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Global environmental impacts and planetary boundaries in LCA

Data sources and methodological choices for the calculation of global and consumption-based normalisation factors

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Abstract

A crucial point in the discussion on planetary boundaries relates to the difficulties and the uncertainties in their quantification, given the underpinning ecological and environmental complexity inherent to the assessed phenomena, together with the level of normativity which such definition entails. When Planetary Boundaries' thresholds are used for comparing current level of pressure on environment and ecosystems another aspect becomes as well critical. This is the robustness of the quantification of the underpinning current levels of environmental pressures. In fact, the quantification of such levels may entail critical aspects, as it usually consists of emission accounting (often incomplete) or modelling exercise (with the clear limitations linked to any modelling effort). In order to monitor progress towards the reduction of resources use and the associated environmental impacts, the present study aims at shading light on the different options for assessing the level of environmental pressure and impacts, adopting life cycle impact assessment models for estimating the impacts. Actually, the present report aims at assessing the available information related to the environmental pressure at European and global scale in relation to 15 categories of impact (climate change, ozone depletion potential, human toxicity cancer and no cancer, ecotoxicity, particulate matter, ionising radiation, photochemical ozone formation, acidification, eutrophication, land use, water depletion and resource depletion). The estimated impacts may represent the so called "normalisation factors" (NFs) used in the context of Life Cycle Assessment (LCA), which are used to estimate the relevance of the impacts associated to a product or a system. Moreover, this study explores the feasibility of the calculation of different sets of normalisation factors applicable in the LCA context and examines how those reference values perform when compared to planetary boundaries.

1 Introduction

Over the last decades, the technological developments taking place at global level and the continuous increase in human population have led to an unprecedented demand for natural resources for various sectors (e.g. energy, transport, materials and chemicals production) and to an increasing pressure to the environment due to emissions in air, soil and water. The high level of consumption of natural resources, in particular easily accessible ones such as fossils, which characterize economies especially in developed countries, has raised concerns about the sustainability of global socio-economic systems, due mainly to the impacts associated to their combustion, both at the local and global scale, as well as in relation to their finiteness. On such a background, a primary challenge for sustainability is meeting human socio-economic prosperity and welfare while preserving environmental health on the Earth (Fang et al., 2015). Therefore, environmental policies focusing on efficiency improvements, such as European 7th Environment Action Programme (7th EAP), have been established to meet the 2050 visions of "living well within the ecological limits of the planet" (EC, 2013; EEA, 2015). The 7th EAP provides a systemic framework to address efforts towards meeting challenging objectives such those included in the Sustainable Development Goals (UN-SDG, 2016). It entails reaching economic development, by limiting natural capital degradation, by managing natural resources sustainably within the environmental limits of the planet. Therefore, it becomes crucial understanding how global production-consumption patterns are affecting the environment by means of measuring human-driven impacts.

The assessment of the level of pressure to the environment and the underpinning causes is a key element for the identification of possible solutions in terms of impact reduction and improved sustainability. More and more, life cycle based methodology are adopted to assess production and consumption patterns along supply chains and to identify hotspots of impact. Those hotspots may represent, then, the key areas of interventions to be considered both in the private and public sector for reducing impacts.

Life cycle assessment (LCA) is a reference methodology for the evaluation of impact along supply chain. Through the so called "normalisation step" impacts related to a specific supply chain are compared with reference values related to impacts related to a given system (being a country, continent or the entire globe). Indeed, in the context of LCA and according to ISO 14044 (ISO 2006), normalisation is the optional step that allows the interpretation of the characterized results in terms of relative environmental relevance of the impacts (Benini & Sala, 2016). In fact, normalisation offers a common reference situation of the impacts on the environment for every impact category (Sleeswijk et al., 2008), meaning that through normalisation abstract impact scores for each impact category are converted into relative contributions of the analyzed product or system to a reference situation. Normalisation factors (NFs) are based on both existing regional and global inventories of emissions and resource use, together with estimations for missing flows (e.g. proxy for toxicity related impacts, Cucurachi et al., 2014), characterized by using impact assessment methods.

Recently, the UNEP/SETAC Life Cycle Initiative (UNEP/SETAC LCI) has been discussing the role of normalisation (Pizzol et al. 2016), recommending the use of global NFs as they are perceived by practitioners as relevant for decision-making. In fact, normalisation can play an important role in providing information on the magnitude of impacts, by comparing them with a reference state, thus facilitating the communication to the stakeholders. Moreover, these assessments may support meeting the challenging goals related to the 7th EAP and the UN-SDG.

In order to identify the distance to the ideal reference state, the concept of Planetary Boundaries (PBs) has been recently introduced. PBs framework was firstly proposed, in 2009, by Rockström and colleagues (Rockström et al., 2009), then improved by Steffen et al. (2015) to define the "safe operating space for humanity". Specifically, PBs represent a set of global limits for critical biophysical subsystems or processes of the planet which regulate the resilience of the Earth, namely the interactions of land, oceans, atmosphere and life which underpin the stability of the planet. PBs are designed as safety borders around complex science-based and ecology-based thresholds within which human activities can develop without inducing irreversible environmental changes. In fact, human activities may both directly or indirectly impact the state of the environment, triggering cumulative (i.e. from local to regional scale) and systemic changes (i.e. at global scale) (EEA, 2015) that may exceed the carrying capacity of the Earth system, namely the boundary between global environmental sustainability and unsustainability. According to Bjørn and Hauschild (2015), carrying capacity has been defined as "the maximum sustained environmental intervention a natural system (e.g. Earth system) can withstand without experiencing negative changes in structure or functioning that are difficult or impossible to revert."

The set of PBs can be used for identifying consensus-based impact-reduction targets at the global scale in LCA contexts, namely a basis for assessing the potential of interventions to reduce the environmental impact of the socio-economic systems (Sandin et al., 2015). Indeed, in the context of the discussion on absolute sustainability (e.g. Bjørn & Hauschild, 2013 and 2015), proposals for linking the impacts quantified by the midpoint categories commonly included in the impact assessment of LCA (LCIA) and the carrying capacity of the affected ecosystems have been recently presented both through the development of carrying capacity-based normalisation references (Bjørn & Hauschild, 2015), and the development of the planetary boundary allowance method (Doka, 2015).

Although knowledge of PBs can improve environmental policy relevance, by measuring the sustainability gap between current human-driven impacts and their related carrying capacity thresholds (Fang et al., 2015), a crucial point is usually linked to the difficulties and the consequent uncertainties in defining a boundary, due to the underpinning ecological and environmental complexity of their evaluation. Furthermore, another aspect becomes critical, if considering that those boundaries should be set in order to compare the current level of human-driven pressure on the environment with a reference state representing an ecological threshold. In fact, defining an unequivocal level of pressure due to human activities may be also difficult as it is usually the result of emission accounting (often incomplete) or of modelling exercise (bringing with it the clear limitations that any modelling effort may involve).

Nowadays, several gaps remain in the knowledge around PBs, which represent a still under discussion concept. Besides the difficulties in identifying a valuable and measurable threshold in relation to human-driven impacts, several impact categories from the LCIA framework, such as those related to human toxicity, are still missing to be accounted for in the context of PBs. Proposals for addressing them have been recently discussed, e.g. in terms of planetary health framework (Whitmee et al., 2015).

In order to monitor the progress towards the goal of decoupling economic growth from the use of natural resources and their environmental impacts, the present study aims at shading light on the different options for assessing the level of environmental pressure and impacts due to human interventions, adopting LCIA models for estimating the impacts. Specifically, the study builds on the calculation of different sets of NFs applicable in the LCA context, as a result of an effort in extending the coverage of emissions and resource use, explicitly describing strengths and innovations, as well as limitations and possible uncertainties. Then, this study explores how those references stand when compared to planetary boundaries, which represent the sustainability reference point for "living well" on the Earth.

2 Methodology for the calculation of normalisation factors

The estimation of environmental pressures, in terms of emissions into air, soil and water as well as resource use, and potential impacts related to emission and resource consumption could be conducted by adopting several strategies, as reported in Table 1. Traditionally, NFs in LCA have been defined according to a territorial perspective, namely collecting statistical information associated with emissions and resource use at a certain geographical scale (country, continent, global) (Sala et al., 2015). Consumption-oriented approaches could be also considered, either based on the assessment of emissions and resource use in the context of a specific consumption areas (e.g. the LCA of representative food products, Notarnicola et al., 2017) or on the assessment of emissions and resource used by allocating them to economic sectors, such as in the environmental extended input-output approaches (Merciai & Schmidt, 2016). A number of hybrid approaches have been proposed in literature in order to take the advantages of each of the techniques, according to the specific scope and resolution of the analysis. One of these options is represented by a hybrid framework in which the domestic profile is coupled with a product-based estimate for the trade (namely, adding impact due to imported goods and subtracting that of exported ones), as performed in the Raw Material Equivalents study by Eurostat (2015).

Table 1: Different approaches and perspectives for the estimate of pressure and impact on the environment.

Accounting perspective	Rationale	Resolution of the assessment	Source of data for the estimation	Limits of the estimation
Territorial	Direct emissions and extraction of resources occurring within territorial boundaries	Overall economy, with possible differentiation in sectors	Statistical data, models for emission estimation	Only local emissions and resource extraction are taken into account import and export are not accounted for
Consumption-based products	Direct emissions and extraction of resources occurring within territorial boundaries as well as indirect ones, both modelled as products' supply chains	Final products	LCI of representative products and categories of consumption (e.g. Food, mobility, housing)	The selection of representative products may lead to incomplete estimation of the overall impacts
Consumption-based sectors	Direct emissions and extraction of resources occurring within territorial boundaries as well as indirect ones (both import and export), both modelled as sectoral supply chains	Economic sectors	Based on extended environmental input output	The sector- based approach is usually associated with a relatively limited coverage of emissions and resource.
Hybrid consumption based (territorial and consumption based)	Direct emissions and extraction of resources occurring within territorial boundaries modelled as in the territorial perspective indirect ones (import and export) modelled as products' supply chains	Direct impacts: overall economy, with possible differentiation in sectors Indirect impacts: products	Territorial for domestic and product-based for trade	High uncertainty due to: discrepancy in the coverage of emissions and resource. The number of products that could be modelled is anymay limited.

In the present report, the calculation of NFs, as common reference situation of the impacts on the environment, was built on a vast collection of international data on emissions and resources extracted at the following scales:

a. EU-27 (territorial, consumption- and production- based)
b. Global (territorial, covering both production and consumption at global scale)

After their translation into the International reference Life Cycle Data system (ILCD) elementary flows, emission and extraction data were characterized through the ILCD recommended impact assessment methods (EC-JRC, 2011), using characterization factors (CFs) at midpoint (Sala et al., 2015), whose related categories are typically consistent with the focus points of environmental policy (Sleeswijk et al., 2008).

Several key choices were made in relation to the sources of data and on mapping of elementary flows, along with methodological assumptions for building the inventories and the normalisation references:

- The year 2010 has been taken as reference year.
- The inventories cover emissions into the environmental compartments (i.e. air, water and soil), as well as resource extracted within defined boundaries according to the selected scale, taking into account both production and consumption features related to the reference year.
- In the selection on the sources, official statistics based on measured values and with a large coverage of emission flows were preferred. However, considering the broad variety of scientific sources available at different scales, we adopted a more detailed procedure, according to the hierarchical approach proposed by Sala et al. (2015) and based on the criteria of Sleeswijk et al. (2008). This allows guiding the authors in the selection of data when alternatives options for the same inventory flows were available. Specifically, the preferences were the following, in decreasing importance: i) authoritative literature sources, such as officially reported measured or estimated emission values provided by EU and international governance bodies, based on agreed models, methods and standards, with documented and reliable metadata, and recurrent quality checks. Datasets already used in EU/global monitoring and policy making and providing consistent time-series were preferred since they ensure a high degree of robustness and stakeholders acceptability; ii) activity-based estimations, derived as "activity data * emission factor", coming from official datasets, scientific or grey literature (e.g. sectorial reports), and available Life Cycle Inventories (LCIs); iii) statistical proxies in terms of time or flows, when the correlation is statistically tested and significant; iv) reasonable although untested assumption(s), based on cause-effect models. We generally used this procedure in order to fill-in punctual data gaps (e.g. use of a value available for a specific year, not coinciding with the reference year, without evident underlying trend).
- In case of relevant data missing, spatial extrapolation and temporal data gap filling procedures (following the hierarchy from iii to iv) were used for completing the inventories. Particularly, in the case of temporal extrapolation, we adopted the following sequential prioritization rules to select data for covering the gaps: a) data for 2010, strictly from the same primary source; b) data for 2010 from an alternative source; c) data relating to years which are different from the reference (e.g. from 2008 to 2011, preferably, but in any case within 2008-2014) coming from the primary source; d) if no one of the previous alternatives is valid, data for a year different from the reference one, coming from an alternative source. The details of the extrapolations are reported in the next sections for each impact category in the relative reference scale. Overall, a complete list of methodologies is reported in Sala et al. (2014).

- A qualitative assessment of the coverage completeness and robustness of datasets used for building the inventories is included, according to specific criteria defined through an expert judgement. Inventory coverage completeness was evaluated in terms of the extent to which the inventory data were available compared to available flows in ILCD for specific impact categories and a score of I (highest coverage, from 60% to 100% of completeness) or II (medium coverage, from 30% to 59%) or III (lowest coverage, from 0 to 29%) was given. The robustness of the inventory was evaluated in relation to several aspects linked to the quality of data, namely the combination of different sources and the adoption of extrapolation strategies. Specifically, a three-level score was attributed, as follows: I (highest robustness, meaning data from published datasets from official data sources, subjected to a quality assurance procedure and limited use of extrapolation methods, i.e. <20 % of the impact derived from extrapolation); II (medium robustness, meaning unpublished datasets and/or use of extrapolation methods for more than 20 % but less than 80 % of the impact); III (lowest robustness, meaning use of extrapolation methods for more than 80 % of the impact).

The sets of final NFs at different scales could be used as self-standing normalisation references in LCA studies. Furthermore, the resulting European and global NFs could be compared against the planetary boundaries' references (according to the definition of Rockström et al., 2009) in order to identify the extent to which the different references are overcoming thresholds related to the safe operating space at planetary level.

Moreover, additional set of normalisation factors could be calculated according to the approaches presented in table 1. The methodology for their calculation is reported below.

2.1 EU-27 inventory

As reported in Sala et al. (2015), the calculation of the NFs for Europe is based on the refinement and update of the 'Resource Life Cycle indicators' dataset developed by the EC-JRC (Benini et al., 2014a), that was used as a basis for building the inventory. These indicators were developed within the Life Cycle Indicators framework (EC-JRC, 2012b) following the EU Communication "Roadmap to a resource efficient Europe" (CEC, 2011).

The EU-27 inventory, defined as domestic inventory, is built on a vast data collection at country scale, covering the releases into air, water and soil and resources extracted in the EU-27 territory, related to the reference year 2010. According to the abovementioned hierarchical approach, the EU-27 inventory is predominantly constituted of raw data proceeding from national and international agencies, which provide environmental statistics, such as FAO, Eurostat, EEA, etc. When the selected statistical datasets were not complete with respect to relevant data, namely important data were missing or only partially available at a country or time-series basis, specific extrapolation procedures were adopted to fill the data gaps, according to the methodologies proposed in Sala et al. (2014). As a result, the domestic inventory includes also data derived from estimations and assumptions performed in order to complement the available datasets. The final list of data sources by group of substances is reported in Table 2, with relation to each impact category.

Table 2: Data sources used to compile the EU-27 domestic inventory. Source: Sala et al., 2015.

Impact category	*Substance groups as in ILCD*	*Data sources*[1]
Climate change	CO_2, CH_4, N_2O both from direct emissions and those associated to LULUCF (land use, land-use change and forestry)	- UNFCCC (2013)
	HFCs, PFCs and SF_6	- UNFCCC (2013)

[1] All the references reported in this table could be retrieved from Sala et al. 2015, with the specific links at the data source that has been used at the time of the calculation of the European domestic inventory

Impact category	***Substance groups as in ILCD***	***Data sources[1]***
	Other substances**	- Total NMVOC per sector from: CORINAIR/EEA (2007; 2009); EMEP/CEIP (2013a) for sector activity modelling; speciation per sectors (Laurent and Hauschild, 2014)
	HCFC-141b, HCFC-142b	- EDGARv4.2 (EC – JRC & PBL, 2011)
	1,1,1-trichloroethane	- E-PRTR database (EEA, 2013a)
Ozone depletion potential	CFCs, HCFCs, etc.	- Total NMVOC per sector from: CORINAIR/EEA (2007; 2009);EMEP/CEIP (2013a) 'EMEP_reported' for sector activity modelling; speciation per sectors (Laurent and Hauschild, 2014)
	HCFC-141b, HCFC-142b	- EDGARv4.2 (EC – JRC & PBL, 2011)
	1,1,1-trichloroethane	- E-PRTR database (EEA, 2013a)
Human toxicity (cancer, non-cancer) and Ecotoxicity	Air emissions	
	Heavy metals (HMs)	- EMEP/CEIP (2013a) 'EMEP_reported'
	Organics (non-NMVOC): e.g. dioxins, PAH,, HCB, etc.	- EMEP/CEIP (2013a) 'EMEP_reported', - E-PRTR (EEA 2013a)
	NMVOC	• - Total NMVOC per sector from: CORINAIR/EEA (2007; 2009);EMEP/CEIP (2013a) for sector activity modelling; speciation per sectors (Laurent and Hauschild, 2014)
	Water emissions	
	Industrial releases of HMs + organics	- E-PRTR (EEA, 2013a) - Waterbase (EEA, 2013b) - Eurostat (2013a)
	Urban WWTP (HMs + organics)	- Waterbase (EEA, 2013b), OECD (2013a), Eurostat (2013b)
	Soil emission:	•
	Industrial releases (HMs, POPs)	• - E-PRTR (EEA 2013a)
	Sewage sludge (containing organics and metals)	- usage EEA (2013b) and Eurostat (2013c) - EC (2010) for Heavy Metal composition - EC (2001) for dioxins
	Manure	• - FAOstat (2013a), Amlinger et al. (2004), Chambers et al. (2001)
	Pesticides	
	Active ingredients (AI) breakdown	- Pesticide usage data: FAOstat (2013d; 2013e) (F, H, I, O + chemical classes) + Eurostat (2013f) for second check - Eurostat (2013d) for crop harvested areas; FAOstat (2013b) - FAOstat (2013c) for organic areas
Particulate matter/ Respiratory inorganics	CO, NO_X (as NO_2)	- UNFCCC (2013)
	SO_2, NH_3	- EMEP/CEIP (2013b) – 'EMEP_modeled' dataset
	PM_{10}, $PM_{2.5}$	- EEA (2013c)
	$PM_{0.1}$	- EDGARv4.2 (EC-JRC/PBL, 2011)
Ionising Radiations	emissions of radionuclides to air and water from energy production (nuclear and coal)	- UNSCEAR data on emissions factors (2008) for 14C, 3H, 131I; - nuclear energy production (Eurostat, 2013l; 2013m) - Ecoinvent 3.01 (Weidema et al., 2013) - OSPAR (2013a)
	emissions of radionuclides to air and water from nuclear spent-fuel reprocessing	- UNSCEAR data (2008) on emissions emission factors for 3H, 14C, 60Co, 90Sr, 99Tc, 129I, 106Ru, 137Cs and 241Pu - Spent fuel reprocessing statistics are from the International Panel on Fissile Materials (IPFM) (Forwood, 2008; Schneider and Marignac, 2008).
	discharge of radionuclides from non-nuclear activities (radio-chemicals production and research facilities)	- OSPAR Commission database (OSPAR, 2013b) for: radio-chemicals production and research facilities
	discharge of radionuclides from oil & gas industry	- OSPAR Commission database (OSPAR, 2013c) - overall oil production figures (Eurostat, 2013r)

Impact category	Substance groups as in ILCD	Data sources[1]
	emissions to air and water from the end-of-life scenario of gypsum boards	- Ecoinvent (v 3.01) unit processes (Weidema et al., 2013); - PRODCOM data (PRODCOM/Eurostat 2013).
Photochemical ozone formation	NMVOC	- Total NMVOC per sector from: CORINAIR/EEA (2007; 2009);EMEP/CEIP (2013a) for sector activity modelling; speciation per sectors (Laurent and Hauschild, 2014)
	NO_X (as NO_2)	- UNFCCC (2013)
	SO_2	- EMEP/CEIP (2013b) – 'EMEP_modeled' dataset
Acidification	NO_X (as NO_2)	- UNFCCC (2013)
	SO_2, NH_3	- EMEP/CEIP (2013b) – EMEP_modeled dataset
Terrestrial eutrophication	NO_X (as NO_2)	- UNFCCC (2013)
	NH_3	- EMEP/CEIP (2013b) – 'EMEP_modeled' dataset
Freshwater eutrophication	Phosphorous (total) to soil and water, from agriculture	- Eurostat (2013g) for phosphorous Input and Output data - UNFCCC (2013) for nitrogen input - FAOstat (2013b) for cultivated cereal surfaces - Bouwman et al. (2009) 10% loss of P to water as global average
	Phosphorous (total) to soil and water, from sewages	- removal efficiency of Phosphorous Van Drecht et al (2009) - Use of laundry and dishwater detergents, (RPA 2006) - Fraction of P-free laundry detergent (RPA 2006) - % of people connected to wastewater treatment OECD (2013a), Eurostat (2013h)
Marine eutrophication	NO_x (as NO_2)	- UNFCCC (2013)
	NH_3	- EMEP/CEIP (2013b) – 'EMEP_modeled' dataset
	Nitrogen (total) to water, from agriculture	- Ntot input data, losses to water and to air, synthetic fertilizers, manure UNFCCC (2013). - N output based on ratios (by country, by year) between Input and Output by Eurostat (2013g), multiplied to Inputs from UNFCCC (2013)
	Nitrogen (total) to soil and water, from sewages	- protein intake, FAOstat (2013f) - removal efficiency of Nitrogen Van Drecht et al (2009) - Percentage of people connected to WWTP OECD (2013a) and Eurostat (2013h)
Land use	"Land occupation" and "land transformation" : forest, cropland, grassland, settlements, unspecified	- UNFCCC (2013) national inventories - Corine Land Cover (EEA, 2012) for CY and MT
Water depletion	Gross freshwater abstraction	- Eurostat (2013i) ; OECD (2013b) ;FAO-Aquastat (2013)
Resource depletion - energy carriers, minerals and metals	Metals	- British Geological Survey -BGS (1995, 2000, 2002, 2012) - Raw Material Group RMG (2013) - World Mining Data WMD (2014) - EC (2014)
	Minerals	- PRODCOM (PRODCOM/Eurostat, 2013)
	Energy carriers	- Eurostat (2013l; 2013m; 2013n; 2013o; 2013p; 2013q)

*method for extrapolation as reported in Sala et al 2014.

** including 1,1,2-trichloro-1,2,2-trifluoroethane, methylenchloride, chloroform, tetrachloromethane, chlorodifluoromethane, dichlorofluoromethane, CFCs, Dichloromethane

2.2 Global inventory

The set of NFs as estimate of the global environmental pressures and impact in 2010 was built by following a territorial approach similar to the one described in Sala et al. (2015) for the EU-27 reference system.

International statistics on emissions and resources extracted at global level were gathered, translated into elementary flows according to ILCD nomenclature and characterized through the ILCD recommended impact assessment models (EC-JRC, 2011), using CFs at midpoint.

The inventory, which refers to the year 2010, is based on a vast data collection, covering the emissions into the environmental compartments (i.e. air, water and soil) and resource extracted at the global scale. When relevant data were missing, specific extrapolation procedures were adopted to fill the data gaps, according to the methodologies for extrapolation available in Sala et al. (2014). The overall list of data sources by group of substances is reported in Table 3, with relation to each impact category. When different data sources were available, all the retrieved data have been reported in order to allow a qualitative evaluation of the uncertainties associated to the global inventory estimates.

