. Regionalization may lead to different results on mid- and endpoint levels, especially if not all regionally relevant mechanisms are already included in the midpoint calculation. In addition, there is for some indicators an ambiguity of which indicator (where in the cause–effect chain) would be best suited as a midpoint indicator. These are issues that need to be further investigated to come up with a robust set of midpoint indicators. Further details can be found in the qualitative LCIA method comparison tables by Rosenbaum (2018) providing an in-depth comparison of available and current LCIA methods including LC-IMPACT and ImpactWorld+.

4.3 | Living method

We consider LC-IMPACT to be a “living” method. That means that we strive for including new impact pathways and improve already covered impact pathways on a regular basis. The current version 1.0 of LC-IMPACT is available both on the website (www.lc-impact.eu) and as a zip-file on Zenodo (10.5281/zenodo.3663305). Potential new developments for future incorporation include those from the EU-FP7-funded LC-IMPACT project that are not yet considered to be mature at a global level, such as human health impacts due to noise. Prerequisites for including new impact pathways are that they are consistent with the modeling framework of LC-IMPACT (e.g., include aspects of vulnerability consistently), and that they are spatially differentiated (if appropriate) and available at a global scale. We therefore encourage method developers to inform us about models that fulfill these requirements by contacting us through the website (www.lc-impact.eu), in order to integrate them and further the development of LC-IMPACT. Quality and consistency checking will then be carried out in collaboration between the developers of the new impact category and members of the LC-IMPACT team. The user will be informed of changes through updated version numbering on the LC-IMPACT website and on Zenodo. Older versions will, however, remain available. We encourage practitioners to apply LC-IMPACT in their case studies and share their experiences, in order to further strengthen and improve the method. The method is recommended especially if the focus is placed on impacts on global species extinctions, even though LC-IMPACT can be generally applied for any damage level assessment. By providing a living and spatially differentiated LCIA method we strive to further contribute to the reliability and relevancy of LCA studies.

4.4 | Outlook

No LCIA method is complete in terms of coverage of, or level of detail within, impact categories today. As mentioned, impacts such as aspects of noise (also for ecosystem quality), invasive species, salinization, plastics, ocean acidification, specific ocean climate change, different pollutants/toxicants and their potential synergies, as well as issues such as impacts on ecosystem services remain lacking and require more research. Other impact categories (such as water consumption and land stress) do cover some impacts today, but could be complemented to cover more impact pathways. In addition, further development is needed for regionalized midpoint indicators, including the spatial dilemma these may cause in comparison to the endpoints and the completion of both marginal and average models for all (present and future) impact categories.

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CONFLICT OF INTEREST

The authors have no conflict to declare.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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