Table 3: Data sources used to compile the global inventory for the reference year 2010.

Impact category	***Substance groups as in ILCD***	***Data sources***[2]
Climate change	CO_2, CH_4, N_2O both from direct emissions and those associated to LULUCF (land use, land-use change and forestry); PCFs; HFCs; SF_6	- EDGAR v4.2 (EC-JRC & PBL, 2013)
	HCFC-141b; HCFC-142b	- EDGAR v.4.2 (EC-JRC & PBL, 2011a)
	HCFC-22; CFC-11; Halon-1211	- Fraser et al., 2014
	Aggregated datum	- EDGAR v4.2 (EC-JRC & PBL, 2011b); UNFCCC (2015)
Ozone depletion potential	HCFC-140	- Fraser et al., 2015
	CFC-11	- Fraser et al., 2014
	HCFC-22; Halon-1211, Halon total	- Fraser et al., 2013
Human toxicity (cancer, non-cancer) and Ecotoxicity	Air emissions: Heavy metals (HMs) Organics (non-NMVOC): e.g. dioxins, PAH, HCB, etc. NMVOC Water emissions: Industrial releases of HMs + organics Urban WWTP (HMs + organics) Soil emission: Industrial releases (HMs, POPs) Sewage sludge (containing organics and metals) Manure Pesticides: Active ingredients (AI) breakdown	- Cucurachi et al., 2014
Particulate matter/Respiratory inorganics	NO_x (as NO_2); NH_3	- EDGAR v4.3.1. (EC-JRC & PBL, 2016); ECCAD v6.6.3 (GEIA, 2016); Oita et al., 2016
	SO_2	- EDGAR v4.3.1. (EC-JRC & PBL, 2016); ECCAD v6.6.3 (GEIA, 2016); Klimont et al., 2013
	PM_{10}, $PM_{2.5}$	- EDGAR v4.3.1. (EC-JRC & PBL, 2016); Winijkul et al., 2015
	CO	- EDGAR v4.3.1. (EC-JRC & PBL, 2016); ECCAD v6.6.3 (GEIA, 2016)
Ionising radiation	emissions of radionuclides to air and water from energy production (nuclear)	- nuclear energy production (IAEA-PRIS, 2016)
	Emissions of radionuclides to air and water from nuclear spent-fuel reprocessing	- RADD (2016); UNSCEAR (2016); WNA (2016a)
Photochemical ozone formation	NMVOC; NO_x (as NO_2), CH_4;CO	- EDGAR v4.3.1 (EC-JRC & PBL, 2016)

[2] These references are within the reference list of the present report

Impact category	Substance groups as in ILCD	Data sources[2]
Acidification	NO_X (as NO_2); SO_2; NH_3	- EDGAR v4.3.1 (EC-JRC & PBL, 2016); ECCAD v6.6.3 (GEIA, 2016); Oita et al., 2016
Terrestrial eutrophication	NO_X (as NO_2); NH_3	- EDGAR v4.3.1. (EC-JRC & PBL, 2016); ECCAD v6.6.3 (GEIA, 2016); Oita et al., 2016
Freshwater eutrophication	Phosphorous (total) to soil and water, from agriculture	- Bouwman et al., 2013
Marine eutrophication	NO_x (as NO_2); NH_3	- EDGAR v4.2 (EC-JRC & PBL, 2011a); EDGAR v.4.3.1 (EC-JRC & PBL, 2016); ECCAD v6.6.3 (GEIA, 2016); Oita et al., 2016
	Nitrogen (total) to water, from agriculture	- Bouwman et al., 2013
Land use	"land occupation" and "land transformation" : forest, cropland, grassland, settlements, unspecified	- Farago et al., (submitted)
Water depletion	Gross freshwater abstraction & Gross water consumption	- FAO-Aquastat (2016); Eurostat (2016); OECD (2016)
Resource depletion - energy carriers, minerals and metals	Metals; minerals	•- USGS, 2011 a, b
	energy carriers	•- WNA, 2016b •- IEA, 2014

In the following sub-sections, (i) the data sources and (ii) the extrapolation methods adopted in case of missing data along with the related sources are presented for each impact category. The file containing all the calculations described in the following sections is available upon request.

2.2.1 Climate change (GWP)

Emissions of greenhouse gases into air, contributing to climate change, were predominantly retrieved from the EDGAR (Emission Database for Global Atmospheric Research) database v. 4.2 (EC-JRC & PBL, 2011a, b and 2013), both as single elementary flows in terms of Gg emitted per year and as characterized aggregated value, referred to as "GHG total" (total of greenhouse gases measured in Gg CO_2 equivalent). Specifically, EDGAR v4.2 is a bottom-up modelling exercise based on activity data and emission factors from time periods up to 2010 (single flows' case) or 2012 (aggregated value). EDGAR has the advantage of being coherent among the different Member States. However, there is no periodical review and update process.

Two additional data sources were taken into account: i) the Commonwealth Scientific and Industrial Research Organisation (CSIRO) report (Fraser et al., 2014); ii) the report of the United Nation Framework Convention on Climate Change (UNFCCC, 2015). In the first mentioned publication, global emissions to air up to 2014 are derived from background observations at Cape Grim (Australia) and from other AGAGE (Advanced Global Atmospheric Gases Experiment) stations in the Northern and Southern Hemispheres. These emissions are expressed in Gg and calculated using a global model of atmospheric chemistry and transport and a Bayesian method based on Rigby et al. (2013). Instead, in UNFCCC report (2015), data are built on national greenhouse gas inventories from the Parties included in Annex I to the Convention for the period 1990-2013. Data from the national inventories are expressed in kTonnes (i.e. Gg) CO_2 equivalent, following the characterization based on the GWP_{100} from IPCC (2007). Data proceeding from the Parties not included in the Annex I of the Convention were not taken into account, since they were out of date (e.g. 1990/1994) and no references to an underlying trend were provided in order to apply an extrapolation strategy.

According to the presented data sources, it was possible to build four different inventories. The main features of each inventory are listed below.

1. An inventory composed by single flows (Global 2010 (i)) emissions was based mainly on EDGAR v4.2 (EC-JRC & PBL, 2011a). Direct greenhouse gas emissions in EDGAR include: carbon dioxide (CO_2) totals excluding short-cycle biomass burning (such as agricultural waste burning and Savannah burning) and excluding other biomass burning (such as forest fires, post-burn decay, peat fires and decay of drained peatlands); methane (CH_4) totals and N_2O totals including also biofuel and biomass; fluorinated gases (F-gases), namely hydrofluorocarbures (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6), and nitrogen trifluoride (NF_3). To complement the inventory with 2010 data, values for HCFC-22, CFC-11 and halon-1211, were taken from the CSIRO report (Fraser et al., 2014)
2. To cover the remaining gaps for 2010 in the previous inventory, a temporal extrapolation was applied in order to obtain a more comprehensive inventory option (Global 2010 (ii)). We extrapolated data for HCFCs, namely HCFC-141b and HCFC-142b, from EDGAR v.4.2 (EC-JRC & PBL, 2011a), for emissions in 2008. Then, all the emission data from EDGAR (i.e. both 2008 and 2010) were combined with the estimations from Fraser et al. (2014) model. This was possible, since data were quite complementary, i.e. no alternative options for the same flow were available.
3. An additional option (Global 2010 (iii)) is represented by the aggregated value from EDGAR v.4.2 (EC-JRC & PBL, 2011b). This is based on all the anthropogenic CH_4 sources, N_2O sources and emissions of F-gases (HFCs, PFCs and SF_6). It also includes CO_2 totals excluding short-cycle biomass burning, but including other biomass burning. This latter aspect has to be taken into consideration as source of bias when comparing the two calculated NFs, since this may cause underestimation of the NF in the first case (i.e. single flow cases). The aggregated value was calculated using the GWP_{100} metric of IPCC (1996, not updated).
4. Another aggregated GHGs value (Global 2010 (iv)) was taken from the UNFCCC (2015) report. This GHG value was already characterized, as the GHG total value from EDGAR (EC-JRC & PBL, 2011b).

Option 3 is assumed to be incomparable with the other: although, all the methods use CFs according to the GWP_{100} from IPCC, the aggregated value by EDGAR (Global 2010 (iii)) was calculated using an old version of GWP_{100} metric of IPCC (1996, not updated); whereas ILCD adopted CFs based on GWP_{100} metric from IPCC (2007).

2.2.2 Ozone depletion potential (ODP)

Ozone depleting substances' emissions to air, were taken from CSIRO reports (Fraser et al., 2013, 2014, 2015), as for some substances accounting for climate impacts. Specifically, data on HCFC-140 (referred to as "MC" in the reference report), CFC-11, HCFC-22 and halon-1211 were retrieved respectively from Fraser et al., 2015, 2014 and 2013, in terms of Gg of substance emitted to air per year.

Due to the lack of several emission data for the year 2010, a temporal data gap filling procedure was applied to some substances, namely halon-1001, HCFC-141b and HCFC-142b. In these cases, we used the values available for 2008, estimated by the same authors through the same methodology as 2010 extrapolations, assuming that the emission remained unchanged during the years between 2008 and 2010. We preferred to use data from CSIRO calculations instead of adopting different sources, to be consistent with the prioritization of data sources explained at the beginning of section 2.

Except for halon-1211, whose figure was available as single flow, and halon-1001, whose value was extrapolated from 2008, data on halons were provided by CSIRO as aggregated value in terms of total Gg emitted into air in 2010. In order to estimate halons' contribution to the global impact to the ozone layer, an average characterization factor was applied. For consistency with the study, the average was calculated considering the CFs of all the eight halon elementary flows contributing to ozone depletion available in ILCD.

Halon-1211 and the extrapolated halon-1001 taken as single (potentially representative) flows for halons, and the aggregated value for halons may represent possible alternatives to be considered for calculating global reference for the ozone depletion category.

2.2.3 Human toxicity cancer (HTOXC), non-cancer (HTOXNC) and freshwater ecotoxicity (FRWTOX)

Emissions into air, water and soil contributing to toxicity-related impacts were collected from Cucurachi et al. (2014), as characterized aggregated value for each impact category. These data derive from the combination of actual emissions and additional extrapolated values. As extensively explained in Cucurachi et al. (2014) and Sala et al. (2014), due to a limited availability of emission data, extrapolation strategies were applied to existing chemical inventories from Europe, USA, Canada, Japan and Australia for filling the data gaps for certain flows and then calculating the three global normalisation references associated to each impact category. Adopted extrapolation procedures were based on CO_2 emissions, GDP (Gross Domestic Product) values and Hg emissions.

CO_2 emission-based strategy was used owing to the fact that they may represent the level of industrialisation and the energy intensity of a country. Alternatively, GDP-based strategy was used assuming the close and direct relationship between economic growth and the industrial production with the associated releases into the environment. Furthermore, a procedure based on Hg emissions was applied, since the occurrence of Hg is related to activities that may be not captured neither by GDP nor by CO_2, e.g. mining which may occur in relatively underdeveloped and poor countries.

Additionally, we calculated five alternatives global references for each toxicity-related category, based on:

- A global average, calculated as geometric mean of the extrapolated global references (i.e. those estimated by Cucurachi et al. (2014) scaling up EU-27 plus inventory to the world using CO_2, GDP and Hg emissions);

- A global average calculated as the global geometric mean obtained according to the previous point, multiplied by the relative ratio between EU-27 value (Sala et al., 2015) and EU value measured by Cucurachi et al. (2014);

- Three global references for CO_2, GDP and Hg emissions, calculated as the global extrapolated reference for CO_2, GDP and Hg emissions respectively, multiplied by the relative ratio between EU-27 value (Sala et al., 2015) and EU value measured by Cucurachi et al. (2014).

Multiplying the extrapolated global values by the ratio between the EU-27 value from Sala et al. (2015) and EU value from Cucurachi et al. (2014) is necessary in order to adjust the global values proposed by Cucurachi et al. (2014) to the scale of the inventory built by Sala et al. (2015), which represents the EU-27 normalisation factor proposed by EC-JRC.

2.2.4 Particulate matter/Respiratory inorganics (RIPM)

Data on nitrogen and sulphur dioxide (NO_2 and SO_2, respectively), ammonia (NH_3), carbon monoxide (CO) and particulates such as PM_{10} and $PM_{2.5}$, which represent the predominant flows contributing to the global impacts associated to the category particulate matter and respiratory organics (RIPM), come from different sources, mainly EDGAR v.4.3.1 (EC-JRC & PBL, 2016) and MACCIty database distributed by ECCAD v.6.6.3 (GEIA, 2016). ECCAD is a project of the Global Emissions InitiAtive (GEIA), launched by the Ether Pole, the French Center of Atmospheric Products and Service, and developed under a partnership between CNES (Centre National d'Etudes Spatiales) and INSU (Institut National des Sciences de l'Univers).

EDGAR v.4.3.1 database covers emissions to air in terms of Gg per year from 1970 to 2010 by country for several sectors (i.e. energy industry, transport, chemical industry, manure management, agricultural waste burning, solid waste disposal, etc.). Whereas, ECCAD dataset provides the access to global and regional emission data of atmospheric compounds in terms of Tg emitted per year, collected and linearly interpolated, for each sector and each year between 1960, 1970, 1980, 1990, 2000, 2005 and 2010.

Other information related to the emission of nitrogen compounds to the air was retrieved from the paper of Oita et al. (2016), which reported data of Tg of NO_x emitted for the year 2010, mapped in ILCD as nitrogen dioxide (NO_2). The corresponding ILCD characterization factor was adopted for quantifying the midpoint impact category indicator. Oita and colleagues (2016) provided data on anthropogenic emissions of nitrogen compounds to the atmosphere mainly coming from agriculture and industry sector, especially energy generation and transport, collected respectively from FAO and the International Fertilizer Association (IFA) databases.

The same online available datasets, except for Oita et al. (2016), were used to compile the inventory of SO_2 flows. Additional data for global SO_2 flow, in terms of Tg emitted in 2010, were retrieved from Klimont et al. (2013), whose calculations were based on an agreed bottom-up model used for estimating the changes in atmospheric SO_2 between 2000 and 2011.

More data on $PM_{2.5}$ and PM_{10} emissions were taken from the publication of Winijkul et al. (2015), where the authors built a global and regional, size-resolved inventory of PM emissions (Gg/yr) from various sources, including urban, industrial, and transportation for the year 2010.

2.2.5 Ionising radiation (IR)

The inventory for the ionising radiation impact category for 2010 was built on the emissions of radionuclides to air and water from energy production both from nuclear sources and nuclear spent-fuel reprocessing.

As explained by Sala et al. (2014), to take into consideration the fact that not all the countries that produce energy from nuclear sources have a commercial reprocessing facility, the emissions from electricity production and spent-fuel reprocessing were accounted separately.

The aggregated characterized value representing the impact due to the radiative emissions following energy production was estimated on the total nuclear installed net capacity at global level, in terms of Megawatt (MW). Particularly, nuclear power capacity data were retrieved from the International Atomic Energy Agency’s Power Reactor Information System (IAEA-PRIS, 2016) for 31 countries on a global scale, for a total of 441 operating reactors in 2010, mostly located in Europe, Northern America, East Asia and South Asia.

According to the definition given by IAEA, operating reactors are those reactors that were in operation at least for a short time during 2010, including reactors that were shutdown (permanently or into medium-long term) during the reference year.

From this data, MW of total nuclear power installed in the EU-27 territory in 2010 were selected for calculating the ratio EU-27/World of the installed energy capacity. Once calculated the above-mentioned ratio, its reciprocal was multiplied by EU-27 impact value (i.e. the normalisation factor for ionising radiation) from Sala et al. (2015), to get the total value for the world, measured in kBq U-235 eq.

The emissions of ionising radiations to airborne and liquid effluents in 2010 due to nuclear spent-fuel reprocessing activities were retrieved from the European Commission’s Radioactive Discharges Database (RADD, 2016) for the reprocessing plants of UK (Sellafield and Dounreay), France (La Hague) and Germany (Karlsruhe). Emissions were expressed in terms of GBq of emitted substance.

Within 2010 data for the UK, a temporal extrapolation was applied for estimating the emission of antimony-125 (Sb-125) to liquid effluents. According to the downwards trend of emissions for this substance, the value was calculated as geometric mean of 2009 and 2011 values.

Radioactive emissions from reprocessing activities in India and Russia were derived from UK and France data, respectively, according to the reprocessing technology employed and assuming the full capacity of the reprocessing plant. Specifically, the full commercial reprocessing capacity of plants in India and Russia was multiplied by emissions factors calculated for each substance as ratio between GBq of emitted substance and the full commercial reprocessing capacity of plants of the UK and France, respectively. Final emission profile for India and Russia was expressed in GBq of emitted substance. Reprocessing capacity information was retrieved from the World Nuclear Association report (WNA, 2016a)

Additional data on radioactive emissions from nuclear spent-fuel reprocessing was taken from the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR, 2016) for Tokai plant, in Japan, for the years 1998 to 2002. No updated data were available. In any case, the relative contribution of those data is negligible (i.e. 0.2% of the total emission from reprocessing activities). The emission profile for Japan was calculated as geometric mean of all data from the temporal series for each substance.

2.2.6 Photochemical ozone formation (POF)

Data related to the flows that contribute to photochemical ozone formation for 2010 were taken from EDGAR v.4.3.1 (EC-JRC & PBL, 2016).

Data on non-methane volatile organic compounds (NMVOC), nitrogen dioxides (NO_2), ammonia (NH_3) and carbon monoxide (CO), which represent the predominant flows contributing to the global impacts associated to this category, were retrieved in terms of Gg of emissions for the year 2010.

NMVOC group includes a high number of substances that are known to cause effects related to photochemical ozone formation. In EDGAR database, we retrieved an aggregated value for this elementary flow, which has a specific and unique CF in ILCD, allowing us to characterize the impacts deriving from these substances.

Alternatively, according to the methodology developed by Laurent and Hauschild (2014), a substance breakdown could be done, using available speciation profiles based on specific sectoral activity data. Breakdown strategy would allow us to have a more comprehensive and precise inventory base on a greater number of elementary flows, characterizing the impact of each substance by using their specific CF available in ILCD. In the EU-27 exercise made by Sala et al. (2015), the characterized result for NMVOC based on breakdown procedure remains relatively unchanged with respect to the characterized value obtained by using total NMVOC aggregated value (no-breakdown procedures). However, unlike the EU-27 emissions, information on speciation profiles for NMVOC substances at global level was not readily available in the current literature, as only total NMVOC emissions were reported. Therefore, we used only the aggregated value for NMVOC.

2.2.7 Acidification (AC)

As for RIPM inventory, the atmospheric emissions of nitrogen oxides (NO_x) contributing to acidification-related impacts were taken from EDGAR v4.3.1 (EC-JRC & PBL, 2016) in terms of mass (Gg) of NO_2 and from ECCAD v6.6.3 (GEIA, 2016) and Oita et al. (2016) in terms of Tg/yr of NO_x. In ILCD NO_x flows are mapped as NO_2, i.e. they share the same CF. We decided to map the flows of NO_x and NO_2 as NO_2, since the ratio between NO and NO_2 is unknown from the statistics. Subsequently, after the adequate transformation to kg of mass flows, the corresponding characterization factor was used for calculating the midpoint impact indicator.

Data on sulphur dioxides (SO_2) and ammonia (NH_3) were retrieved from the same sources. There was no need to apply either temporal or spatial extrapolations to cover data gaps.

2.2.8 Terrestrial eutrophication (EUTT)

The flows contributing to terrestrial eutrophication are NO_x and NH_3 to air, whose statistics were taken as mass flows from EDGAR v4.3.1 (EC-JRC & PBL, 2016), ECCAD v6.6.3 (GEIA, 2016) and Oita et al. (2016). NO_x was retrieved as both NO_x and NO_2, and mapped into NO_2 since these flows have the same CF in ILCD and statistics do not provide detailed information on the amount of NO and NO_2. Then, as for the other categories dealing with NO_x, the corresponding characterization factor was used for calculating the midpoint impact indicator.

Neither temporal nor spatial extrapolations were applied to cover data gaps.

2.2.9 Freshwater eutrophication (EUTF)

Data on the total emissions of phosphorus (P) to soil and water, leading to freshwater eutrophication, were collected from the publication of Bouwman et al. (2013) and estimated for the reference year 2010, as data for this year were not directly available. In Bouwman et al. (2013), a comprehensive inventory of global P availability in the agricultural systems is presented, covering the following years: 1900, 1950, 2000, and the possible future changes in 2050, based on the United Nations medium projection which depicts a world with a population in continuous expansion, constantly growing economy, increasing consumption, especially of meat- and milk-based products.

Global P budget (i.e. the difference between inputs from the application of fertilizer and manure, and the loss through crop harvesting, grazing or grass mowing) and global P runoff (i.e. the only pathway which is assumed to move P to water sources), were mapped into ILCD elementary flows as "Phosphorus, total (to soil)" and "Phosphorus, total (to water)", respectively. No details about specific emissions, such as phosphate and phosphoric acid, were found.

According to the linear growth of global P amount underlined by the study, a linear extrapolation strategy was applied for calculating the annual increase of both P budget and runoff from crop-livestock production systems at global level between the years 2000 and 2050. The figures related to 2010 were then estimated.

2.2.10 Marine eutrophication (EUTM)

In order to build the inventory for marine eutrophication, statistics on nitrogen compounds were retrieved from various sources. The flows of NO_x to air for 2010 were taken from EDGAR v4.3.1 (EC-JRC & PBL, 2016) in terms of NO_2, while from ECCAD v6.6.3 (GEIA, 2016) and Oita et al. (2016) in terms of NO_x. In ILCD, NO_x flows are mapped as NO_2, i.e. they are characterized by the same CF. Both for this reason and for the fact that the NO_2 and NO amounts are unknown from the statistics, we mapped the flows of NO_x and NO_2 as NO_2. Subsequently, the corresponding characterization factor was used for calculating the midpoint impact indicator.

Airborne emission data on ammonia (NH_3) were available in EDGAR v4.3.1 and Oita et al. (2016). In the latter, also the NO_3^- emission to water was available.

The total emission of nitrogen (N tot) to water was obtained from the paper of Bouwman et al. (2013), following the same procedure explained for P in the previous paragraph on freshwater eutrophication. Firstly, global N budget (i.e. the difference between inputs from the application of fertilizer and manure, and the loss through crop harvesting, grazing or grass mowing) was mapped into ILCD elementary flows as "Nitrogen total (to water)". This is because we assumed that the global N budget available in the soil can move to water through leaching and runoff. Then, according to the linear growth of global N tot amount observed in the study, a linear extrapolation was applied for calculating the annual increase of N budget from crop-livestock production systems at global level between the years 2000 and 2050. The figures related to 2010 were finally estimated.

To cover several data gaps, thus obtaining a more complete inventory, emission data from different sources were used and combined, according to the prioritisation of sources proposed by Sala et al. (2015), maintaining the consistency with the choices made for the other impact categories.

2.2.11 Land use (LU)

The inventory related to the land use impact category was developed according to the following criteria, as reported in Farago et al. (submitted): a) global coverage, b) spatially-differentiated at a country level, c) land use occupation and transformation flows, d) consistent with the reference year of 2010.

According to Sala et al. (2014), data on occupation and transformation from UNFCCC were considered not adequate because of inconsistencies and lack of completeness. Given that, with the exception of UNFCCC, no publicly available data exist for land transformation, the approach applied in this work implied deriving transformation values as differences of occupation data between years.

Concerning agricultural and forestry land use classes, data were extracted from the statistics provided by FAOstat (FAOstat 2016), whose nomenclature was not compliant with the one adopted by ILCD. Therefore, a previous mapping step was needed. Farago and colleagues (submitted) exhaustively report the outcome of this classification.

In order to calculate inventories for transformation flows, FAOstat time series at country-scale resolution were used: the transformation inventories were estimated as the difference between two consecutive years of occupation data. In order to get an average transformation data to represent the 2010 reference year, Farago and colleagues chose to take into account the 2005-2010 time-span.

Since data about urban areas global coverage were publicly not available, another extrapolation strategy was necessary, based on the population density as a proxy indicator of urban areas. This kind of data was retrieved from NASA, by adopting a 300 inhabitants/km^2 as a suitable threshold for identify urban areas, following the OECD methodology. NASA population density grids adjusted to the March 2015 Revisions of the United Nations World Population Prospects (UN WPP) Country Totals (CIESIN, 2016) was chosen in this work. Similarly to what was done for agriculture and forestry, the transformation inventories for urban areas were calculated adopting the time-series extrapolation strategy.

Data retrieved from the FAO map "Dominant land cover type" representative for the year 2010 were used to obtain the inventories values for 'other' land use classes (namely shrub land, grassland, bare soil and water bodies). Since no datasets providing time series were available, it was not possible to calculate transformation inventories for these flows. Consequently, the final impact reference for land use category could be underestimated due to the lack of impact data of these land use classes.

2.2.12 Water depletion (WD)

In order to calculate NF for water depletion, two different inventories were built by taking into account two kinds of data: the gross freshwater (i.e. from river and from the ground) abstraction and the water consumption. In order to be compliant with the methodology indicated in Sala et al. (2015), no distinctions were made between fresh and ground water. Data on water withdrawals for hydropower generation are not accounted within the NFs, according to the Swiss Ecological Scarcity impact assessment method by Frischknecht al. (2009), which is currently recommended by EC-JRC (EC-JRC, 2011).

Concerning water withdrawal, data were mainly retrieved from FAO database (FAO-Aquastat, 2016). Given that many gaps were found for our reference year, i.e. 2010, other databases were consulted, namely Eurostat database (Eurostat, 2016a) and OECD database (OECD, 2016), both accessed in November 2016. Although some additional data were found, many countries were still without an inventory value, some of them with a potentially significant role in the water depletion category. For this reason, values referred to other years were used to fill the gaps, considering the 2008-2014 timespan, in line with the hierarchical approach explained at the beginning of section 2.

As already mentioned, also a consumption-based inventory was built, starting from WAterGAP (Müller Schmied et al., 2014) data. This inventory was compiled as well because it is more complete in terms of data. However, it should be used as a proxy for withdrawal because the ILCD model for water depletion requests a withdrawal inventory to be correctly applied.

2.2.13 Resources depletion - Energy carriers, mineral and metals (RD-E-MM)

In order to compile a global inventory for resources depletion, two different kind of data were retrieved: (i) minerals and metals and (ii) energy carriers.

The inventory for the first group of resources was built by means of the USGS commodity report (USGS, 2011a) and the USGS mineral yearbooks (USGS, 2011b). Mine production data at global scale were extracted from the above-mentioned documents privileging values related to the metal content, in order to be consistent with ILCD characterization factors. For a number of elements, i.e. arsenic, chromium, phosphorus, potassium and rare earths, the data retrieved were representative for the oxide compound of the element (e.g. arsenic trioxide, chromite, potash) which is effectively mined. In these cases, the amount of the element itself was extrapolated by using the molecular weight of the oxide compound and the atomic weight of the element.

Concerning the accounting of each energy carrier in a global inventory, two different data sources were adopted, for fossils and uranium. Data on fossils, namely peat, brown and hard coal, natural gas and crude oil, were retrieved for the reference year 2013 from the International Energy Agency (IEA, 2014). Actually it was not possible to find the same data for 2010 since they are constantly updated. Data retrieved described the total production in terms of mass, therefore a conversion to energy amount was necessary, by using the average energy content (EC-JRC, 2012a).

On the hand, uranium inventory amount was extrapolated from the World Nuclear Association website (WNA, 2016b). Data on uranium production were referred to 2013 as well in order to be consistent with the reference year selected for fossil energy carriers. Moreover, they data were representative of its production in terms of amount but, since ILCD characterization factor refers to the produced energy, a conversion was operated, using the energy content as for the fossil carriers' conversion.

2.3 EU-27 Basket of products for selected final consumption categories

In order to track the overall environmental impacts of the European Union and ultimately of each Member State, while taking into account also the burdens associated with trade, in 2012, the EC-JRC developed a lifecycle-based approach that focus on specific representative products. These products are then up-scaled to overall EU consumption figures, named the Basket of Products (BoP) indicators (EC-JRC, 2012b). The project focuses on indicators that measure the environmental impact of the consumption of goods and services by the average European citizen, partly focusing on selected areas of consumption (food, housing and mobility) and partly on the total apparent consumption.

The development of the basket of products is largely explained in Notarnicola et al. (2017) and Sala et al. (2016). The methodology is based on the following steps:

1. Selection of the most representative products in terms of mass and economic values.
2. Disaggregation of the inventory model used to represent average EU basket products.

3. Definition of the main assumptions according to goal and scope of the study.
4. Data collection and adaptation.
5. Environmental assessment adopting ILCD methodology.

The BoP Food (Table 4) is built for modeling the food and beverage consumption in Europe. The composition of the basket reflected the relative importance of the products categories in terms of mass and economic value. The BoP Housing (Table 5) represents the housing consumption in Europe by taking into account: i) two dwelling types (Single family house -SFH and Multi-family house - MFH), ii) 3 climate zones (warm, moderate and cold) and iii) four periods of construction. Source of these data were adapted (aggregated data) from Intelligent Energy Europe (IEE) Project ENTRANZE (2014) Finally, the BoP mobility (Table 6) was built for modeling the mobility of citizens in Europe. The composition of the basket reflects the relative importance of the products categories in terms of mass used by citizens.

Table 4: Product groups in the BoP food and related quantities (per-capita consumption in one year). Source: Sala et al. (2016).

Product Groups	Basket product	Per-capita consumption (kg/pers.*yr^{-1})	Per-capita consumption %
MEAT	Pig meat	41	8%
	Beef	14	3%
	Poultry	23	4%
DAIRY	Milk & Cream	80	15%
	Cheese	15	3%
	Butter	4	1%
CEREAL-BASED	Bread	39	7%
SUGAR	Sugar	30	6%
OILS	Sunflower oil	5	1%
	Olive oil	5	1%
VEGETABLES	Potatoes	70	13%
FRUIT	Oranges	17	3%
	Apples	16	3%
BEVERAGES	Mineral water	105(*)	19%
	Roasted Coffee	4	1%
	Beer	70(*)	13%
PRE-PREPARED MEALS	Meat based dishes	3	1%
Total		541	100%[3]

(*) This value is expressed in liters

[3] 100% of the products in the BoP, which actually covered 58% of the food consumed by an average EU citizen in one year

Table 5: Composition of the residential building stock. Average floor area per dwelling type, by climate zone and by period of construction in EU-27 and relative number of dwellings and dwellers. Source: Sala et al. (2016).

Type of dwelling	Climate	Year	Average floor area/dwelling (m^2)	N° dwellings	Total floor area (m^2)	N° dwellers
SFH	WARM	<1945	1.10E+02	3.99E+06	4.39E+08	5.48E+07
SFH	WARM	1945-1969	9.77E+01	3.94E+06	3.85E+08	
SFH	WARM	1970-1989	1.00E+02	5.03E+06	5.03E+08	
SFH	WARM	1990-2008	1.29E+02	3.02E+06	3.89E+08	
SFH	MODERATE	<1945	8.98E+01	1.91E+07	1.71E+09	2.21E+08
SFH	MODERATE	1945-1969	9.12E+01	2.17E+07	1.98E+09	
SFH	MODERATE	1970-1989	9.58E+01	2.49E+07	2.38E+09	
SFH	MODERATE	1990-2008	1.02E+02	1.58E+07	1.61E+09	
SFH	COLD	<1945	1.02E+02	1.14E+06	1.16E+08	1.17E+07
SFH	COLD	1945-1969	9.99E+01	1.12E+06	1.12E+08	
SFH	COLD	1970-1989	1.17E+02	1.26E+06	1.47E+08	
SFH	COLD	1990-2008	1.25E+02	6.30E+05	7.86E+07	
MFH	WARM	<1945	8.97E+01	5.56E+06	4.99E+08	7.26E+07
MFH	WARM	1945-1969	8.57E+01	1.10E+07	9.41E+08	
MFH	WARM	1970-1989	9.00E+01	1.23E+07	1.11E+09	
MFH	WARM	1990-2008	9.52E+01	6.92E+06	6.59E+08	
MFH	MODERATE	<1945	5.85E+01	1.29E+07	7.54E+08	1.25E+08
MFH	MODERATE	1945-1969	6.10E+01	1.65E+07	1.01E+09	
MFH	MODERATE	1970-1989	5.71E+01	1.98E+07	1.13E+09	
MFH	MODERATE	1990-2008	6.00E+01	1.20E+07	7.17E+08	
MFH	COLD	<1945	5.55E+01	1.33E+06	7.36E+07	9.46E+06
MFH	COLD	1945-1969	5.96E+01	1.58E+06	9.42E+07	
MFH	COLD	1970-1989	6.03E+01	1.83E+06	1.10E+08	
MFH	COLD	1990-2008	6.44E+01	9.11E+05	5.86E+07	

Table 6: Products in the BoP Mobility: EU28 fleet composition, vehicle-km and passenger-km travelled. Source: Sala et al. (2016).

Products	Sub-products in Use stage			Sub-product code	Vehicle-kilometers (million)	Passenger-kilometers (million)
Road transport	Passenger Cars	Gasoline <1,4 l	5.88E+05		5.88E+05	
		Gasoline <1,4 l	1.13E+05		1.13E+05	
		Gasoline <1,4 l	7.46E+04		7.46E+04	
		Gasoline 1,4 - 2,0 l	5.31E+05		5.31E+05	
		Gasoline 1,4 - 2,0 l	1.01E+05		1.01E+05	
		Gasoline 1,4 - 2,0 l	6.70E+04		6.70E+04	
		Gasoline >2,0 l	9.79E+04		9.79E+04	
		Gasoline >2,0 l	1.88E+04		1.88E+04	
		Gasoline >2,0 l	1.24E+04		1.24E+04	
		Diesel 1,4 - 2,0 l	8.17E+05		8.17E+05	
		Diesel 1,4 - 2,0 l	1.56E+05		1.56E+05	
		Diesel 1,4 - 2,0 l	1.03E+05		1.03E+05	
		Diesel >2,0 l	2.07E+05		2.07E+05	
		Diesel >2,0 l	3.96E+04		3.96E+04	
		Diesel >2,0 l	2.62E+04		2.62E+04	
		LPG	4.90E+04		4.90E+04	
	2W	Mopeds <50 cm^3	4.82E+04		4.82E+04	
		Motorcycles <250 cm^3	2.24E+04		2.24E+04	
		Motorcycles >250 cm^3	4.44E+04		4.44E+04	
	Buses	Urban Buses Standard 15 - 18 t	2.50E+04		2.50E+04	
		Coaches Standard <=18 t	2.29E+03		2.29E+03	
		Urban CNG Buses	2.29E+03		2.29E+03	
Rail transport	Electric			SP 23	-	2.86E+05
	Diesel			SP 24	-	1.15E+05
Air transport	National flights			SP 25	-	1.21E+05
	Intra-EU flights			SP 26	-	7.27E+05
	Extra-EU flights			SP 27	-	1.86E+06
Totals					3.15E+06	3.11E+06

2.4 Estimation of global inventory from input/output (I/O) approach

As pointed out in Sala et al. (2016), to obtain more detailed insights on the contribution of specific sectors to the environmental impact and on the supply chains underneath global final consumption, a disaggregation of the inventory by economic sectors should be provided. One option to gain such information is to use a top-down approach, i.e. to disaggregate into a large number of sectors (or products) through multi-regional input output tables (MRIOTs), e.g. EXIOBASE v.3. A full description of EXIOBASE v3 is yet not available in literature. However, it has been communicated by the DESIRE[4] project team in several occasions to EC bodies and EEA. A description of its prior version (EXIOBASE

[4] http://fp7desire.eu/

v2) is reported in Wood et al. (2015) and a methodological report by Merciai and Schmidt (2016) is available online.

The database is the result of a series of EU funded research projects (EXIOPOL[5], CREEA[6] and DESIRE), the last one (DESIRE) completed in February 2016. The database should allow for the consistent construction of resource efficiency indicators (91 indicators in total) addressing the EU production and consumption, including impacts which happens outside of the EU, as it covers 44 countries + 5 Rest of the World regions, and 200 sectors x 163 products, and the production and consumption perspective. The time series cover the period 2000 – 2011. As pointed out by Wood and colleagues (2015), EXIOBASE v3 should provide more sector detail and the greatest amount of environmental data compared to any other MRIO database, with a time series and sectorial resolution which are suitable for the purposes of this analysis. Its main drawback consists in the limited coverage of countries/regions if compared to other MRIO databases, e.g. GTAP (Narayanan et al. 2014) or EORA (Lenzen et al., 2013).

On one hand, this disaggregation option has the advantage of leading to highly resolved classifications (i.e. 200 products by 163 sectors); on the other hand, such resolution builds on specific technical assumptions for which it is not clear the effect on the overall results and therefore uncertainty cannot be estimated. Nevertheless, EXIOBASE v3 provides SUT (Supply Use Tables) tables and I/O tables in physical extensions, which are of interest and relevance for use in the accounting of environmental impacts.

The top-down approach has been already used by Huysman et al. (2016), who carried out an estimation of the environmental impacts of a European citizen by combining EXIOBASE v2 with ILCD recommended impact categories, focusing particularly on global warming. The main disadvantage of the approach was the fact that, out of the 15 midpoint impact categories recommended by the ILCD handbook (EC-JRC, 2011) only a limited number of impact categories (i.e. 10) were actually calculated because of the low level of compatibility between inventory and LCIA method (see also section 3.4).

2.5 EU-27 apparent consumption

In the same project presented in section 2.3 developed by EC-JRC, another approach to track the overall environmental impacts of the European Union and ultimately of each Member State is evaluated. According to this second approach, three different components, i.e. domestic, import and export, are identified and inventoried in order to quantify the environmental impacts associated with EU apparent consumption according to the following equation:

Impacts due to Apparent Consumption = Impacts due to Imports + Impacts due to activities occurring within the Territorial boundary – Impacts due to Exports

The 'domestic' component accounted for the environmental impacts associated with emissions and resource extraction occurring within a member state boundary. The domestic inventory was compiled through a systematized collection of emissions and extraction of resources occurring within the territorial boundaries of EU member states was carried out and classified according to ILCD nomenclature. As explained in Benini et al. (2014b), used data were from officially reported statistics on emissions into air, water and soil and resources extracted in EU-27 territory, relying on the data reported by Eurostat and other international and national statistical bodies. Specific choices made by dataset were the same discussed in Sala et al. (2015).

The import and export components are taken into consideration in the accounting of environmental impacts associated with product's supply chains. The sum of all of the environmental burdens associated with the entire volume of imported, or exported, goods led to the total environmental impact associated with import, or export. Trade statistics from Comext (Eurostat, 2016b) were used and a set of representative products was

[5] http://www.feem-project.net/exiopol/index.php
[6] http://creea.eu/

selected by mass (15 products) and value (5 products). The selection procedure (Skenhall et al., 2015) was composed by the following steps:

- Identification of the most relevant groups of imported (or exported) goods, classified according to the harmonized commodity description and coding system (HS) nomenclature, focusing on the 2-digits codes (HS2) out of 98 HS 2-digit groups by application of a (mass or value) selection rule (i.e. the selected HS2 product groups must cover at least 80% of the imported goods in mass or value);
- Within each of the selected HS2 categories, a representative product out of the Combined Nomenclature (CN) with 8 digits (i.e. one CN8 product) was identified.
- A set of life-cycle inventories (LCI) was built so to approximate all the CN8 products selected (i.e. one for each HS 2-digits group).
- The results of the LCI, which consist of a vector of resources in input and emissions in output which were associated to the production of the representative product, were scaled up to the total mass (or value) of the HS2 category to which it belongs to.
- The HS2 categories selected were scaled up to the total mass (or value) of imported (or exported) goods.

The selection of the representative products and the respective LCI inventories was based on 2010 statistics and technologies, whereas the changes observed for 2000 and 2005 reflected only changes to the share of traded goods by HS2 product groups. In modelling the trade inventory, data on Land use was not available due to the fact that LCI datasets used for modelling the representative products do not provide information on land use.

The potential impact for all the components above (domestic, import, export) was calculated using the 15 impact categories and related impact indicators currently recommended by the ILCD (EC-JRC, 2011; Sala et al., 2012).

2.6 Planetary boundaries in LCA

2.6.1 Estimated planetary boundaries in literature

The Planetary Boundaries identified in 2009 by Rockström, presented in Table 7 with the associated ecological thresholds, are the following: (i) climate change; (ii) rate of biodiversity loss; (iii) nitrogen and phosporus cycle; (iv) stratospheric ozone depletion; (v) ocean acidification; (vi) global freshwater use; (vii) change in land use; (viii) atmospheric aerosol loading; and (ix) chemical pollution.

Although PBs are chategorized as individual processes, they are tangled and interact from the local to the global scale. In fact, exceeding a boundary may imply that another one is put under risk. Particularly, overcoming the PBs means generating large-scale alterations of the planetary functions, leading to ecological collapse and increasing significantly the risks to socio-economic stability across the world (Rockström et al., 2009).

Table 7: Overview of Planetary Boundaries proposed by Rockström et al. (2009). Boundaries for processes in orange have been already crossed. Source: Rockström et al. (2009).

Earth system process	Parameters	Proposed boundary threshold	Current status	Pre-industrial value
Climate change	Atmospheric carbon dioxide concentration (parts per million by volume)	350	387	280
	Change in radiative forcing (watts per m^2)	1	1.5	0
Rate of biodiversity loss	Extinction rate (Number of species per million species per year)	10	>100	0.1-1

Earth system process	Parameters	Proposed boundary threshold	Current status	Pre-industrial value
Nitrogen cycle (*part of a boundary with the phosphorus cycle*)	Amount of N2 removed from the atmosphere for human use (millions of tonnes per year)	35	121	0
Phosphorus cycle (*part of a boundary with nitrogen cycle*)	Quantity of phosphorus flowing into the oceans (millions of tonnes per year)	11	8.5-9.5	-1
Stratospheric ozone depletion	Concentration of ozone (Dobson unit)	276	283	290
Ocean acidification	Global mean saturation state of aragonite in surface sea water	2.75	2.90	3.44
Global freshwater use	Consumption of freshwater by humans (Km^3 per year)	4,000	2,600	415
Change in land use	Percentage of global land converted to cropland	15	11.7	Low
Atmospheric aerosol loading	Overall particulate concentration in the atmosphere, on a regional basis	To be determined		
Chemical pollution	Amount emitted to, or concentration of persistent organic pollutants, plastics, endocrine disrupters, heavy metals and nuclear waste in the global environment or the effects on ecosystem and functioning of Earth system thereof	To be determined		

Evidence reports that the threshold for at least three of these boundaries (i.e.climate change, rate of biodiversity loss and nitrogen cycle, in orange in table 7) have already been crossed due to massive human interventions, thus threatening socio-economic wellbeing worldwide. Therefore, the PB framework may represent a practical solution, raising important opportunities for governance and policy. In fact, these limits could be adopted to define goals at global level in order to reduce the human-driven environmental impacts (Sandin et al., 2015). However, due to their intertwisted nature, the PB framework requires the development of a novel governance approach at global, regional and local scales (Stockholm Resilience Centre, 2016).

Recently, PBs have been updated (Steffen et al., 2015 – Table 8), confirming the original set of boundaries and providing updated quantification for several of them. Specifically, two boundaries, namely rate of biodiversity loss and chemical pollution, were re-named and their scope was re-set. Respectively, the updated "changes in biosphere integrity" focuses not only on biological diversity, but also on ecosystem functioning; whereas, the updated "release of novel entities" (previously, "chemical pollution") reflects the need to cope with environmental emissions of potentially toxic chemical pollutants, as well as with other physical and biological interventions that can trigger global impacts.

Table 8: Planetary boundary framework, modified from Steffen et al. (2015). Boundaries for processes in orange have been already crossed.

Planetary Boundaries	Parameters	Proposed boundary threshold	Current status
Climate change	Atmospheric concentration of carbon dioxide (parts per million by volume)	350	400 (rising)
Loss of biosphere integrity (previously: biodiversity loss)	Extinction rate (extinctions per million species-years)	10	about 1000 (rising)
Change to biochemical flows – Nitrogen and Phosphorus	Quantity of nitrogen applied to land (millions of tonnes per year)	62	about 150 (rising)

Planetary Boundaries	Parameters	Proposed boundary threshold	Current status
	Quantity of phosphorus applied to land (millions of tonnes per year)	6.2	about 14 (rising)
Loss of stratospheric ozone (previously: stratospheric ozone depletion	Concentration of ozone (Dobson unit)	(no lower than) 276	283 (improving)
Ocean acidification	Global mean saturation state of aragonite in surface seawater (%)	>80% of pre-industrial level	about 84%
Freshwater abstraction (previously: global freshwater use)	Annual consumption of freshwater (km^3 per year)	4,000	2,600
Land use change (previously: change in land use)	Percentage of global forests converted to croplands, roads and cities	(no less than) 75% biome intactness	62% (shrinking)
Atmospheric aerosol loading	Particulate concentration in the atmosphere, measured as Aerosol Optical Depth. Regionally determined for South Asia.	Regional threshold: 0.25	Regional status: 0.30
Release of novel entities (previously: chemical pollution)	Multiple boundaries, yet to be determined	To be determined	

On their attempt to quantify the global carrying capacity for each impact category, Bjørn and Hauschild (2015) translated the science-based thresholds proposed in literature for PB (such as critical loads for terrestrial eutrophication and acidification, 2°C global warming for climate change and the planetary boundary for stratospheric ozone depletion) in the metrics of the midpoint indicators, prioritizing those recommended by EC's ILCD. As a result, they obtained the so-called global average carrying capacity-based normalisation references (Table 9) which are compatible with characterized indicators values at midpoint for 6 out of 15 impact categories, namely: climate change, ozone depletion, photochemical ozone formation, freshwater eutrophication and freshwater ecotoxicity. The authors estimated PB also for other four categories (i.e. terrestrial acidification, terrestrial eutrophication, land use and water depletion). However, the values for these indicators are not compliant with the normalisation factors calculated using ILCD methods since the models underpinning the calculations made by Bjørn and Hauschild are different.

Table 9: Planetary Boundaries as reported in Bjørn and Hauschild (2015).

Impact categories compliant with ILCD	Unit	PB estimates per person	PB estimates total
Climate change - GWP	kg CO_2 eq	9.85E+02	6.81E+12
Ozone Depletion Potential	kg CFC-11 eq	7.80E-02	5.39E+08
Photochemical Ozone Formation	kg NMVOC eq	3.80E+00	2.63E+10
Freshwater Eutrophication	kg P eq	8.40E-01	5.81E+09
Marine Eutrophication	kg N eq	2.90E+01	2.01E+11
Freshwater Ecotoxicity	[PAF]*m^3*day	1.90E+04	1.31E+14
Impact categories not compliant with ILCD			
Terrestrial Acidification	mole H+ eq	1.45E+02	1.59E+13
Terrestrial Eutrophication	mole N eq	8.87E+02	1.94E+13
Land Use, soil erosion	Tonnes eroded soil	1.83E+00	1.24E+10
Land Use, biodiversity	m^2*year	1.49E+04	1.03E+14
Water Depletion	m^3	9.93E+01	1.04E+14

In order to monitor the current global situation, we adopted the set of ILCD compliant PBs per person proposed by Bjørn and Hauschild (2015) as literature reference to be compared to the normalisation factors we calculated under the previously described perspectives. In order to be consistent with the other calculations, we then multiplied these values for the world population according to Farago et al. (submitted), thus obtaining PB values significantly close to Bjørn and Hauschild's total ones.

Furthermore, for the other categories, PB values were recalculated following a procedure suggested by Bjørn (personal communication). The recalculations are based on a conversion factor corresponding to the ratios between the CFs applied in Bjørn and Hauschild (2015) and the ILCD recommended CFs. Given that this ratio varies across substances, an overall substance-generic conversion factor (from the normalisation references in Bjørn & Hauschild (2015) to ILCD compliant NFs) was estimated. This estimation derives from the weighted average of the substance-specific ratios, where the weights are based on each substance's contribution to the impact score of the global inventory (resulting from EC-JRC calculations for 2010 reference year), according to the ILCD method.

Concerning water depletion, two procedures were adopted, obtaining two different planetary boundaries for this category. Since the CF originally applied by Bjørn was a generic average for water consumption, a corresponding CF from ILCD should have been selected in order to obtain the abovementioned conversion factor. To be compliant with the previous work by Sala et al. (2015), the CF representing the average water scarcity in OECD countries was preliminarily taken from ILCD. This PB value for water depletion was used for comparing all the EU-27 and the I/O results.

However, given that the characterization at global level in the present work was carried out with ILCD country-specific CFs, another CF was calculated as arithmetic average of all the country-specific CFs used in the LCIA step. This value was adopted when comparing PB with the global NFs by EC-JRC (see section 3.6.4).

2.6.2 Proposal of additional Planetary Boundaries in literature

Planetary Boundaries represent a concept still under development, in order to meet the goals of Sustainable Development, by identifying a safe space for humanity where developing without generating irreversible consequences for the whole planetary system's functioning.

To cover the conceptual and methodological gaps, several authors recently proposed additional PB or further improvements for the already existing ones.

Whitmee et al. (2015) suggested the concept of Planetary Health, meaning social boundaries based on the understanding that human health relies on harmonized natural systems. Designed according to the priorities of the Sustainable Development Goals, this framework includes a social foundation of the use of resources, addressing both social needs (such as equal access to resources and protection for future generations) and environmental constraints. In fact, a fundamental principle for the improvement of human health boundaries is the development of more robust indicators of human welfare which account for the integrity of natural systems, thus translated into metrics comparable within the LCIA framework in order to quantitatively assess the sustainability of human intervention.

Furthermore, in 2013, the methodological framework of One Planet Thinking (OPT) for the power sector was developed (Bijloo & Kerkhof, 2015) with the aim of measuring the threshold for mineral depletion within the boundaries of our planet. The OPT framework was built on the concept of preserving the same available amount of resources (i.e. copper, iron, nickel, manganese and tin, which are the most relevant minerals for the energy sector) for future generation. Therefore, the global boundary for mineral depletion (Table 10) was estimated on the basis of the mineral reserves made available by improvement in technology and on the total quantity of minerals made available through recycling.

Table 10: Planetary Boundaries for resource depletion. Source: Bijloo & Kerkhof (2015).

Mineral	Global Boundary (Mton)	Global Index
Copper	29.5	0.83
Iron	1530	0.87
Nickel	1.85	0.98
Manganese	28.7	0.73
Tin	1.39	2.58

The OPT methodology is still under development, involving the efforts of private companies and public institutions, such as ONG operating at global level and the academic community.

More problematic is the issue about biodiversity loss related PB. Biodiversity is recognized as a complex concept, whose loss is associated with drivers and responses which are largely heterogeneous both on the temporal and spatial scales (Mace et al., 2014). Therefore, the proposal of Rockström and colleagues (2009), which measure biodiversity loss in terms of global species extinction rate, appears extremely simplified, for many reasons. Particularly, abundance of species and their functions miss to be accounted for, thus preventing this metric from successfully defining a safe operating space for human activities (Mace et al., 2014). The most recent proposals for a PBs around biodiversity loss come from Mace et al., (2014) and Wolff et al.(2016), which is still based on Mace et al. (2014) definitions (Figure 1).

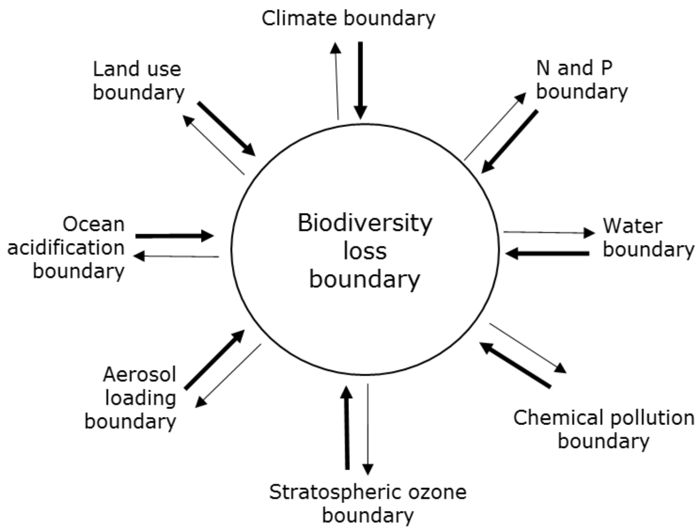

Figure 1: Biodiversity boundary and related system of impact drivers. Interacting nature of Planetary Boundaries, is shown. Modified from Mace et al. (2014).

Mace and colleagues (2014) recognized the need of identifying novel and comprehensive approaches based on phylogenetic diversity, functional diversity and biome integrity. However, so far none of the proposed approaches contributes to give an operational definition of a global boundary for biodiversity loss. Moreover, Wolff et al. (2016) highlighted the need of taking into consideration the intertwisted nature of the other ecological planetary boundaries to secure biodiversity conservation. However, the step forward, to the inclusion of biodiversity loss boundary within the LCIA framework is not immediate. Accordingly, when coming to translate biodiversity loss according to the LCIA categories, it implies to be accounted as an endpoint because many of the other impact categories converge resulting in loss of biodiversity.

Further improvements in the field of chemical impact assessment within the PB framework were proposed by Sala and Goralczyk (2013). The authors presented a methodological framework, preliminarily applied at the macroscale for the European Union, for bridging life cycle assessment approach and planetary boundaries for chemical pollution. The definition of a threshold for global chemical pollution, that should not be exceeded to ensure a sustainable use of chemicals, is still ongoing. However, this study represents an important step that contributes to the widely open discussion on planetary boundaries.

A potentially operational framework quantitatively assessing PBs, in parallel with the methodology developed by Bjørn and Hauschild (2016), has been recently proposed by Doka and other authors (2015) (Table 11). Accordingly, the PBA'05 (Planetary Boundary Allowance 05) approach translates PB into per-capita-allowances, namely the equitable annual allowance of environmental burden for each person. Characterization factors are given with a homogenized unit in terms of fraction of the per-capita-allowance for eight implemented planetary boundaries out of nine proposed by Rockström (2009).

Table 11: Planetary boundaries as proposed by Doka et al. (2015), both in terms of per-capita and global allowance. Compatibility with ILCD impact categories is shown in the last column.

Boundary	Unit	1 PBA value	Global value	ILCD compatible (Y or N)
Climate change	kg CO_2/person	1.15E+03	1.15E+13	Y
Biodiversity loss	species*year/person*year	2.81E-05	2.81E+05	N
N cycle	kg N emission/person	3.50E+00	3.50E+10	Y
P cycle	g P*year/person	1.10E+00	1.10E+10	N
Stratosferic ozone depletion	kg ODP equivalent/person*year	4.09E-02	4.09E+08	Y
Ocean acidification	-	NA	NA	-
Land occupation	m^2 cropland*year/person	2.00E+03	2.00E+13	N
Global freshwater consumption	m^3 blue water/person	4.00E+02	4.00E+12	Y
Atmosferic aerosol loading	kg PM_{10} equivalent/person	1.46E+00	1.46E+10	Y (assuming that, within PM10 emissions, PM2.5 is the impacting fraction)
Chemical pollution	-	NA	NA	-

3 Results and discussion

Following the collection of data for building the European and global inventories and their translation into elementary flows according to the ILCD nomenclature, the inventories have been characterized, using ILCD CFs at midpoint (EC-JRC, 2011).

According to the methodologies mentioned in section 2, different sets of normalisation factors have been calculated and reported in the following paragraphs for each system scale (EU-27 or global) and for each impact category. Unless some already stated and explained reasons has led to the selection of specific values as NF, in case more than one plausible data sources was available, we decided to apply a sort of precautionary principle, selecting the one with the highest value.

Information on environmental emissions and resource extractions for the specific reference year 2010 were generally limited, namely in some cases they were only partially available in the form or at the geographical scale needed for this study. Therefore, data estimates were inevitably used, leading to the occurrence of uncertainties in the corresponding normalisation factors. Uncertainties in the calculation of the normalisation factors may be due to different sources, such as the selection of the sources of data among statistical database (Benini & Sala, 2016). The uncertainties related to the adopted extrapolation procedures are detailed for each impact category in the following paragraphs.

3.1 EU-27 normalisation factors

As presented in Sala et al. (2015), the NFs based on the characterized EU-27 domestic inventory for the year 2010 are reported in the following Table 12.

Table 12: EU-27 normalisation factors for domestic emissions and resource extraction in 2010. The scoring is given from I: highest to III: lowest. Source: Sala et al. (2015).

ILCD Impact category	Unit	NFs for EU-27	Coverage completeness	Robustness inventory
Climate change	kg CO_2 eq	4.60E+12	I/II	I
Ozone depletion potential	kg CFC-11 eq	1.08E+07	II	III
Human toxicity- cancer	CTUh	1.88E+04	III	III
Human toxicity- non cancer	CTUh	2.69E+05	II	III
Particulate matter/Respiratory inorganics	kg $PM_{2.5}$ eq	1.90E+09	I	I/II
Ionising radiations	kBq U-235 eq	5.64E+11	I	II
Photochemical ozone formation	kg NMVOC eq	1.58E+10	I	II
Acidification	mol H^+ eq	2.36E+10	I	II
Terrestrial eutrophication	mol N eq	8.76E+10	I/II	I
Freshwater eutrophication	kg P eq	7.41E+08	I/II	II/III
Marine eutrophication	kg N eq	8.44E+09	II	II
Land use	kg C deficit	3.78E+13	II/III	II

ILCD Impact category	Unit	NFs for EU-27	Coverage completeness	Robustness inventory
Freshwater ecotoxicity	CTUe	4.46E+12	III	III
Water depletion	m^3 water eq	4.06E+10	III	II
Resource depletion - energy carriers, minerals and metals	kg Sb eq	5.03E+07	II	II

The completeness of the coverage of datasets used for building the EU-27 inventories was evaluated by Sala et al. (2015). This coverage varies within a broad range, from minimum values (level I-lowest coverage according to table 12 associated to the categories human toxicity-cancer effects and freshwater ecotoxicity, to maximum values (level III-highest coverage according to table 12) for acidification, particulate matter, photochemical ozone formation and ionising radiation. Overall, the completeness of the EU-27 inventory coverage is affected by the availability of data in the original sources.

The robustness of the inventory is based on the quality of data, depending for example on the variety of sources which the data come from and their combination in a single inventory, and on the robustness of the extrapolation strategies adopted for each impact category. In the calculation of the NF for EU-27, the impact categories showing the less robust inventories are those related to the toxicity impacts, i.e. human toxicity (both cancer and non-cancer effects) and ecotoxicity which are based on the same inventory. As already explained in Sala et al. (2015), the low robustness of this inventory mainly stemmed from the poor quality of data, associated to the high amount of extrapolation strategies (e.g. temporal data gap filling; spatial extrapolation across different countries) employed to cover a much broader range of flows. On the other hand, Climate change and terrestrial eutrophication categories present a high inventory robustness, when compared to all the other categories.

Overall, as analysed in Benini & Sala (2016), uncertainties in the calculation of normalisation references for EU-27 in 2010 were due to several aspects, stemming from both the inventory data and the available characterization factors. In particular, uncertainties were mainly related to the selection for the sources of data among different statistical database (e.g. for NO_x, SO_x, NH_3, CO, $PM_{2.5}$/PM_{10} and water withdrawals), the classification of environmental statistics as ILCD elementary flows (e.g. mapping of NO_x and SO_x and inconsistence in the flow naming), the use of extrapolation procedures in order to fill the data gaps in the inventories (e.g. NMVOC breakdown for climate change and Photochemical Ozone Formation categories), the use of regionalized characterization factors for water depletion only and the lack of characterization factors for some measured flows, leading to the underestimation of NFs. Overall, a merely qualitative assessment of the uncertainty associated to the calculation of NFs for EU-27 was possible due to the diversity of sources of uncertainty and biases, which in many cases were not quantifiable.

3.2 Global normalisation factors

In the following sections, for each impact category, the results of the calculation of the NFs based on the global inventory are reported for the year 2010 and for each impact category. Each paragraph includes: (i) the coverage of the flows in the inventory with respect to the available flows in ILCD; (ii) the contribution of each flow to the final global impact; (iii) the main drivers of uncertainty; and (iv) the relationship between global NF 2010 and the NFs calculated for EU-27 in 2010.

The overall list of global NFs for 2010 is reported in table 13. The above-mentioned considerations related to coverage completeness and robustness of the inventory apply to the global estimates. However, in some cases, lower scores are attributed to global NF’s due to further limitation in the data coverage compared to EU-27 inventory.

Table 13: EC-JRC Global normalisation factors for emissions and resource extraction in 2010.

ILCD Impact Category	Unit	Global NFs (2010)	Range of variation (min-max) or alternative results	Coverage completeness	Robustness inventory
Climate change	kg CO_2 eq	4.81E+13	(8.40E+12; 5.09E+13)	II	I
Ozone depletion potential	kg CFC-11 eq.	1.34E+08	(alternative result:1.24E+08)	III	II
Human toxicity, cancer effects	CTUh	9.16E+04	(4.06E+04; 2.66E+05)	III	III
Human toxicity, non-cancer effects	CTUh	1.13E+06	(5.01E+05; 3.36E+06)	III	III
Particulate matter/Respiratory inorganics	kg $PM_{2.5}$ eq	6.86E+10	(alternative results: 3.25E+09; 6.27E+0; 9.49E+09; 4.68E+10)	I	I
Ionising radiation	kBq U-235 eq.	2.04E+12		II	III
Photochemical ozone formation	kg NMVOC eq.	2.80E+11		III	I/II
Acidification	mol H+ eq	3.83E+11	(alternatives results: 3.07E+11; 3.26E+11)	II	I/II
Terrestrial eutrophication	mol N eq	1.22E+12	(alternative results: 7.55E+11; 8.68E+11)	II	I/II
Freshwater eutrophication	kg P eq	1.76E+10		II	III
Marine eutrophication	kg N eq	1.95E+11	(alternative results: 1.99E+10; 3.14E+10; 4.89E+10; 1.44E+11)	II	II/III
Land use	kg C deficit	1.00E+15		II	I
Ecotoxicity freshwater	CTUe	2.75E+13	(4.06E+12; 8.15E+13)	III	III
Water depletion	m^3 water eq	4.81E+13	(alternative result from consumption inventory: 6.80E+13)	II	II
Resource depletion - energy carriers, minerals and metals	kg Sb eq	3.70E+09		I	I

3.2.1 Climate change

The calculation of the global NF for climate change led to four possible results, respectively based on (i) the single flows' inventory, (ii) its variation with HCFCs data as results of temporal extrapolation, (iii) the already characterized GHG totals (aggregated value) according to both EDGAR v4.2 (EC-JRC & PBL, 2011b) and (iv) UNFCCC (2015). Results are reported in tables 14 and 15.

Table 14: Characterized inventory of single flows' global emissions for Climate Change – GWP indicator, reference year: 2010.

ILCD elementary flows (EDGAR single flows' values, GWP_{100} from IPCC 2007)	Formula/abbr.	Global 2010 (i) (kg CO_2 eq)	Global 2010 (ii) (kg CO_2 eq)
carbon dioxide	CO_2	3.36E+13	3.36E+13
methane	CH_4	9.30E+12	9.30E+12
nitrous oxide	N_2O	2.97E+12	2.97E+12
HFC-116	C_2F_6	2.26E+10	2.26E+10
perfluoropropane	C_3F_8	3.35E+09	3.35E+09
perfluorobutane	C_4F_{10}	1.77E+08	1.77E+08
dodecafluoropentane	C_5F_{12}	8.49E+04	8.49E+04
perfluorohexane	C_6F_{14}	3.15E+09	3.15E+09
FC-318	C_4F_8	2.08E+08	2.08E+08
FC-14	CF_4	1.17E+11	1.17E+11
HFC-23	HFC-23	2.67E+11	2.67E+11
HFC-32	HFC-32	2.58E+09	2.58E+09
HFC-4310mee	HFC-4310mee	5.01E+08	5.01E+08
HFC-125	HFC-125	1.48E+11	1.48E+11
HFC-134a	HFC-134a	2.59E+11	2.59E+11
1,1,1-trifluoroethane	HFC-143a	1.82E+11	1.82E+11
HFC-152a	HFC-152a	4.28E+09	4.28E+09
1,1,1,2,3,3,3-heptafluoropropane	HFC-227ea	3.08E+10	3.08E+10
HFC-236fa	HFC-236fa	1.64E+09	1.64E+09
HFC-245fa	HFC-245fa	5.55E+09	5.55E+09
HFC-365mfc	HFC-365mfc	1.80E+09	1.80E+09
sulfur hexafluoride	SF_6	1.59E+11	1.59E+11
HCFC-22	HCFC-22	6.63E+11	6.63E+11
HCFC-141b	HCFC-141b	-	5.58E+08
HCFC-142b	HCFC-142b	-	1.43E+10
CFC-11	CFC-11	3.33E+11	3.33E+11
Halon-1211	Halon-1211	9.09E+09	9.09E+09
nitrogen trifluoride	NF_3	3.69E+09	3.69E+09
	total	**4.81E+13**	**4.81E+13**

Table 15: Characterized aggregated values for Climate Change – GWP indicator.

ILCD elementary flows (EDGAR aggregated value; GWP_{100} from IPCC 1996)	Global 2010 (iii) (kg CO_2 eq)
GHG total (CO_2, CH_4, N_2O, F-gases)	**5.09E+13**
ILCD elementary flows (UNFCCC aggregated value; GWP_{100} from IPCC 2007)	**Global 2010 (iv) (kg CO_2 eq)**
GHG total (CO_2, CH_4, N_2O, HFCs, PFCs, SF_6, unspecified mix of HFCs and PFCs, and NF_3 with emissions/removals from LULUC and forestry)	**8.40E+12**

Aggregated values were basically discarded. In fact, the aggregated GHG total value from EDGAR database (Global 2010 (iii); source: EC-JRC & PBL, 2011b) were excluded as potentially useful result, since their calculation is based on outdated CFs (i.e. from IPCC, 1996). Whereas, although the aggregated value from UNFCCC (Global 2010 (iv)) is based on CFs which is in line with the ILCD recommendations for LCIA, it was considered unrepresentative of the world situation, since many important GHG emission contributors such as USA and Japan were not included and the value is, therefore, too close to the EU 27 reference. As a confirmation, 25 out of 30 parties providing data on which the UNFCCC aggregated value are EU-27 countries.

Considering the single flows' alternatives (i and ii), no relevant difference was outlined in the results, due to the inclusion of two additional flows namely HCFC 141b and HCFC142b. In fact, the result remained basically unchanged. The two inventories can be, therefore, considered comparable.

The most representative reference for the global impact is represented by EDGAR single flows' (Global 2010 (i)) characterized inventory of emissions, including HCFCs data. It covers 28 substances out of 101 for which a CF is available in ILCD.

According to the single flows' characterized inventory, three substances dominate the overall impact, namely: CO_2 (nearly 70%), CH_4 (19%) and N_2O (6%). The remaining 25 mapped substances contribute to 5% of the total world impact.

Mixing reported data from different datasets e.g. bottom-up modelling exercises (EDGAR) and extrapolations from CSIRO model (Fraser et al., 2014), may lead to uncertainties. Particularly, the NF for climate change derived from the single flows' inventory is likely to be slightly underestimated with respect to the aggregated value due to missing data for some substances, such as HFCs, and due to the exclusion of biomass burning emissions (such as forest fires, post-burn decay, peat fires and decay of drained peatlands).

Robustness of the climate change-related inventory for the world 2010 appears to be relatively high in comparison to other impact categories, according to the good quality of data (EDGAR is at the second place when referring to the hierarchy for sources selection) and with the lack of extrapolation strategies adopted for building the inventory.

3.2.2 Ozone depletion potential

The calculation of the global normalisation factor for ozone depletion led to two results, depending on the use of halons single flows (Global 2010 (i) in table 16) or halons total aggregated value (Global 2010 (ii)).

Single flows' inventory data are available for seven flows out of 23 for which there is a CF in the ILCD. Of these seven flows, four are originally from 2010, while the remaining three were extrapolated from 2008 as explained in the relative methodology (section 2.2.2).
Different sources were available for HCFCs, namely CSIRO data (Fraser et al. 2013) and EDGAR v.4.2 (EC-JRC & PBL, 2011a). To be compliant with the hierarchy we proposed (i.e.

in case of temporal extrapolation, preferring data from a year which is different from the reference, but coming from the primary source), we took 2008 data from CSIRO estimations, instead of using HCFC data from EDGAR as done for GWP.
According to the approach beneath Global 2010 (i) with only single flows, the normalisation factor for this impact category stands at 1.34E+08 kg CFC-11 equivalent. The highest contributor to this figure is CFC-11 flow, which is responsible for 52% of the global impact. This is followed by Halon-1211 and HCFC-22 which cover about 22% and 14% of the overall impact, respectively. HCFC-140, halon-1001 and the other HCFCs exert the minor role, accounted at less than 12%).

Considering the alternative inventory option, where halon total is used as aggregated flows excluding halon-1001 and halon-1211 single flows, the normalisation factor for this impact category slightly change, standing at a value of 1.24E+08 kg CFC-11 equivalent. This may be due to the use of an average CF value for characterizing halon flows. The order of contributor flows to the overall impact remains unchanged, with CFC-11 covering the overwhelming majority of the total impact (57%), followed by Halons (21%) and HCFC-22 (15%).

According to the procedure stated in section 2, we decide to select as NF for ozone depletion category the Global 2010 (i) final score, since according to the precautionary principle it is likely to cover the impacts and the related uncertainties of Global 2010 (ii).

Table 16: Characterized inventories of global emissions for Ozone Depletion Potential indicator.

ILCD elementary flows	Global 2010 (i) (kg CFC-11 eq)	Global 2010 (ii) (kg CFC-11 eq)
CFC-11	7.00E+07	7.00E+07
HCFC-22	1.83E+07	1.83E+07
HCFC-140	5.52E+05	5.52E+05
HCFC-141b	6.60E+06(*)	6.60E+06(*)
HCFC-142b	2.80E+06(*)	2.80E+06(*)
Halon-1001	6.84E+06(*)	-
Halon-1211	2.89E+07	-
Halon totals	-	7.40E+06
Total:	**1.34E+08**	**1.24E+08**

(*) Extrapolated values from EDGAR v.4.2, year 2008

Uncertainties in the estimation of the global NF for ozone depletion category are considered quite high, mostly because the majority of the substances contributing to ozone depletion impacts are not accounted in the inventory, leading to a very low coverage completeness. In fact, limited data on ozone depleting substances are available in the scientific literature. Furthermore, the application of extrapolation strategies for filling the temporal data gap led to a rather low robustness of the inventory for this category.

3.2.3 Human toxicity (cancer, non-cancer) and freshwater ecotoxicity

A series of eight alternative options for the calculation of the global reference for each toxicity-related impact category was possible, depending on the calculation strategy applied according to section 2.2.3. The results are presented in table 17.

Table 17: Final impact scores for toxicity-related categories, based on data from Cucurachi et al. (2014).

		GLOBAL (years between 2008 and 2013), based on:							
	Units	**AVG**	**AVG - adjusted**	**CO_2**	**CO_2 - adjusted**	**GDP**	**GDP - adjusted**	**Hg**	**Hg - adjusted**
HTOXC	CTUh	2.03E+04	9.16E+04	1.58E+04	7.12E+04	9.01E+03	4.06E+04	5.89E+04	2.66E+05
HTOXNC	CTUh	1.16E+06	1.13E+06	9.00E+05	8.77E+05	5.14E+05	5.01E+05	3.36E+06	3.27E+06
FRWTOX	CTUe	9.25E+12	2.75E+13	7.12E+12	2.12E+13	4.06E+12	1.21E+13	2.74E+13	8.15E+13

Three out of eight global normalisation references (namely CO_2, GDP, Hg, as referred to in table 17) for each toxicity-related impact category were directly taken from the publication of Cucurachi et al. (2014). Additionally, following the methodology described in section 2.2.3, for each category we calculated (i) the global average (AVG), as geometric mean of the above-mentioned extrapolated global references; (ii) the adjusted global average (AVG-adjusted) and (iii) the adjusted global references for CO_2, GDP and HG emissions (namely CO_2-adjusted, GDP-adjusted, Hg-adjusted).

Human toxicity-cancer effects and freshwater ecotoxicity present the same scheme: each adjusted value is pretty higher than their relative reference, due to the fact that the ratio between EU-27 value from Sala et al (2015) and EU value from Cucurachi et al. (2014), on which the calculation of the adjusted values is based, is greater than one. The divergence between the two European values is linked to the different underpinning inventories. For instance, the top contributor substances which affect these two categories do not match, when comparing the European inventories.

However, the EU reference value from Cucurachi et al. (2014) is calculated not only on the toxic emissions of the 27 European Member States, but also on the emission releases from Norway, Switzerland, Iceland and Serbia. Therefore, as the sources for EU-27 Member States are shared by both the authors and a greater number of countries contribute to the emissions for the EU reference of Cucurachi et al. (2014), this latter value should be higher than or at least or at least close to the value calculated by Sala et al. (2015). The top contributors and their relative impacts (i.e. zinc and mercury) are comparable across both the characterized inventories.

Based on the abovementioned considerations, the AVG-adjusted values has been selected as global reference for all the toxicity-related impact categories. Cucurachi et al. (2014) were not recommending any of the three options. Indeed, they stated that the three estimators used for calculated the global references were not representative of the global situation, although a strong correlation was found between CO_2 and GDP. Furthermore, as a support of the selection made, the values of the AVG-adjusted, at least in the cases of human toxicity-non cancer effects and ecotoxicity, approach the geometric and arithmetic mean of the series if eight extrapolations proposed in this section.

Generally, according to Cucurachi et al. (2014), the inventory used for extrapolating both human toxicity (cancer and non-cancer effects) and freshwater ecotoxicity are characterized by a high level of uncertainties, especially due to the large use of extrapolation strategies and the relative low coverage of the substances emitted into the environmental compartments, leading to over- and under-estimations of the final global figures.

3.2.4 Particulate matter/Respiratory inorganics

According to the broad variety of sources retrieved, several potential combinations of data are possible to define the global inventory for RIPM impact category. The results of the characterized inventories are presented in table 18.

Table 18: Characterized inventories of global emissions for Particulate matter/Respiratory inorganics category.

		Global 2010 (kg $PM_{2.5}$ eq)				
ILCD elementary flows	**elementary flows**	**EDGAR v.4.3.1**	**ECCAD v.6.6.3**	**Winijkul et al. (2015)**	**Oita et al. (2016)**	**Klimont et al. (2013)**
nitrogen oxides	NO_x (as NO_2)	8.15E+08	5.11E+08	-	2.53E+08	-
sulfur dioxide	SO_2	6.26E+09	5.97E+09	-	-	6.27E+09
ammonia	NH_3	3.65E+09	2.80E+09	-	3.00E+09	-
particles (PM10)	PM_{10}	1.48E+10	-	1.02E+10	-	-
particles (PM2.5)	$PM_{2.5}$	4.28E+10	-	3.66E+10	-	-
carbon monoxide	CO	2.21E+08	2.08E+08	-	-	-
	Total	**6.86E+10**	**9.49E+09**	**4.68E+10**	**3.25E+09**	**6.27E+09**

EDGAR (EC-JRC & PBL, 2016) has been selected as unique source of data for this impact category, mainly due to better completeness and robustness of the inventory. EDGAR dataset is widely considered a reliable and authoritative source of data, even if it is not characterized by periodical checks. Furthermore, it shows a higher coverage of flows when compared with the other sources. In fact, inventory data stemming from EDGAR database are available for 6 out of 9 flows for which there is a CF in the ILCD. Additionally, as explained in section 2, EDGAR database cover emissions coming from a broader range of sectors.

Although ECCAD dataset v. 6.6.3 (GEIA, 2016) presents a medium-high inventory coverage, it resulted to be less complete than EDGAR, needing the application of extrapolation procedures to be complemented. The inventories built on data from Winijkul et al. (2015), Oita et al. (2016) and Klimont et al. (2013) were discarded since they present a comparatively poor coverage, dealing with just two or three flows out of the total.

Overall, figures provided by all the sources appear to be consistent with each other. Specifically, in some cases, e.g. SO_2 and CO flows, values are very close one to the other.

According to the characterized inventory built on EDGAR data, the highest contributor to this impact category is CO covering 62% of the overall impact, distantly followed by NO_2 (11%). Generally, emissions deriving from manure and fertilizers' applications are indirectly accounted for as NH_3 emissions, as already mentioned by Sala et al. (2015) for EU-27 reference.

3.2.5 Ionising radiation

In order to obtain the global reference for ionising radiation impact category, some assumptions were made, especially with respect to the characterization step:

- CF "emissions to air, unspecified" and "to water, unspecified" were adopted.
- in order to raise the coverage level, emissions of "U-235 + U-236" to liquid effluents for France and Russia were characterized by using the CF of U-235 to water, unspecified; no CF is available in ILCD for U-236.

- With the same purpose, emissions of "U-233 + U-234" for France and Russia, were characterized by using the CF of U-234; no CF is available in ILCD for U-233.
- "Uranium" flows for the UK and India were characterized by using the CF of U-235, which is the reference elementary flow for ionising radiation category.
- In order to cover a higher number of flows, the aggregated flow of "Pu-238 + Pu-239 + Pu-240" to airborne effluents was characterized by using the CF available for "plutonium, to air unspecified").

Inventory data at country level (Table 19) were available for the emissions due to nuclear spent fuel reprocessing activities. They were available for 21 flows out of 42 for which there is a CF in ILCD, contributing to a good (medium-high) inventory coverage.

Table 19: Characterized inventory of country-based emissions of radionuclides from nuclear spent-fuel reprocessing.

Country	Type of Emission	Nuclide	kBq U-235 eq
DE	Airborne	C-14	1.60E+08
RU	Airborne	C-14	3.76E+10
IN	Airborne	C-14	3.75E+08
UK	Airborne	C-14	2.73E+09
JP	airborne	C-14	6.23E+08
FR	Airborne	C-14	1.60E+11
RU	Liquid	Co-58	3.30E+06
FR	Liquid	Co-58	2.01E+02
RU	Airborne	Co-60	9.67E+04
RU	Liquid	Co-60	3.54E+09
IN	Liquid	Co-60	2.79E+07
UK	Liquid	Co-60	2.03E+08
FR	Airborne	Co-60	5.72E+03
FR	Liquid	Co-60	1.34E+08
RU	Airborne	Cs-134	6.94E+04
RU	Liquid	Cs-134	1.16E+10
IN	Liquid	Cs-134	1.03E+08
UK	Airborne	Cs-134	3.55E+02
UK	Liquid	Cs-134	7.47E+08
FR	Airborne	Cs-134	2.96E+03
FR	Liquid	Cs-134	5.12E+08
RU	Airborne	Cs-137	7.83E+04
RU	Liquid	Cs-137	1.34E+10
IN	Airborne	Cs-137	8.16E+03
IN	Liquid	Cs-137	5.24E+09
UK	Airborne	Cs-137	1.18E+03
UK	Liquid	Cs-137	4.05E+07
UK	Airborne	Cs-137	5.93E+04
UK	Liquid	Cs-137	3.81E+10
FR	Airborne	Cs-137	2.78E+03
FR	Liquid	Cs-137	8.49E+09

Country	Type of Emission	Nuclide	kBq U-235 eq
DE	Airborne	H-3	1.29E+06
DE	Liquid	H-3	1.84E+03
RU	Airborne	H-3	9.07E+06
RU	Liquid	H-3	5.01E+07
IN	Airborne	H-3	9.11E+06
IN	Liquid	H-3	4.09E+06
UK	Airborne	H-3	1.77E+05
UK	Liquid	H-3	1.95E+03
UK	Airborne	H-3	6.63E+07
UK	Liquid	H-3	2.97E+07
JP	airborne	H-3	1.19E+06
JP	liquid	H-3	2.32E+05
FR	Airborne	H-3	3.86E+07
FR	Liquid	H-3	2.13E+08
DE	Airborne	I-129	7.09E+04
RU	Airborne	I-129	4.73E+07
RU	Liquid	I-129	8.05E+09
IN	Airborne	I-129	5.87E+07
IN	Liquid	I-129	1.77E+08
UK	Airborne	I-129	2.93E+06
UK	Airborne	I-129	4.27E+08
UK	Liquid	I-129	1.29E+09
JP	airborne	I-129	4.37E+05
JP	liquid	I-129	3.91E+04
FR	Airborne	I-129	2.01E+08
FR	Liquid	I-129	6.45E+09
DE	Airborne	I-131	8.57E+00
RU	Airborne	I-131	8.79E+02
RU	Liquid	I-131	4.03E+07
IN	Airborne	I-131	3.69E+02
UK	Airborne	I-131	9.07E+01
UK	Airborne	I-131	2.68E+03
FR	Airborne	I-131	1.73E+03
FR	Liquid	I-131	2.74E+05
RU	Airborne	I-133	5.45E+01
FR	Airborne	I-133	7.44E+01
RU	Airborne	Kr-85	3.50E+08
IN	Airborne	Kr-85	4.14E+07
UK	Airborne	Kr-85	0.00E+00
UK	Airborne	Kr-85	3.01E+08
JP	airborne	Kr-85	2.18E+05
FR	Airborne	Kr-85	1.49E+09
RU	Liquid	Mn-54	2.56E+07

Country	Type of Emission	Nuclide	kBq U-235 eq
FR	Liquid	Mn-54	3.05E+04
IN	Airborne	Pu-238+Pu-239+Pu-240	1.06E+04
UK	Airborne	Pu-238+Pu-239+Pu-240	7.70E+04
RU	Liquid	U-233+U-234	4.37E+05
FR	Liquid	U-233+U-234	1.39E+05
RU	Liquid	U-235+U-236	3.84E+06
FR	Liquid	U-235+U-236	2.71E+05
RU	Liquid	U-238	4.10E+05
FR	Liquid	U-238	3.72E+04
IN	Liquid	Uranium	3.47E+07
UK	Liquid	Uranium	2.52E+08
		Emission - totals:	**3.03E+11**

In this case, the major contributors to the global impact due to reprocessing activities were the emissions to air of C-14 (nearly 53%) from La Hague, French reprocessing plant; followed by C-14 emitted to air by Russian reprocessing structures and Cs-137 to liquid effluents from UK which stand at approximately 13% out of the overall impact.

Generally, energy production from nuclear sources contributes the most top the overall global impact, when compared with reprocessing (Table 20).

Table 20: Nuclear energy production and nuclear spent-fuel reprocessing contribution to ionising radiation global impacts.

Radiative emission type	kBq U-235 eq	Percentage
Global Radiative emissions to air and water from energy production (nuclear) - 2010	1.74E+12	85%
Global Radiative emissions to air and water from nuclear spent-fuel reprocessing - 2010	3.04E+11	15%

Uncertainties in the calculation of the global reference for ionising radiation may derive from the selection of characterization factors; the extrapolation of Indian and Russian emission profiles; the inclusion of Japanese emissions which are not updated; the lack of accounting for the emissions from non-nuclear activities (radio-chemicals production and research facilities), the discharge of radionuclides from oil and gas industry and the emissions to air and water from the end-of-life scenario of gypsum boards (taken into consideration for the EU-27 reference).

3.2.6 Photochemical ozone formation

The global normalisation factor for photochemical ozone formation was built on the data collected from EDGAR v.4.3.1 (EC-JRC & PBL, 2016) and presented in table 21. Inventory data are available for four flows out of 132 for which there is a CF in the ILCD. Values for single NMVOC flows are missing in the current literature. Overall, this led to a very low completeness of inventory coverage.

Table 21: Characterized inventory of global emissions for photochemical ozone formation.

ILCD elementary flows	Formula/abbreviations	Global 2010 (kg NMVOC eq)
non-methane volatile organic compounds	NMVOC	1.35E+11
methane	CH_4	3.76E+09
nitrogen oxides	NO_2	1.13E+11
carbon monoxide	CO	2.83E+10
	Total	**2.80E+11**

The NF for photochemical ozone formation presents a relative contribution as follows: 48% NMVOC, which is the major contributor to the overall impact, followed by NO_2 (40%), CO (10) and CH_4 (less than 2%).

3.2.7 Acidification

The calculation of the global normalisation factor for acidification led to three results, respectively built on the inventories taken from EDGAR v.4.3.1 (EC-JRC & PBL, 2016), ECCAD v.6.6.3 (GEIA, 2016) and Oita et al. (2016). In ILCD NO_x flows are mapped as NO_2, i.e. they share the same CF. We decided to map the flows of NO_x and NO_2 as NO_2, since the ratio between NO and NO_2 is unknown from the statistics. The results are reported in table 22.

Table 22: Characterized inventories of global emissions for Acidification category.

		Global 2010 (mol H^+ eq)		
ILCD elementary flows	**formula**	**EDGAR v.4.3.1**	**ECCAD v.6.6.3**	**Oita et al. (2016)**
nitrogen oxides	NO_x (as NO_2)	8.35E+10	5.24E+10	2.59E+10
sulfur dioxides	SO_2	1.34E+11	1.28E+11	1.64E+11
ammonia	NH_3	1.65E+11	1.27E+11	1.36E+11
	Total	**3.83E+11**	**3.07E+11**	**3.26E+11**

Comparing the alternative inventories, they all cover the same number and type of flows, appearing complete in terms of the three flows found for this impact category. In fact, inventory data are available for three flows out of six for which there is a CF in the ILCD. The flows of nitrogen monoxide (NO), sulfur trioxide (SO_3) and sulfur oxides (SO_x) were missing for each inventory, mainly because no statistics on these compounds were available in the current literature.

According to the hierarchical approach proposed in section 2, each inventory is based on a reliable source, thus the characterized inventories can be considered as comparable. However, comparing the figures across the characterized single flows (see table 23), the corresponding substances do not contribute with the same magnitude to the overall impact. For instance, for each characterized inventory NO_2 represents the minor contributor as acidifying substance, although figures vary within a range from 8% to 22%. SO_2 and NH_3, instead, represent the first or the second most important contributor to acidification depending on the source taken into account.

Table 23: Contribution (%) of each flow to the relative global impact, according to each data source adopted.

ILCD elementary flows	formula	EDGAR v.4.3.1	ECCAD v.6.6.3.	Oita et al. (2016)
nitrogen oxides	NO_x (as NO_2)	22%	17%	8%
sulfur dioxides	SO_2	35%	42%	50%
ammonia	NH_3	43%	41%	42%
	total	**100%**	**100%**	**100%**

In order to overcome these discrepancies and to be consistent with the previous choices made for other impact categories dealing with the same substances, we decided to adopt EDGAR as unique source of data. The reason of this choice refers to the fact that EDGAR characterized total score for the acidification global reference is the highest, compared with the other figures, thus avoiding underestimation of the overall impact. It is relevant to note that this choice may generate a certain level of uncertainty (e.g. over-estimation) of the global normalisation factor for acidification category.

It is important to highlight that the ILCD method does not include characterization factors for acidifying substances emitted to soil, such as manure and fertilizers. Their impact, as previously mentioned in section 2, is accounted as emissions into air of NH_3 from secondary volatilization after their application to soil. Together with the uncertainties associated to the selection of the inventory source, this may be an additional source of uncertainty, affecting the calculation of normalisation factor in terms of underestimation of the global impacts due to acidifying substances. Also the choice underlying the use of characterization factors, e.g. for NO_x mapped as NO_2, may potential generate uncertainty, lowering the robustness of the inventory.

3.2.8 Terrestrial eutrophication

The calculation of the global reference for terrestrial acidification led to three possible results, respectively built on the inventories taken from EDGAR v.4.3.1 (EC-JRC & PBL, 2016), ECCAD v.6.6.3 (GEIA, 2016) and Oita et al. (2016). NO_x was retrieved as both NO_x and NO_2, and mapped into NO_2 since these flows have the same CF in ILCD and statistics do not provide detailed information on the amount of NO and NO_2. Then, as for the other categories dealing with NO_x, the corresponding characterization factor was used for calculating the midpoint impact indicator. The results are reported in table 24.

Table 24: Characterized inventories of global emissions for Terrestrial eutrophication category.

		Global 2010 (mol N eq.)		
ILCD elementary flows	**emission formula**	**EDGAR v.4.3.1**	**ECCAD v.6.6.3**	**Oita et al. (2016)**
ammonia	NH_3 (to air)	7.38E+11	5.66E+11	6.06E+11
nitrogen oxides	NO_x (as NO_2, to air)	4.81E+11	3.02E+11	1.49E+11
	Total	**1.22E+12**	**8.68E+11**	**7.55E+11**

All the options for the inventory cover the same number and type of flows, appearing complete in terms of the two flows found for this impact category, although the coverage is relatively low for each inventory option. In fact, inventory statistics are available for two flows out of six for which there is a CF in the ILCD.

The flows of nitrogen monoxide (NO), nitrate (NO_3^-), nitrite (NO_2^-) and ammonium (NH_4^+) were not included within the inventories, as that no statistics on these compounds were available in the literature.

According to the hierarchical approach proposed in section 2, each inventory is based on a reliable source providing estimations of atmospheric emissions coming from governmental or national research institutions. Additionally, comparing the figures across the characterized single flows of NH_3 and NO_x (see table 25), corresponding substances in at least two out of three characterized inventories (i.e. EDGAR v.4.3.1 and ECCAD v.6.6.3) approximately contribute with the same magnitude to the overall impact, thus these characterized inventories can be considered as comparable. For instance, NH_3 represents the major contributor to terrestrial eutrophication-related impacts; while, NO_x, as NO_2, represents the substance that less contribute to the overall impact.

Table 25: Contribution (%) of each flow to the relative global impact, according to each data source adopted

ILCD elementary flows	emission formula	EDGAR v.4.3.1	ECCAD v.6.6.3.	Oita et al. (2016)
ammonia	NH_3 (to air)	61%	65%	80%
nitrogen oxides	NO_x (as NO_2, to air)	39%	35%	20%
	Total	100%	100%	100%

However, as explained in section 2, EDGAR database cover emissions coming from a broader range of sectors, when compared with the other data sources. Therefore, for the sake of inventory completeness and to be consistent with the previous choices made for other impact categories dealing with the same substances (e.g. acidification and particulate matter/respiratory inorganics), we chose of using EDGAR as unique source of data. The reason behind this decision is due even to the fact that EDGAR total score for the global reference is the highest, compared with the other figures, thus avoiding underestimation of the overall impact. Nevertheless, it is relevant to highlight that this choice may generate a certain level of uncertainty (e.g. over-estimation) of the global normalisation factor for terrestrial eutrophication category.

Uncertainty may derive also from the fact that characterisation factors are provided for deposition from air and not for emissions into soil. Additionally, the choice underlying the use of characterization factors, e.g. for NO_x mapped as NO_2, may potential generate uncertainty, lowering the robustness of the inventory.

Generally, although the pretty good quality of data, the robustness of the inventories is to be considered medium-high due to the uncertainties stemming from the limited completeness of the inventory and the characterization factors, as mentioned above.

3.2.9 Freshwater eutrophication

The global reference for 2010 for freshwater eutrophication (table 26) has been built on inventory data available for two flows out of six for which ILCD provides a CF in the freshwater eutrophication impact category. Values for phosphate and phosphoric acid, both to water and to soil, are missing in the available statistics and literature, limiting the completeness of the inventory.

Global P budget (i.e. the difference between inputs from the application of fertilizer and manure, and the loss through crop harvesting, grazing or grass mowing) and global P runoff (i.e. the only pathway which is assumed to move P to water sources), were mapped into ILCD elementary flows as “Phosphorus, total (to soil)” and “Phosphorus, total (to water)”, respectively. No details about specific emissions, such as phosphate and phosphoric acid, were found.

Table 26: Characterized inventory of global emissions for Freshwater eutrophication category.

ILCD elementary flows	Global 2010 (kg P eq) Bouwman et al., 2013
Phosphorus, total (to soil)	1.32E+10
Phosphorus, total (to water)	4.40E+09
Total	**1.76E+10**

Approximately 75% of the eutrophication impact on freshwater is due to emissions of phosphorous to soil, predominantly following the application of fertilizers and animal manure. The remaining impact derives from phosphorous emissions to water. In fact, it is worth noting that the global reference calculated on the data from Bouwman et al. (2013) cover the impacts associated to the agricultural systems, including both crop production and livestock. This may lead to a potential underestimation of the overall figure for freshwater eutrophication category, thus, limiting the robustness of the normalisation factor.

3.2.10 Marine eutrophication

The calculation of the global reference for marine eutrophication is based on the inventory deriving from the combination of statistics that proceed from different sources, as presented in table 27. In ILCD, NO_x flows are mapped as NO_2, i.e. they are characterized by the same CF. Both for this reason and for the fact that the NO_2 and NO amounts are unknown from the statistics, we mapped the flows of NO_x and NO_2 as NO_2. Subsequently, the corresponding characterization factor was used for calculating the midpoint impact indicator.

Table 27: Characterized inventories of global emissions for Marine eutrophication category.

		Global 2010 (Kg N eq)				
ILCD elementary flows	**formula/abbr.**	**EDGAR v.4.3.1**	**ECCAD v.6.6.3**	**Bouwman et al. (2013)**	**Oita et al. (2016)**	**Global combined inventory**
nitrogen, total (excluding N_2)	N total (excluding N_2)	-	-	1.44E+11	-	1.44E+11(*)
nitrogen oxides	NO_x (as NO_2)	4.39E+10	2.75E+10	-	1.36E+10	4.39E+10(**)
ammonia	NH_3	5.04E+09	3.87E+09	-	4.14E+09	5.04E+09(**)
nitrate	NO_3-	-	-	-	2.10E+09	2.10E+09(***)
	total	**4.89E+10**	**3.14E+10**	**1.44E+11**	**1.99E+10**	**1.95E+11**

(*) values from Bouwman et al., 2013; (**) values from EDGAR v.4.3.1; (***) values from Oita et al., 2016

Three out of four data sources retrieved for building the inventory for marine eutrophication, i.e. EDGAR v.4.3.1 (EC-JRC & PBL, 2016), ECCAD v.6.6.3 (GEIA, 2016) and Oita et al. (2016), cover the same type of flows, namely NO_x (mapped as NO_2, according to the methodology presented in section 2) and NH_3. Oita et al., (2016) covered also the nitrate flow, appearing to be the most complete data source. However, as explained in section 2, EDGAR database covers emissions coming from a broader range of sectors, when compared with the other data sources. Therefore, according to that and to be consistent with the previous choices made for the other impact categories dealing with these flows, we decided to use EDGAR v.4.3.1 as main source of data, although it is not the most complete dataset in terms of number of covered flows. In order to build a more comprehensive and robust inventory for the calculation of global NF for marine eutrophication, we filled the gaps with data from the other reliable sources. In fact, we included in the final inventory the value of N total from Bouwman et al. (2014) and the figure associated to nitrate flow from Oita et al. (2016). These values are comparable with the others from EEDGAR v.4.3.1 in terms of their magnitude; hence, we used them to complement the inventory.

According to the inventory built on EDGAR, data were available for four flows out of 10 for which there is a CF in the ILCD for marine eutrophication. The flows of nitrogen monoxide (NO), nitrite (NO_2^-) and ammonium (NH_4^+) were not accounted within the inventories, as no statistics on these compounds were found in the current literature. Generally, emissions deriving from manure and fertilizers' applications are indirectly accounted as NH_3 emissions, as already mentioned by Sala et al. (2015) for EU-27 reference.

Within the characterized combined inventory, the highest contributor to this impact category is N total covering 74% of the overall impact, distantly followed by NO_x (as NO_2) (22%). NH_3 and nitrate, summed together cover less than 5% of the global impact.

3.2.11 Land use

The results for Land use impact category are reported in table 28.

Table 28: Characterized global inventory for Land use category.

ILCD elementary flow - aggregated	Global 2010 (Farago et al., *submitted*)
Land Use / Soil quality	1.00E+15

The impact assessment model (Mila i Canals, 2007) provides only few characterization factors (9 for occupation, 21 for transformation – from and to). Actually, all the macro-classes of Land use mapped by Milà i Canals (2007) are covered by an inventory value, however, for the additionally differentiated classes (e.g. irrigated vs non-irrigated agricultural systems), was not possible to find a match from the inventory side. Concerning country-specific data, complete unavailability occurs only in few cases, i.e. 13 – 26 countries out of 208, with the exception of some transformation flows and fallow land, whose data are mostly missing. Nevertheless, all the land use flows for which inventory data are available are mapped, with a final coverage of >99% at global scale. This leads to a significant global representativeness. In order to evaluate the robustness and accuracy of the current results, a number of comparisons with other inventories or data sources is reported in Farago et al. (submitted).

Additionally, a contribution analysis highlights urban land transformation (38%), permanent meadows occupation (17%), grassland occupation (14%), arable land occupation (13%) and urban land occupation (8%) as the most contributing flows (Laurent et al., submitted).

It is important to highlight that the necessary extrapolation carried out in order to fill the data gaps related to transformation flows could reduce the robustness of the inventory, as already explained in section 2.2.11. This could constitute a bias in the calculation of the final normalisation reference.

3.2.12 Water depletion

Results for the water depletion impact category are reported in table 29.

Differently from Sala et al. (2015), a specific CF was assigned to every country without taking an average one, although in this way the calculation for this indicator could not be in line with the ones built for the other impact categories. The rationale was to avoid additional underestimations of the impact. Furthermore, the LCIA guidelines (EC-JRC 2012) and the underpinning model (Frischknecht and Büsser Knöpfel, 2013) suggest a scheme providing country-specific CFs based on the scarcity ratio of each country. In this work we adopted the abovementioned scheme and the scarcity ratio reported in

Frischknecht and Büsser Knöpfel (2013). In order not to limit the coverage, some approximations were made:

- CFs for Bosnia & Herzegovina, Serbia and Montenegro were based on Albania scarcity ratio.
- CF for Singapore was based on Malaysia scarcity ratio.
- CFs for San Marino and Vatican City were assumed to be the same as for Italy.

Concerning withdrawal-based calculation, the robustness of the inventory is strongly undermined by the poor coverage of the inventory: only 79 countries, i.e. 37%, out of a list of 215 countries originally selected (namely, a summary of all the countries reported in the consulted databases), were associated to an inventory value referred to the 2008-2014 timespan taken into account. However, for each of these inventory values, a country-specific CF was available. The final calculation returned a very high contribution respectively by India (53%), Pakistan (14%) and China (13%).

On the other hand, by using the consumption-based inventory, a global very high coverage is reached throughout the inventory: 212 countries out of 215 were associated to an inventory value. Despite that, from the impact assessment side the coverage was poor: by adopting the current ILCD method, it was possible to calculate a CF just for 54% of the countries' list, i.e. 157 out of 212. The most significant contributors were, respectively, India (35%) and Egypt, Pakistan and Iran (all covering 10% of the total impact), followed by China contributing for 7%.

Table 29: Country-based characterized inventory (withdrawal and consumption of blue water) for Water depletion category. Sources: Aquastat (2016), Eurostat (2016), OECD (2016), WaterGAP (Müller Schmied et al., 2014).

Country	Water depletion withdrawal data (m^3 water eq)	Water depletion consumption data (m^3 water eq)
Afghanistan		1.80E+12
Albania		9.52E+09
Algeria	3.38E+10	7.52E+10
Angola		3.98E+07
Argentina	1.51E+09	8.67E+08
Armenia	1.08E+11	1.33E+11
Australia	5.39E+08	1.26E+09
Austria	4.19E+07	1.21E+07
Azerbaijan	4.41E+11	7.36E+11
Bahrain		5.90E+09
Bangladesh	1.32E+10	2.34E+10
Barbados		4.24E+08
Belarus	5.57E+08	2.95E+08
Belgium	1.69E+10	6.19E+09
Belize		3.38E+06
Benin		5.16E+06
Bhutan	1.35E+07	1.80E+07
Bolivia	8.35E+07	3.97E+07
Bosnia & Herzegovina		9.60E+08
Botswana		6.71E+06
Brazil	2.99E+09	8.22E+08
Bulgaria	2.19E+11	5.16E+11

Country	Water depletion withdrawal data (m^3 water eq)	Water depletion consumption data (m^3 water eq)
Burkina Faso		1.08E+08
Burundi		5.13E+07
Cambodia		1.51E+08
Cameroon		2.61E+07
Canada	1.55E+09	4.42E+08
Chad		2.39E+07
Chile		1.61E+09
China	6.19E+12	4.64E+12
Colombia	4.71E+08	2.03E+08
Comoros		6.24E+04
Congo		1.08E+06
Congo, DRC		9.88E+06
Costa Rica	3.14E+02	2.84E+08
Croatia	2.70E+07	4.66E+07
Cuba	7.22E+10	7.76E+10
Cyprus	7.39E+09	1.07E+11
Czech Republic	1.21E+09	8.34E+08
Denmark	4.81E+08	2.41E+09
Djibouti		1.47E+08
Dominican Republic	7.42E+10	3.71E+10
Ecuador		1.57E+09
Egypt	2.87E+12	6.75E+12
El Salvador		4.78E+08
Equatorial Guinea		3.60E+05
Eritrea		2.65E+09
Estonia	6.78E+08	1.45E+08
Ethiopia		4.90E+09
Finland		5.93E+07
France	1.75E+10	2.03E+08
French Guiana		9.36E+06
Georgia	6.71E+08	7.26E+08
Germany	5.03E+10	1.17E+10
Ghana		1.36E+07
Greece		1.04E+10
Guatemala		3.80E+08
Guinea		1.42E+07
Guinea-Bissau		7.75E+06
Guyana	5.78E+07	4.99E+07
Haiti	5.82E+09	7.87E+09
Honduras		2.79E+07
Hungary	4.78E+08	1.24E+08
Iceland	2.94E+08	4.24E+06
India	2.80E+13	2.38E+13

Country	Water depletion withdrawal data (m^3 water eq)	Water depletion consumption data (m^3 water eq)
Indonesia		8.95E+10
Iran		6.49E+12
Iraq		2.30E+12
Ireland	6.06E+06	7.42E+06
Israel	4.93E+10	3.27E+11
Italy	4.68E+10	5.98E+10
Jamaica		5.36E+08
Japan	5.59E+10	2.70E+10
Jordan		8.47E+10
Kazakhstan	7.78E+11	1.23E+12
Kenya	1.29E+10	6.01E+09
Kuwait		2.29E+10
Kyrgyzstan		5.63E+11
Laos		4.92E+07
Latvia	1.10E+07	1.40E+07
Lebanon		2.58E+11
Lesotho		1.04E+07
Liberia		1.91E+06
Libya	2.15E+11	6.20E+11
Lithuania	2.98E+09	1.48E+09
Luxembourg	1.35E+08	6.19E+08
Macedonia (The former Yugoslav Republic of)	1.55E+09	4.69E+09
Madagascar		4.35E+08
Malawi		2.99E+08
Malaysia		2.51E+09
Mali		3.90E+09
Malta	1.51E+09	1.24E+09
Mauritania		2.54E+10
Mauritius		6.62E+08
Mexico	3.75E+10	3.63E+10
Moldova (Republic of)		3.13E+10
Mongolia	2.20E+07	3.32E+07
Montenegro	2.37E+08	6.94E+08
Morocco	4.19E+10	1.58E+11
Mozambique		4.30E+07
Myanmar		4.67E+09
Namibia		9.75E+06
Nepal		1.51E+10
Netherlands	1.35E+09	4.89E+08
New Zealand	5.20E+06	5.32E+06
Nicaragua	6.18E+07	5.98E+07
Niger		9.87E+08
Nigeria	4.59E+09	1.03E+09

Country	Water depletion withdrawal data (m^3 water eq)	Water depletion consumption data (m^3 water eq)
North Korea		1.16E+10
Norway		1.41E+06
Oman		1.49E+11
Pakistan	6.75E+12	6.47E+12
Panama	4.15E+07	2.08E+07
Paraguay	9.65E+07	1.54E+07
Peru	5.46E+08	1.19E+09
Philippines	8.46E+11	2.31E+11
Poland	1.31E+10	3.82E+09
Portugal		7.08E+09
Puerto Rico	4.31E+10	4.08E+09
Qatar		2.28E+10
Romania	2.29E+09	5.66E+09
Russia	2.44E+09	1.67E+09
Rwanda		3.07E+06
San Marino		9.90E+07
Saudi Arabia		1.11E+12
Senegal		4.79E+09
Serbia	5.74E+09	2.92E+09
Sierra Leone		7.95E+06
Singapore		5.07E+07
Slovakia	2.40E+07	4.32E+07
Slovenia	3.70E+07	3.65E+07
Somalia		1.56E+11
South Africa	6.22E+10	1.01E+11
South Korea		2.74E+09
South Sudan	2.64E+09	0.00E+00
Spain	5.90E+10	1.07E+11
Sri Lanka		6.25E+11
Sudan	1.08E+11	1.03E+11
Suriname		1.91E+07
Swaziland		9.30E+09
Sweden	1.36E+07	1.05E+07
Switzerland	7.42E+07	3.39E+07
Syria		1.20E+12
Tajikistan		1.27E+11
Thailand		2.67E+11
Togo		3.97E+06
Trinidad & Tobago	5.66E+08	2.27E+08
Tunisia	1.33E+10	5.32E+10
Turkey	1.73E+10	4.72E+10
Turkmenistan		1.25E+12
Uganda	2.55E+07	8.28E+06

Country	Water depletion withdrawal data (m^3 water eq)	Water depletion consumption data (m^3 water eq)
Ukraine	5.47E+11	1.39E+12
United Arab Emirate		3.50E+11
United Kingdom	5.70E+08	6.12E+08
United States	1.95E+11	1.49E+11
Uruguay		6.47E+08
Uzbekistan		2.23E+12
Vatican City		1.03E+08
Venezuela		3.10E+08
Vietnam		1.06E+11
Yemen		4.87E+11
Zambia		1.82E+07
Zimbabwe		4.25E+10
TOTAL	**4.81E+13**	**6.80E+13**

3.2.13 Resource depletion - Energy carriers, mineral and metals

Concerning minerals and metals, an inventory value was associated to 66 out of 73 ILCD elementary flows, reported in table 30. This means that the coverage is very high (i.e. nearly 90%), which positively contributed to the overall robustness of the calculated NF.

Table 30: Characterized inventory of global inventories (minerals and metals and energy carriers) for Resource depletion category.

ILCD elementary flows (minerals and metals)	GLOBAL 2010 (kg Sb eq)
Rare earths (excluding Yttrium)	9.44E+04
aluminum	1.05E+06
antimony	1.35E+08
arsenic	4.95E+07
bauxite	2.07E+03
beryllium	7.51E+05
bismuth	3.41E+07
boron	2.87E+06
cadmium	2.45E+07
carbon	4.88E+05
chromium	3.58E+01
cobalt	2.25E+06
copper	4.06E+07
fluorspar	1.41E+07
gallium	6.68E+02
garnet, industrial	6.20E+06
germanium	2.34E+09
gold	8.99E+07
indium	3.65E+08

ILCD elementary flows (minerals and metals)	GLOBAL 2010 (kg Sb eq)
iodine	6.44E+01
iron	2.14E+06
lead	6.15E+07
lithium	3.36E+05
magnesium	1.88E+00
manganese	3.54E+06
mercury	5.14E+06
molybdenum	1.66E+07
nickel	6.48E+06
niobium	4.13E+06
palladium	1.84E+06
perlite	6.44E+04
phosphorus	7.59E+05
platinum	1.66E+06
potassium	1.17E+05
rhenium	1.53E+06
selenium	1.66E+07
silver	1.87E+08
sodium chloride	1.50E+05
sodium sulfate	5.95E+04
strontium	7.44E+07
sulfur	2.66E+07
talc	2.35E+06
tantalum	7.73E+06
tellurium	6.41E+05
thallium	2.98E+07
tin	3.01E+07
titanium	3.37E+06
tungsten	1.55E+07
vanadium	2.76E+05
ulexite	4.53E+06
yttrium	7.26E+06
zinc	4.38E+07
zirconium	1.95E+07
Total (minerals and metals)	**3.68E+09**
ILCD elementary flows (energy carriers)	**GLOBAL 2010 (kg Sb eq)**
hard coal (26.3 MJ/kg)	6.4E+05

ILCD elementary flows (minerals and metals)	GLOBAL 2010 (kg Sb eq)
brown coal (11.9 MJ/kg)	2.9E+05
peat (8.4 MJ/kg)	8.9E+04
crude oil (42.3 MJ/kg)	1.4E+06
natural gas (44.1 MJ/kg)	8.5E+05
uranium	1.2E+07
Total (energy carriers)	1.5E+07
Total Resources	**3.70E+09**

It should be noticed that the extrapolation strategy necessarily adopted when the data retrieved were associated to an oxide compound of the element instead of the element itself, could influence the reliability of the results. Nevertheless, this strategy was used only in a few cases, namely six out of 60, and the extrapolated fraction (kg) out of the total amount of minerals and metals was very low (1%). The largest contributors to the overall characterized result were germanium (64%) and indium (10%). These two elements, together with a few other (i.e. silver, antimony, lithium, strontium and lead), contribute to the 90% of the impact derived from mineral and metals only.

From the energy carriers inventory side, there is a full coverage (i.e. 100%) since all the ILCD elementary flows are associated to an inventory value. However, some criticalities could derive from the different reference year used to calculate the inventory amounts. This aspect could affect the robustness of the inventory itself and the accuracy of the overall result. From the characterization point of view, uranium leads the total impact for energy carriers by contributing to 78% whereas each other flow covered a <10% fraction.

3.2.14 EU-27 vs Global normalisation factors

A straightforward ratio EU-27 to World was calculated (table 31) in order to understand how the environmental pressures are distributed between the two areas. This ratio clearly shows the EU-27 fraction of the impacts with respect to the global scale.

As reported in the table below, the EU-27 share of impacts does not generally exceed 30% of world impacts. The most significant fractions are registered in ionising radiation (nearly 28%) and the toxicity-related categories (respectively, 21% in Human toxicity cancer, 24% in Human toxicity non-cancer and 16% in Freshwater ecotoxicity). It is worth noting that these categories are the ones with the highest level of uncertainty on the inventory side, thus influencing the results.

On the other hand, all the remaining impact categories present a share of global impacts that is below 10%. In particular, water depletion value is substantially low (i.e >1%). In fact, as reported in section 3.2.12, most of impact for this category is due to water withdrawal in extra-EU countries, namely India, Pakistan and China. Even the EU-27 fraction for resource depletion is considerably low (i.e. < 2%), likely due to the relatively poor extraction activities taking place within EU-27 territory (Sala et al., 2015).

Table 31: Comparison between global and EU-27 normalisation references for each impact category.

Impact category (abbr.)	EU-27 NFs	Global NFs	Share of the EU-27 over the global impact
GWP	4.60E+12	4.81E+13	9.56%
ODP	1.08E+07	1.34E+08	8.06%
HTOXC	1.88E+04	9.16E+04	20.52%
HTOXNC	2.69E+05	1.13E+06	23.81%

Impact category (abbr.)	EU-27 NFs	Global NFs	Share of the EU-27 over the global impact
RIPM	1.90E+09	6.86E+10	2.77%
IR	5.64E+11	2.04E+12	27.65%
POF	1.58E+10	2.80E+11	5.64%
AC	2.36E+10	3.83E+11	6.16%
EUTT	8.76E+10	1.22E+12	7.18%
EUTF	7.41E+08	1.76E+10	4.21%
EUTM	8.44E+09	1.95E+11	4.33%
LU	3.78E+13	1.00E+15	3.78%
FRWTOX	4.46E+12	2.75E+13	16.22%
WD	4.06E+10	4.81E+13	0.08%
RD-E-MM	5.03E+07	3.70E+09	1.36%

To further explain the ratios reported above, we selected a number of human development indicators focusing on socio-economic aspects (e.g. population statistics from FAOstat and UNDESA (2011), gross national income from UNDP). By calculating similar ratios EU-27/World (table 32), we highlighted the possible correlations with the results reported in table 31. For instance, CO_2 emission totals for EU-27/World are comparable with GWP EU-27 share calculated in this paragraph. The overall majority of EU-27 countries lay in the group representing the highest level of human development (see table 33). However, according to table 31, only 10% of global GWP is attributed to EU-27. An hypothetical explanation may be related to the fact that, in addition to the emissions at global level from other well developed countries (such as USA and Japan), EU-27 improved reducing emissions strategies by adopting specific programs (as Horizon 2020). Furthermore, the average European share of impacts is in line with the EU-27 population fraction.

Table 32: Human development indicators (for EU-27 and World) referred to 2010.

Socio-economic indicator	EU-27	World	*Ratio*	Source:
Population	5.00E+08	6.90E+09	7.26%	UNDESA 2011
Population	4.98E+08	6.93E+09	7.18%	FAOstat 2016 (227 world countries)
Urban population	3.7E+08	4.27E+09	8.67%	FAOstat 2016 (227 world countries), data from UNDESA
Gross Domestic Product (GDP) totals ($)	1.69E+13	6.52E+13	25.90%	FAOstat 2016 (227 world countries)
CO_2 emissions totals (kg)	3.57E+12	4.30E+13	8.30%	FAOstat 2016 (227 world countries)
Agricultural area (ha)	1.87E+08	5.38E+09	3.47%	FAOstat 2016 (227 world countries)

Table 33: Number of countries per human development achievement categories (for EU-27 and World). Source: Human report, statistical annex (UNDP, 2015).

	Countries			
	EU-27		World (188 countries)	
Very High Human Development	25	93%	49	26%
High Human Development	2	7%	56	30%
Medium Human Development	0	0%	39	21%
Low Human Development	0	0%	44	23%
totals	27	100%	188	100%

3.3 Normalisation factors based on EU-27 Basket of products for selected final consumption categories

Table 34 presents the results of the BoP indicators for food, mobility and housing, expressed as totals for the entire EU-27 population, for the considered impact categories. Results of the BoP are based on an improvement of those calculated by Dewulf et al. (2014) and Notarnicola et al. (2017).

Table 34: Characterized results for BoP baseline (total EU-27). Source: Sala et al. (2016) .

ILCD Impact Category	Unit	Food	Housing	Mobility	Total BoP
Climate change	kg CO_2 eq	7.81E+11	1.10E+12	1.38E+12	3.26E+12
Ozone depletion potential	kg CFC-11 eq	7.56E+05	1.45E+05	2.37E+05	1.14E+06
Human toxicity, cancer effects	CTUh	9.86E+03	1.05E+05	1.57E+04	1.31E+05
Human toxicity, non-cancer effects	CTUh	7.01E+05	1.60E+04	1.31E+05	8.48E+05
Particulate matter/Respiratory inorganics	kg $PM_{2.5}$ eq	3.60E+08	1.06E+09	6.86E+08	2.10E+09
Ionising radiation	kBq U-235 eq	1.73E+10	8.91E+10	8.76E+10	1.94E+11
Photochemical ozone formation	kg NMVOC eq	1.26E+09	2.53E+09	5.05E+09	8.84E+09
Acidification	mol H^+ eq	1.26E+10	5.66E+09	5.60E+09	2.39E+10
Eutrophication terrestrial	mol N eq	5.40E+10	7.76E+09	1.54E+10	7.72E+10
Eutrophication freshwater	kg P eq	2.05E+08	6.31E+07	4.07E+07	3.09E+08
Eutrophication marine	kg N eq	5.60E+09	7.06E+08	1.56E+09	7.87E+09
Land use	kg C	7.71E+12	1.96E+12	7.41E+12	1.71E+13
Ecotoxicity freshwater	CTUe	1.93E+12	4.92E+11	9.21E+11	3.34E+12
Water depletion	m^3 water eq	3.17E+10	6.55E+10	1.37E+11	2.34E+11
Resource depletion - energy carriers, minerals and metals	kg Sb eq	1.40E+07	5.40E+07	1.62E+08	2.30E+08

Interpretation of the results in the table revealed that the production and use phases dominate the impacts with an average contribution of 51.8 and 45.6%, respectively, whereas EoL was much less contributing. With respect to the production phase, relative contributions to the overall life cycle impacts were the highest for human toxicity (cancer effects) (89.2%) and terrestrial eutrophication (82.8%), moderate for impacts like climate change (31.9%) and low for ozone depletion (15.1%). By analyzing the relative contribution of the use phase to the total life cycle impacts, ozone depletion (85.7%), photochemical ozone formation (71.9%) and climate change (69.8%) emerged as the most significantly impacted categories whereas human toxicity (non-cancer effects) was instead poorly impacted (13.4%). The role of the three BoPs could be analyzed in the production phase. On average, food production contributed 54.5% to the total impact by production, mobility 34.3%, and shelter 11.2%. Analyzing the impacts of the different BoPs at the use phase, on average it turns out that it is dominated by housing (51.8%) and mobility (45.9%), while food only accounts for 2.2%. With respect to EoL, impacts are dominated by mobility: 90.6% on average. Contributions of food is 9.5%, whereas housing is negligible with -0.1% on average. Further refinements of the results are ongoing in the context of LC-IND 2 project (EC-JRC, 2016).

3.4 Normalisation factors based on input/output (I/O) approach

As already mentioned, the impacts estimation through the combination of EXIOBASE v. 3.3.8 (Merciai & Schmidt, 2016) and ILCD (EC-JRC, 2011) presents some important issues. For instance, Huysman et al. (2016) reported that ionising radiation could not be calculated as completely missing from EXIOBASE, toxicity-related categories had insufficient elementary flows for making an adequate assessment and resource depletion could not be assessed as elementary flows are at a very high level of aggregation. For these reasons, a systematic classification of the additional EXIOBASE v. 3.3.8 environmental extensions to the ILCD nomenclature was required in the present work. We made some extrapolations in order to obtain a CF for most of EXIOBASE environmental extensions, even the aggregated ones. This aspect could affect the robustness of the impact assessment.

The final classification is available upon request; the main criteria are listed below.

Extrapolation hierarchy in assigning a CF:

5. Weighted average CF: in EXIOBASE emissions in air are aggregated. In ILCD a characterization factor for a number of CFCs and HCFCs is provided as well as their quantities in our EU-27 inventory (Sala et al., 2015). In these cases, a weighted average CF is adopted. The CF is obtained by summing up the characterized value for each substance member of the aggregated group (i.e. the inventory amount multiplied by the CF) and then dividing this sum by the sum of the inventory amounts:

$$Weighted\ Avg\ CF = \frac{\sum_{n}^{i=1} X_i * CF_i}{\sum_{n}^{i=1} X_i}$$

   Where: *Weighted Avg CF* is the calculated characterization factor, X_i is the inventory amount referred to the substance *i* and CF_i is the characterization factor provided by ILCD method for the substance *i*.

6. Average CF: this assumption is adopted especially for some metal emissions, i.e. chromium and arsenic. EXIOBASE does not provide any speciation referred to the metal emission (namely, metal or ion form) whereas ILCD CFs are calculated for almost three forms. In this case, an average CF calculated on the available ones is taken.

7. Proxy CF: when ILCD does not provide CF for one or more specific EXIOBASE substances, a proxy substance (e.g. same chemical group, i.e. dioxins, or same pollutant group, i.e. POPs, PBTs) is adopted for extrapolating a CF.

   a. Missing substances: when no proxies are available, the inventory amount of the substance is reported anyway.

Main assumptions in the classification:

- Dinitrogen oxide in air: the CF value from UNFCCC (2016) has been adopted.
- HFCs and PFCs in air**:** in EXIOBASE these emissions in air are aggregated as well as in our EU-27 inventory (Sala et al., 2015) because data on HFCs and PFCs are provided by UNFCCC (2016) as aggregates and expressed in kg of CO_2 equivalents. In order to estimate their equivalent aggregate mass, average characterization factors with 100 years horizon were applied (GWP_{100} = 2.53E+03 for HFCs and 7.61E+03 for PFCs). For reasons of consistency with the data source, the average is calculated on the basis of characterization factors as reported by UNFCCC (2016). The average CF as calculated starting from UNFCCC (2016) set is used for GWP.
- Minerals and metals: in order to extrapolate a robust weighted average CF for the EXIOBASE aggregated environmental extensions concerning mineral and metal resources, all the ILCD mineral and metal flows have been mapped to one of the aggregated EXIOBASE resources flows.
  - Bauxite and aluminium: in EXIOBASE this represents a unique environmental extension. Since the metal content of this extension refers 100% to aluminium, the selected ILCD CF is the one referring to aluminium.
- Land use: EXIOBASE provides environmental extensions only focused on the occupation. Transformation is, therefore, excluded from the calculation.

Results coming from the final calculation carried out using EXIOBASE v. 3.3.8 inventory data is reported in table 35.

Table 35: Impact scores associated to World consumption according to EXIOBASE inventory.

Impact category	Unit	Global NFs based on EXIOBASE
Climate change	kg CO_2 eq	4.48E+13
Ozone depletion potential	kg CFC-11 eq	NA
Human toxicity, cancer effects	CTUh	1.94E+05
Human toxicity, non-cancer effects	CTUh	9.70E+06
Particulate matter/Respiratory inorganics	kg $PM_{2.5}$ eq	4.78E+11
Ionising radiation	kBq U-235 eq	NA
Photochemical ozone formation	kg NMVOC eq	7.89E+11
Acidification	mol H^+ eq	4.76E+11
Eutrophication terrestrial	mol N eq	1.27E+12
Eutrophication freshwater	kg P eq	4.74E+10
Eutrophication marine	kg N eq	8.70E+09
Ecotoxicity freshwater	CTUe	2.43E+12
Land use	kg C deficit	3.84E+14
Water depletion	m^3 water eq	4.35E+11
Resource depletion - energy carriers, minerals and metals	kg Sb eq	1.47E+05

3.5 Normalisation factors based on EU-27 apparent consumption

The results related to EU-27 apparent consumption are reported in table 36.

Table 36: Impact scores associated to EU-27 apparent consumption (domestic + trade). Source: Sala et al. (2016).

ILCD Impact Category	Unit	EU27 NFs based on apparent consumption
Climate change	kg CO_2 eq	4.87E+12
Ozone depletion potential	kg CFC-11 eq	1.14E+07
Human toxicity, cancer effects	CTUh	NA
Human toxicity, non-cancer effects	CTUh	NA
Particulate matter/Respiratory inorganics	kg $PM_{2.5}$ eq	2.68E+09
Ionising radiation	kBq U-235 eq	9.02E+12
Photochemical ozone formation	kg NMVOC eq	2.09E+10
Acidification	mol H^+ eq	3.55E+10
Eutrophication terrestrial	mol N eq	1.01E+11
Eutrophication freshwater	kg P eq	6.01E+08
Eutrophication marine	kg N eq	8.76E+09
Ecotoxicity freshwater	CTUe	NA
Land use	kg C deficit	NA
Water depletion	m^3 water eq	3.73E+10
Resource depletion - energy carriers, minerals and metals	kg Sb eq	5.40E+07

As reported in Sala et al. (2016), the uncertainty associated with the domestic inventory is related to several critical aspects: i) the quality of the statistical datasets used, ii) the robustness of the estimation techniques adopted and iii) the classification of environmental statistics into elementary flows consistent with the ILCD format (EC-JRC, 2011). Benini and Sala (2016) estimated the errors due to methodological choices in the calculation of six indicators of impact category (acidification, terrestrial eutrophication, marine eutrophication, photochemical ozone formation, particulate matter, water depletion) for the EU-27 year 2010. The uncertainty and sensitivity related to methodological assumptions were analysed for those substances and resources contributing the most to the abovementioned indicators (i.e. NO_x, SO_x, NH_3, CO, $PM_{2.5}$/PM_{10} and water withdrawals). The following uncertainty sources were identified: i) selection of the sources of data amongst statistical database; ii) classification of environmental statistics as ILCD elementary flows; iii) specification of the emission sources. The most uncertain impact categories turned to be particulate matter and water depletion, whereas the others showed less variability. Other sources of uncertainty, such as input data quality and modelling choices, may play even a bigger role. However, both of them were only estimated by means of qualitative judgement, due to the difficulties in getting information related to the probability distributions associated to the original data sources.

Sala et al. (2016) performed a critical analysis of the trade inventory by means of a sensitivity audit i.e. by detecting, investigating and discussing the most sensitive assumptions that are likely to affect the most the results, both from qualitative and quantitative perspectives. Since the environmental impacts associated to apparent consumption for the toxicity-related impact categories revealed negative values, their reliability was questioned, as by definition the environmental impacts associated to total export cannot be higher than the sum of the environmental impacts stemming from imported goods and domestic activities. Such inconsistency could be explained by the high sensitivity of the results to the selection of the HS2 categories, their representative products and the quality of the LCI datasets. For these reasons, the results for the toxicity-related impact categories have been not taken into account.

In addition, even from a comparison of results with environmentally extended input/output tables, the robustness of the currently available bottom-up estimations associated with trade was questioned. Some already well-known issues related to the use of the bottom-up emerged, particularly on (i) technological representativeness, (ii) high sensitivity to specific LCI datasets parameters, (iii) allocation of environmental burdens and (iv) completeness. In order to evaluate the robustness of this calculation, the comparison of results with environmentally extended input/output tables reported in Sala et al. (2016) is presented (table 37). The comparison included three different methodologies: i) multi-regional input output tables, ii) single region input output table and iii) up-scaling from bottom-up LCI modelling either conducted within the work by Sala et al. (2016) and from Oliveira et al. (2014). The three methodologies are based on different approaches, as explained in EC-JRC (2010). A wide range of results was observed across impact categories. For instance, concerning 'climate change' impact category, the ratio between import and domestic differed substantially across the studies reviewed, ranging from 0.63 (EC-JRC, 2012) to 0.07 (bottom-up modelling, method A v2); this means that, according to EC-JRC (2012), in addition to every kg of CO_2 eq. generated domestically within the EU-27 other 0.63 kg of CO_2 eq. are imported. The results estimated by means of input-output tables (both multi-regional and single region) presented a higher contribution from imports than the bottom-up LCI modelling for acidification and photochemical ozone formation. However, in the case of the method used by Skenhall et al. (2015), the figures tended to be much closer, at least for climate change and acidification. Concerning water resources, the three methodologies differed dramatically. Finally, regarding 'Resource depletion – energy carriers, minerals and metals', it could be argued that the two bottom-up estimations differ substantially and that the method by Skenhall et al. (2015) was the one closer to MRIOT's result.

Such results raised questions on the robustness of the currently available bottom-up estimations associated with trade. The bottom-up LCI modelling can be considered a powerful technique when the sample of products used for modelling trade can be seen as representative of the basket of products imported into an economy. In order to reach such representativeness a high number of products combined with a high representativeness of those products for the traded goods is required. In the current version, only a limited number of products could be included in the analysis; hence, it is likely that the set of products would not be sufficiently representative of the imports that occur within the EU 27. This might explain why the bottom-up exercises reported in the table are always underestimating the contribution of trade if compared to the input output tables. Another possible source of difference is the completeness of the LC inventories used for modelling the products in import, possibly due to the low level of technological, time and geographical representativeness of the inventory.

Table 37: Comparison of import and domestic inventories with EEIOTs studies. Modified from Sala et al. (2016)

Impact category	**Methodology**	**additional details**	**Unit of the indicator**	**Embodied emissions (or resources) in import**	**Domestic emissions (or resources extraction)**	**Ratio: Embodied in Import / Domestic**	**Year**	**Coverage**	**Data source**
Economic accounts	European System of Accounts - ESA 2010	Current prices, EU28	Million euros	4,836,617.3 [7]	12,688,244.4 [8]	0.38	2010	EU-28	Eurostat (2016b)
Emissions									
Climate change	Multi-Regional Env.Ext. Input Output table		kg CO_2 eq.	3.21E+12	5.08E+12	0.63	2008	EU-27	WIOD EC-JRC (2012e)
	Multi-Regional Env.Ext. Input Output table	only CO_2	kg CO_2	1.17E+12	3.96E+12	0.30	2008	EU-27	Peters et al. (2011)
	bottom-up LCI and upscaling	import - method C	kg CO_2 eq.	9.20E+11	4.60E+12	0.20	2010	EU-27	Skenhall et al., (2015)
	bottom-up LCI and upscaling	import - method B	kg CO_2 eq.	9.40E+11	4.60E+12	0.20	2010	EU-27	EC-JRC, (2012a)
	bottom-up LCI and upscaling	import - method Av2	kg CO_2 eq.	3.12E+11	4.60E+12	0.07	2010	EU-27	JRC estimations, as reported in Benini et al. (2014)
Acidification	Multi-Regional Env.Ext. Input Output table		kt acid-eq	6.01E+02	7.24E+02	0.83	2008	EU-27	EC-JRC (2012e)

[7] Value of imports of goods and services
[8] Value of final consumption expenditure and gross capital formation, which is composed in turn by: household and non-profit institutions serving households final expenditure, government final consumption expenditure, gross fixed capital formation, changes in inventories, acquisition less disposal of valuables.

Impact category	Methodology	additional details	Unit of the indicator	Embodied emissions (or resources) in import	Domestic emissions (or resources extraction)	Ratio: Embodied in Import / Domestic	Year	Coverage	Data source
	bottom-up LCI and upscaling	import - method C	mol H+ eq	1.66E+10	2.36E+10	0.70	2010	EU-27	Skenhall et al., (2015)
	bottom-up LCI and upscaling	import - method B	mol H+ eq	1.12E+10	2.36E+10	0.47	2010	EU-27	EC-JRC, (2012a)
	bottom-up LCI and upscaling	import - method Av2	mol H+ eq	3.76E+09	2.36E+10	0.16	2010	EU-27	JRC estimations, as reported in Benini et al. (2014)
Photochemical ozone formation	Multi-Regional Env.Ext. Input Output table		kt NMVOC-eq	3.22E+04	2.90E+04	1.11	2008	EU-27	WIOD EC-JRC (2012e)
	bottom-up LCI and upscaling	import - method C	kg NMVOC eq	7.44E+09	1.59E+10	0.47	2010	EU-27	Skenhall et al., (2015)
	bottom-up LCI and upscaling	import - method B	kg NMVOC eq	3.72E+09	1.59E+10	0.23	2010	EU-27	EC-JRC, (2012a)
	bottom-up LCI and upscaling	import - method Av2	kg NMVOC eq	1.88E+09	1.59E+10	0.12	2010	EU-27	JRC estimations, as reported in Benini et al. (2014)
Resources									
Land Use	Multi-Regional Env.Ext. Input Output table		1000 km^2	4.77E+03	3.04E+03	1.57	2008	EU-27	WIOD (EC-JRC, 2012e)
	bottom-up LCI and upscaling	import - method B	kg C deficit	n.a.	3.74E+13	n.a.	2010	EU-27	EC-JRC, (2012a)

Impact category	**Methodology**	**additional details**	**Unit of the indicator**	**Embodied emissions (or resources) in import**	**Domestic emissions (or resources extraction)**	**Ratio: Embodied in Import / Domestic**	**Year**	**Coverage**	**Data source**
	bottom-up LCI and upscaling	import - method Av2	kg C deficit	4.88E+12	3.74E+13	0.13	2010	EU-27	JRC estimations, as reported in Benini et al. (2014)
Water Use	Multi-Regional Env.Ext. Input Output table		km^3	8.02E+02	7.32E+02	1.10	2008	EU-27	WIOD (EC-JRC, 2012e)
	bottom-up LCI and upscaling	import - method C	m3 water eq	6.75E+11	4.06E+10	16.6	2010	EU-27	Skenhall et al., (2015)
	bottom-up LCI and upscaling	import - method Av2	m^3 water eq	3.81E+08	4.06E+10	0.01	2010	EU-27	JRC estimations, as reported in Benini et al. (2014)
Material extraction	Multi-Regional Env.Ext. Input Output table		Mt	4.99E+03	6.99E+03	0.71	2008	EU-27	WIOD (EC-JRC, 2012e)
	Single region Env.Ext. Input Output table	Energy carriers only	t	1.63E+09	8.12E+08	2.01	2010	EU-27	Schoer et al.(2012a), Eurostat (2013a)
	Single region Env.Ext. Input Output table	Metals only	t	1.30E+09	1.55E+08	8.39	2010	EU-27	Schoer et al.(2012a), Eurostat (2013a)
	Single region Env.Ext. Input Output table	All materials	t	3.52E+09	5.93E+09	0.59	2010	EU-27	Schoer et al.(2012a), Eurostat (2013a)
Resource depletion – energy carriers,	Single region Env.Ext. Input Output table	Energy carriers only	kg Sb eq.	3.96E+06	2.14E+05	18.5	2010	EU-27	EC-JRC estimates on Schoer et al. (2012a)

Impact category	Methodology	additional details	Unit of the indicator	Embodied emissions (or resources) in import	Domestic emissions (or resources extraction)	Ratio: Embodied in Import / Domestic	Year	Coverage	Data source
minerals and metals	Single region Env.Ext. Input Output table	Metals only	kg Sb eq.	1.03E+08	3.36E+07	3.1	2010	EU-27	EC-JRC estimates on Schoer et al. (2012a)
	Single region Env.Ext. Input Output table	All materials	kg Sb eq.	1.07E+08	3.38E+07	3.07	2010	EU-27	EC-JRC estimates on Schoer et al. (2012a)
	bottom-up LCI and upscaling	import - method C	kg Sb eq.	9.98E+09	5.03E+07	198	2010	EU-27	Skenhall et al., (2015)
	bottom-up LCI and upscaling	import - method Av2	kg Sb eq.	1.48E+06	5.03E+07	0.03	2010	EU-27	JRC estimations, as reported in Benini et al. (2014)

3.6 Comparison of normalisation factors with Planetary Boundaries

The final scores obtained applying different options for assessing the level of environmental impacts due to human interventions are summarized in Table 38 and Figure 2, together with the Planetary Boundaries, calculated according section 2.6.1.

Table 38: Overview of the five different perspectives adopted for calculating total NFs, together with the Planetary Boundaries.

ILCD impact category	**Unit**	**EC-JRC EU-27**	**EU-27 BoP**	**EU-27 Apparent consumption**	**EC-JRC Global**	**Global I/O**	**Planetary Boundaries**
GWP	kg CO_2 eq	4.60E+12	3.26E+12	4.87E+12	4.81E+13	4.48E+13	6.79E+12
ODP	kg CFC-11 eq.	1.08E+07	1.14E+06	1.14E+07	1.34E+08	NA	5.38E+08
HTOXC	CTUh	1.88E+04	1.31E+05	NA	9.16E+04	1.94E+05	NA
HTOXNC	CTUh	2.69E+05	8.48E+05	NA	1.13E+06	9.70E+06	NA
RIPM	kg $PM_{2.5}$ eq	1.90E+09	2.10E+09	2.68E+09	6.86E+10	4.78E+11	NA
IR	kBq U-235 eq.	5.64E+11	1.94E+11	9.02E+12	2.04E+12	NA	NA
POF	kg NMVOC eq.	1.58E+10	8.84E+09	2.09E+10	2.80E+11	7.89E+11	2.62E+10
AC	mol H+ eq	2.36E+10	2.39E+10	3.55E+10	3.83E+11	4.76E+11	9.99E+11
EUTT	mol N eq	8.76E+10	7.72E+10	1.01E+11	1.22E+12	1.27E+12	6.12E+12
EUTF	kg P eq	7.41E+08	3.09E+08	6.01E+08	1.76E+10	4.74E+10	5.79E+09
EUTM	kg N eq	8.44E+09	7.87E+09	8.76E+09	1.95E+11	8.70E+09	2.00E+11
LU	kg C deficit	3.78E+13	1.71E+13	NA	1.00E+15	3.84E+14	1.37E+14
FRWTOX	CTUe	4.46E+12	3.34E+12	NA	2.75E+13	2.43E+12	1.31E+14
WD	m^3 water eq	4.06E+10	2.34E+11	3.73E+10	4.81E+13	4.35E+11	6.85E+11
RD-E-MM	kg Sb eq	5.03E+07	2.30E+08	5.40E+07	3.70E+09	1.47E+05	NA

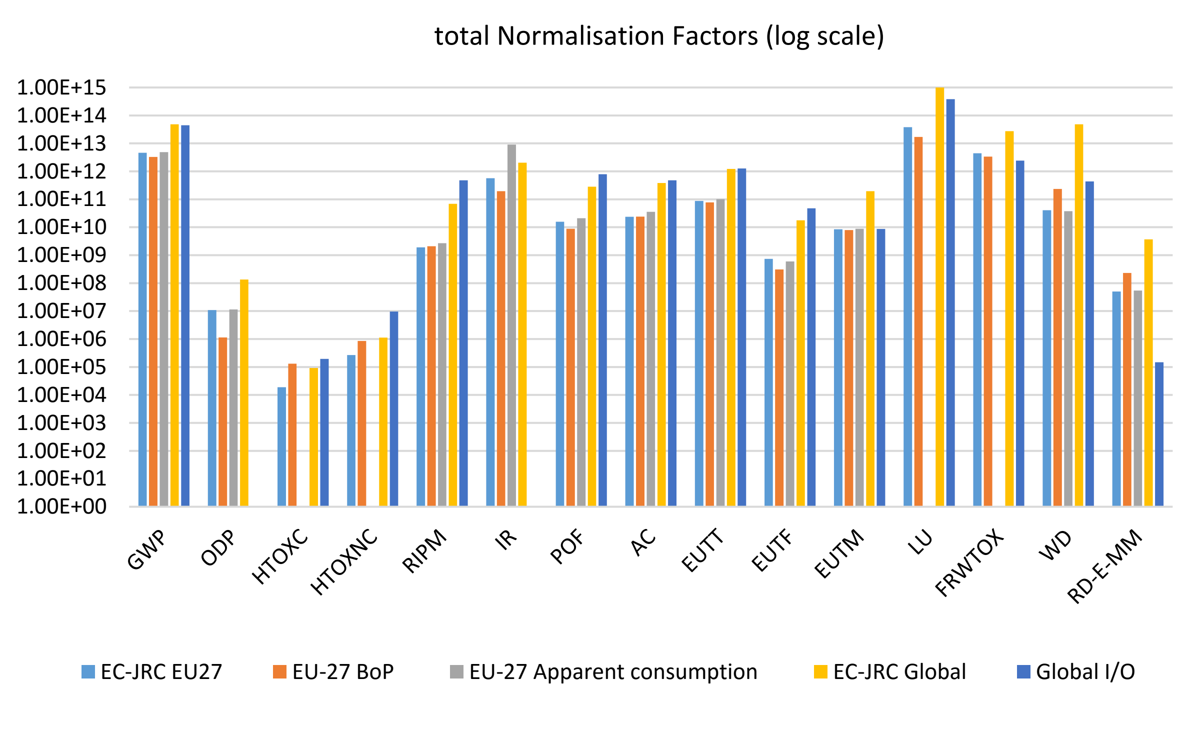

Figure 2: Overview of the five different accounting perspectives adopted for calculating total NFs, displayed in logarithmic scale.

In order to identify whether the framework of emissions and resource use for each applied approach lies within the PBs, we preferred to estimate the allowance per person for each impact category (see table 39 and figure 3) and compare the results with the PBs for a single world citizen. Therefore, the NFs referred to the EU-27 territory, namely EU-27 domestic, BoP and apparent consumption references, were divided by the EU-27 population in 2010 to obtain the European citizen's allowance for each boundary. The EU-27 population's value that we used was taken from Farago et al. (submitted), based on the estimation of the United Nations Department of Economic and Social Affairs (UNDESA, 2011). This value stands at 500.443 million people.
The same procedure was applied to the NFs at global level (i.e. EC-JRC Global NF and the normalisation factor based on I/O approach). In this case, the NF for each impact category was divided by the global population (UNDESA, 2011), thus obtaining the allowance per person on a global scale. Global population in 2010 stands at 6,895,889,018 people.

PB values per person for climate change, ozone depletion, photochemical ozone formation, freshwater eutrophication and freshwater ecotoxicity were directly retrieved from Bjørn and Hauschild (2015). As already mentioned in section 2.6.1, PB values for terrestrial acidification, terrestrial eutrophication, land use and water depletion were recalculated by EC-JRC.

Table 39: NFs per person calculated according to the five different accounting perspectives, to be compared with the per capita allowance of Planetary Boundaries according to Bjørn and Hauschild (2015), complemented by EC-JRC recalculations.

ILCD impact category	Unit	EC-JRC EU-27	EU-27 BoP	EU-27 Apparent consumption	EC-JRC Global	Global I/O	Planetary Boundaries
GWP	kg CO_2 eq/pers.	9.22E+03	6.51E+03	9.73E+03	6.98E+03	6.49E+03	9.85E+02
ODP	kg CFC-11 eq/pers.	2.16E-02	2.28E-03	2.28E-02	1.94E-02	NA	7.80E-02
HTOXC	CTUh/pers.	3.77E-05	2.62E-04	NA	1.33E-05	2.82E-05	NA

ILCD impact category	Unit	EC-JRC EU-27	EU-27 BoP	EU-27 Apparent consumption	EC-JRC Global	Global I/O	Planetary Boundaries
HTOXNC	CTUh/pers.	5.39E-04	1.69E-03	NA	1.64E-04	1.41E-03	NA
RIPM	kg $PM_{2.5}$ eq/pers.	3.80E+00	4.20E+00	5.36E+00	9.95E+00	6.93E+01	NA
IR	kBq U-235 eq/pers.	1.13E+03	3.88E+02	1.80E+04	2.96E+02	NA	NA
POF	kg NMVOC eq/pers.	3.17E+01	1.77E+01	4.18E+01	4.06E+01	1.14E+02	3.80E+00
AC	mol H^+ eq/pers.	4.73E+01	4.78E+01	7.09E+01	5.55E+01	6.90E+01	1.45E+02
EUTT	mol N eq/pers.	1.76E+02	1.54E+02	2.02E+02	1.77E+02	1.85E+02	8.87E+02
EUTF	kg P eq/pers.	1.48E+00	6.17E-01	1.20E+00	2.55E+00	6.87E+00	8.40E-01
EUTM	kg N eq/pers.	1.69E+01	1.57E+01	1.75E+01	2.83E+01	1.26E+00	2.90E+01
LU	kg C deficit/pers.	7.58E+04	3.42E+04	NA	1.45E+05	5.57E+04	1.99E+04
FRWTOX	CTUe/pers.	8.94E+03	6.67E+03	NA	3.99E+03	3.53E+02	1.90E+04
WD	m^3 water eq/pers.	8.14E+01	4.68E+02	7.45E+01	6.98E+03	6.31E+01	9.93E+01
RD-E-MM	kg Sb eq/pers.	1.01E-01	4.60E-01	1.08E-01	5.37E-01	2.14E-05	NA

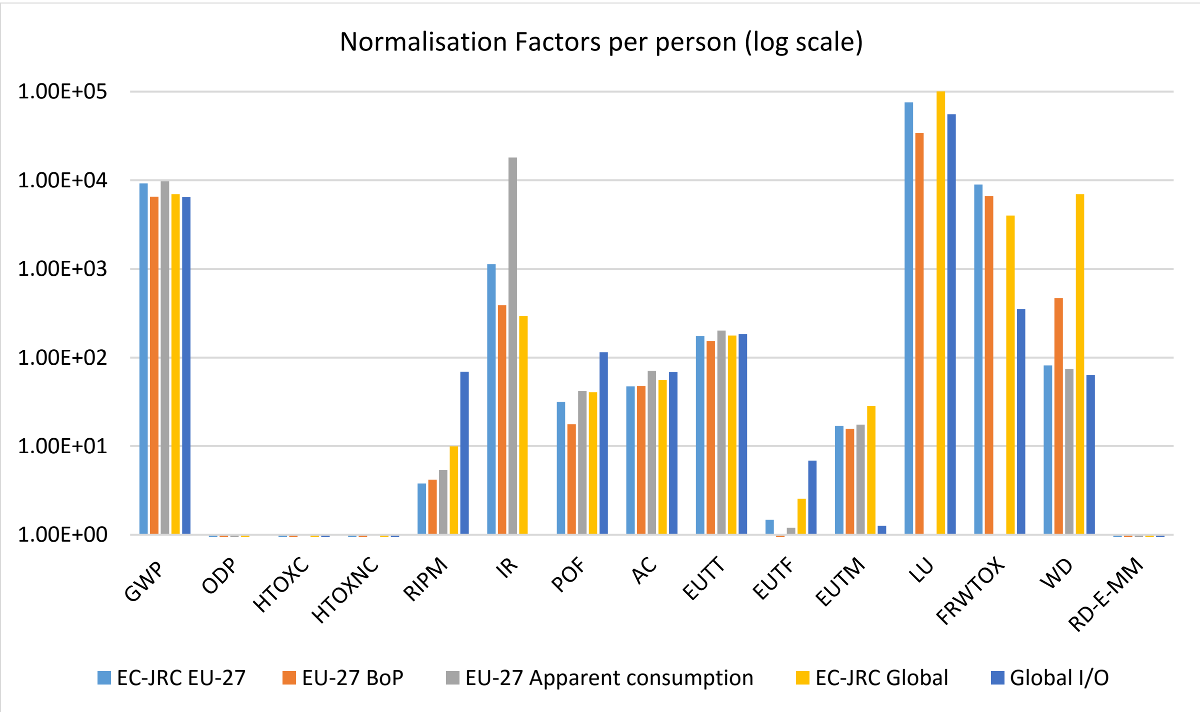

Figure 3: NFs per person, expressed as logarithmic scale, calculated according to the five different accounting perspectives. Some categories (i.e. ODP, HTOXC, HTOXNC and RD-E-MM) are not displayed in the graph, due to the application of the log scale.

According to the methodology adopted for calculating the set of NFs, these estimates are affected by significant uncertainties. The improvement of the estimation is of upmost importance to detect and prioritize the impact categories on which focusing the efforts for reducing the environmental impacts from an absolute sustainability viewpoint.

In the following sub-sections, a comparison between the per capita NFs calculated through each approach and the per capita PBs is presented and discussed.

3.6.1 EU-27 normalisation factors vs Planetary Boundaries

Table 40 and figure 4 report the share of impacts covered by each person in the EU-27 countries with respect to the PBs. It is possible to note that the majority of the European impact scores are far below the planetary limits, showed in green and yellow in figure 4 (i.e. respectively the safe operating space and the critical area, as defined by Rockström). However, climate change, photochemical ozone formation and land use categories considerably overcome the corresponding PBs, respectively more than nine, eight and three times. These categories are followed by freshwater eutrophication, which slightly surpasses the threshold of its safe operating space, remaining within the critical area.

Table 40: Share of EC-JRC EU-27 impact scores with respect to Planetary boundaries, calculated for each impact category for which a planetary boundary score is available.

ILCD impact category	Ratio EU-27 to PB (per person)
GWP	9.36E+00
ODP	2.77E-01
POF	8.34E+00
AC	3.27E-01
EUTT	1.98E-01
EUTF	1.76E+00
EUTM	5.83E-01
LU	3.80E+00
FRWTOX	4.71E-01
WD	8.20E-01

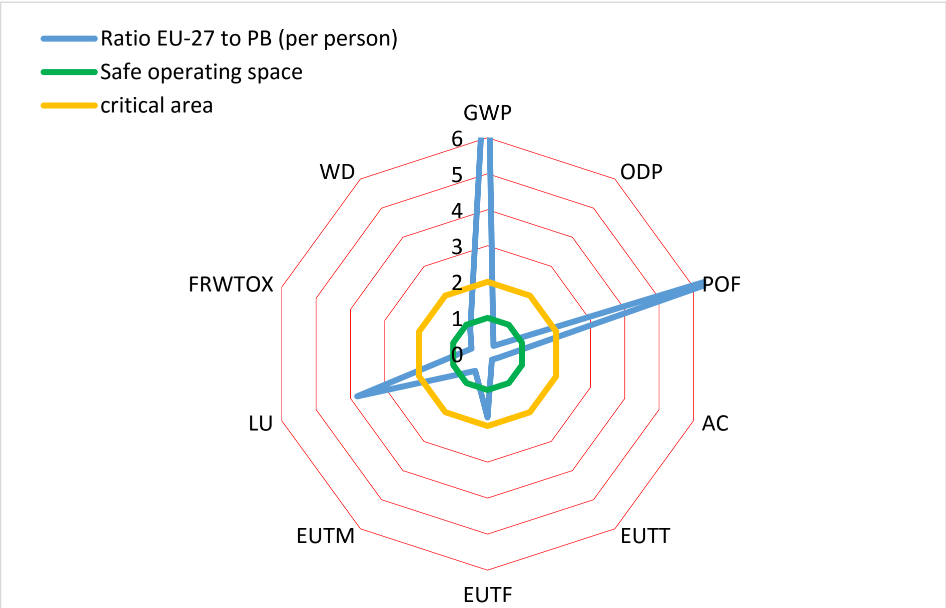

Figure 4: Comparison between EU-27 impact scores and Planetary boundaries as calculated by Bjørn and Hauschild (personal communication based on their 2015 publication) and complemented by EC-JRC.

3.6.2 Normalisation factors based on EU-27 Basket of Products vs Planetary Boundaries

According to the BoP accounting approach, a few impact categories, namely climate change, photochemical ozone formation and land use overcome the proposed PBs (see table 41 and figure 5).

Table 41: Share of EU-27 Basket of Products' impact scores with respect to Planetary boundaries, calculated for each impact category for which a planetary boundary score is available.

ILCD impact category	Ratio EU-27 BoP to PB (per person)
GWP	6.61E+00
ODP	2.92E-02
POF	4.65E+00
AC	3.30E-01
EUTT	1.74E-01
EUTF	7.35E-01
EUTM	5.42E-01
LU	1.71E+00
FRWTOX	3.51E-01
WD	4.71E+00

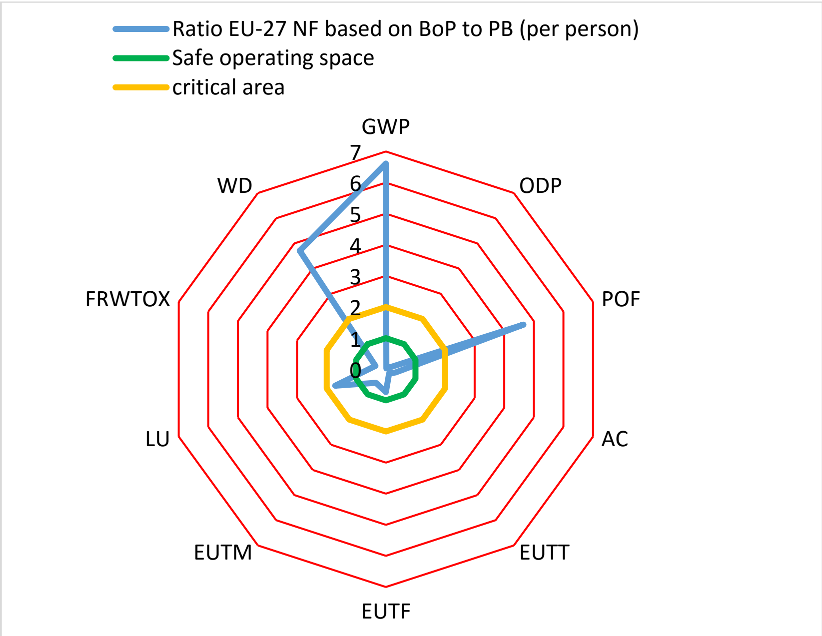

Figure 5: Comparison between BoP impact scores and Planetary boundaries as calculated by Bjørn and Hauschild, (2015) and complemented by EC-JRC.

The indicators that surpass the safety space for humanity are the same identified in the previous analysis (section 3.6.1), namely GWP, POF and LU. The applied methods account for different typologies of emissions: EU-27 domestic inventory takes into consideration direct emissions and extraction of resources occurring within territorial boundaries; while BoP inventory accounts for direct emissions and extraction of resources occurring within territorial boundaries as well as indirect ones, both modelled as products' supply chains for three main sectors. Despite this feature, it is possible to highlight such a convergence for the EU-27 territory. In this case, the abovementioned categories exceed the green line of more than six, four and two times respectively.

Even water depletion category presents a higher impact score than the relative PB, nearly fivefold as greater as its PB. On the other hand, the remaining categories lie within the safe operating space, delimited by the green line in figure 5.

3.6.3 Normalisation factors based on EU-27 apparent consumption vs Planetary Boundaries

The approach based on the apparent consumption, that tracks the overall environmental impacts both in the EU-27 territory and the pressures associated with imports and exports, lacks of a NF for two important categories, i.e. land use and freshwater toxicity. These impact categories, especially land use which generally has been shown to be critical according to the other applied approach, were considered not enough robust in terms of their underpinning model.

However, according to the previously presented accounting perspectives for EU-27, climate change and photochemical ozone formation still represent the categories that more frequently overcome the critical threshold of the PBs. The ratio with their related PBs stand at nearly ten and eleven, respectively (see table 42 and figure 6).

Even freshwater eutrophication represents a worth noting category, whose value is not negligible. In fact, it slightly exceeds its PB threshold, posing a potentially serious risk to human well-being on Earth.

Table 42: Share of Eu-27 apparent consumption impact scores with respect to Planetary boundaries, calculated for each impact category for which a planetary boundary score is available.

ILCD impact category	Ratio EU-27 apparent consumption NF to PB (per person)
GWP	9.88E+00
ODP	2.92E-01
POF	1.10E+01
AC	4.90E-01
EUTT	2.28E-01
EUTF	1.43E+00
EUTM	6.04E-01
LU	NA
FRWTOX	NA
WD	7.51E-01

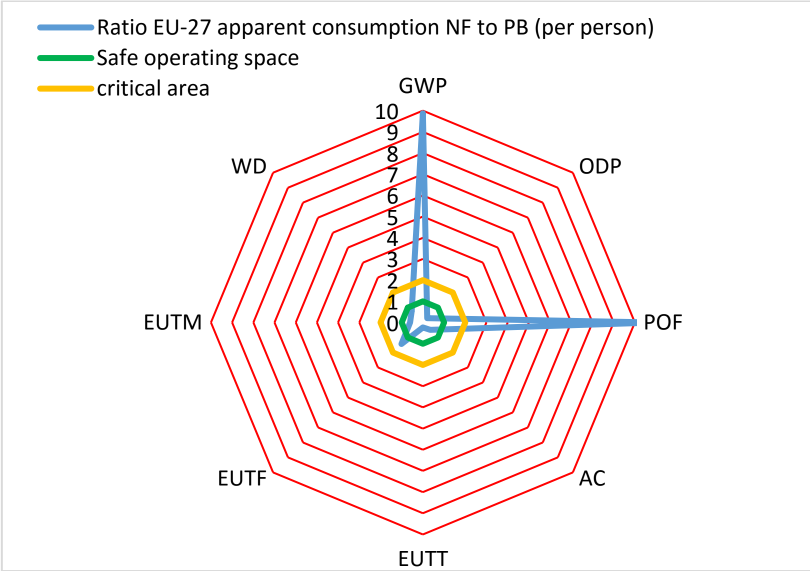

Figure 6: Comparison between EU-27 apparent consumption impact scores and Planetary boundaries as calculated by Bjørn and Hauschild, (2015) and complemented by EC-JRC.

3.6.4 Global normalisation factors vs Planetary Boundaries

According to the global territorial perspective, the situation with respect to the proposed PBs appears more complex and dramatic (see table 43 and figure 7). In fact, almost half categories, namely climate change, photochemical ozone formation, freshwater eutrophication and land use, overcome the critical thresholds, posing a high risk to global health and well-being. As for other applied approaches, the highest score is given by photochemical ozone formation, whose value is nearly eleven times as greater as its related PB. This indicator is followed by land use, climate change and freshwater eutrophication.

It is important to highlight that the inventory underneath the PB value could influence the result reported by land use category. In fact, this inventory is relatively poor (i.e. four land uses, occupation flows only) compared to the one built by Farago et al. (submitted), which include both occupation and transformation flows as well as more land use classes. This difference could lead to an underestimation of the planetary boundary.

In general terms, the global situation appears under a relatively higher pressure when considering the fact that marine eutrophication reference score is closely approaching the critical area for human well-being.

Finally, it is worth noting the twofold result for water depletion category due to the different procedures for recalculating the PB (see section 2.6.1). By calculating the PB with the country-based CFs, the global impact score is within the critical area. On the other hand, by using the OECD average CF, the score becomes critically higher with respect to the related PB, which is seventyfold overcome. As for land use category, these considerably different outcomes should be further investigated by improving the procedure underneath PB recalculation.

Table 43: Share of EC-JRC global impact scores with respect to Planetary Boundaries, calculated for each impact category for which a planetary boundary score is available.

ILCD impact category	Ratio Global NF to PB (per person)
GWP	7.08E+00
ODP	2.49E-01
POF	1.07E+01
AC	3.84E-01
EUTT	1.99E-01
EUTF	3.04E+00
EUTM	9.75E-01
LU	7.27E+00
FRWTOX	2.10E-01
WD (country-based)	1.62E+00
WD (OECD average)	7.03E+01

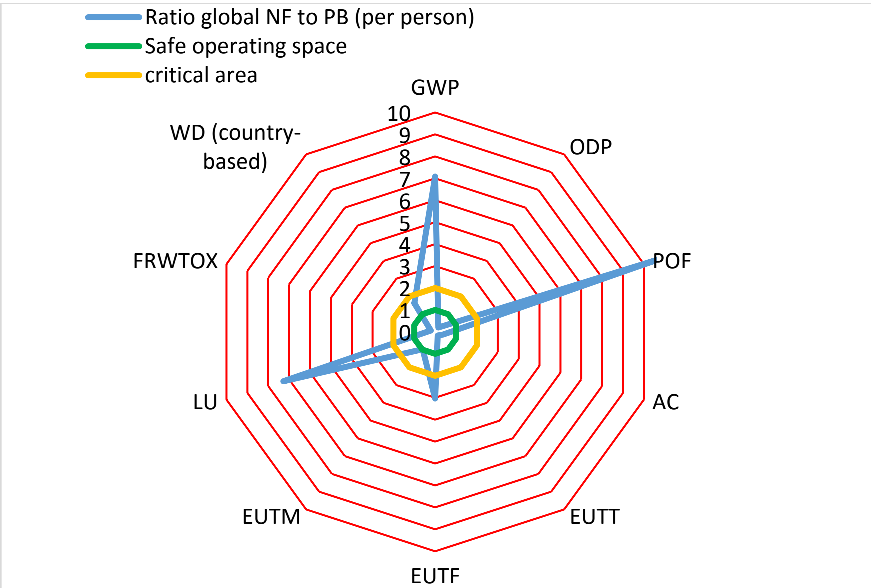

Figure 7: Comparison between global impact scores and Planetary boundaries as calculated by Bjørn and Hauschild, (2015) and complemented by EC-JRC.

3.6.5 Global normalisation factors based on input/output (I/O) approach vs Planetary Boundaries

According to the I/O accounting approach, based on the contribution of specific sectors to the environmental impact and on the supply chains underneath global final consumption, photochemical ozone formation still represents one of the most seriously impacting categories, thirtyfold overcoming the threshold of the critical area of PB. This indicator is far followed by a few impact categories, namely freshwater eutrophication and climate change, whose related impacts are respectively seven and eight times over the proposed PBs (see table 44 and figure 8). According to this approach, land use represents the fourth influent category, which slightly overcome the critical area threshold.

Table 44: Share of global I/O impact scores with respect to Planetary Boundaries, calculated for each impact category for which a planetary boundary score is available.

ILCD impact category	Ratio I/O global NF to PB (per person)
GWP	6.60E+00
ODP	NA
POF	3.01E+01
AC	4.77E-01
EUTT	2.08E-01
EUTF	8.18E+00
EUTM	4.35E-02
LU	2.79E+00
FRWTOX	1.85E-02
WD	6.35E-01

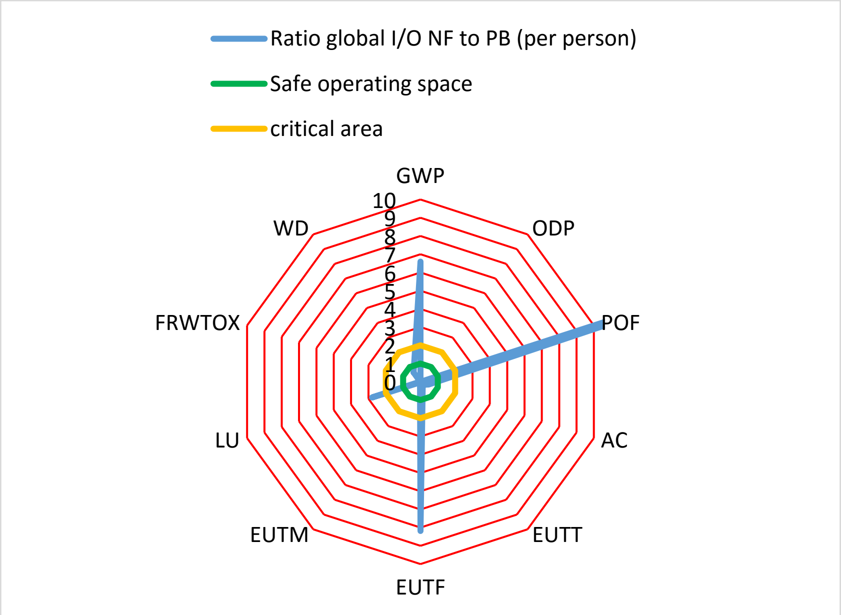

Figure 8: Comparison between global impact scores and Planetary boundaries as calculated by Bjørn and Hauschild, (2015) and complemented by EC-JRC.

4 Conclusions

The knowledge of planetary boundaries can improve environmental policy relevance, by measuring the sustainability gap between current human-driven impacts and their related carrying capacity thresholds. A crucial point is usually linked to the difficulties and the consequent uncertainties in defining a boundary, due to the underpinning ecological and environmental complexity of their evaluation. Those boundaries should be set in order to compare the current level of human-driven pressure on the environment with a reference state representing an ecological threshold. In fact, defining an unequivocal level of pressure due to human activities may be also difficult as it is usually the result of emission accounting (often incomplete) or of modelling exercise (bringing with it the clear limitations that any modelling effort may involve)

The present report focuses primarily on the provision of global estimate of environmental impacts to be compared to planetary boundaries and to be used as normalisation factors in LCA. The global inventory, which refers to the year 2010, is based on a vast data collection, covering the emissions into the environmental compartments (i.e. air, water and soil) and resource extracted at the global scale. When relevant data were missing, specific extrapolation procedures were adopted to fill the data gaps, according to specific methodologies for extrapolation. When different data sources were available, all the retrieved data have been reported in order to allow a qualitative evaluation of the uncertainties associated to the global inventory estimates. Applying a sort of precautionary principle, when different sources where available and their robustness comparable, we selected the highest value.

Moreover, different sets of NFs have been calculated following different methodologies to highlight the pros and cons associated to the methodological choices.

The results of the estimates allow the identification of several research needs, reported as follows. In fact, further research is needed in order to overcome the uncertainties and the limitation of the global normalisation factors, both at the inventory level and LCIA step, and to improve their completeness of the global NFs.

Just to name few aspects, more robust inventories for the impact categories should be set, focusing on their completeness. Global inventories of emissions and resource use are generally affected by limited availability of data from the original sources, especially officially reported data based on accepted models. Specifically for chemicals, too few estimates are available to consider the toxicity related inventories well covered. For several impact categories, the global estimates derived from different sources span over one order of magnitude. This may lead to inconsistency in the way impacts are prioritised.

In our work, we took into consideration the emissions in a defined reference year, namely 2010. However, it could be worthy to analyse the impact trends throughout a temporal series of data. In other cases, a combined inventory was needed to improve the coverage of emissions, as for marine eutrophication.

Regarding the characterisation of the impacts, global normalisation factors may be calculated with new recommended impact assessment models for the environmental footprint (Sala et al., 2016). Moreover, the normalisation factors were estimated with generic default characterisation factors a part from water depletion. However, for several impact categories country-specific CFs are available and a sensitivity assessment of the results could be conducted.

Regarding the use of different approaches for estimating the normalisation factors, currently, the territorial approach to global estimate seems the more robust and transparent. Every approach applied for estimating the magnitude of impacts to the environment may have strengths and weaknesses. Nevertheless, it is worth noting that there is convergence of the results when comparing the NFs calculated according to different perspectives with the available planetary boundaries.

For some impact categories, the differences between the set of normalisation factors are relatively limited. Nevertheless, the different approaches rely on underpinning inventories with a level of completeness not always satisfactory. Based on the considerations made for the methodology for planetary boundaries estimation and in the comparison "Global NFs vs Planetary boundaries", there is the need to further investigate and improve the procedure to calculate the PBs in the LCA framework, since the comparability of the results is not always easy to be ensured.

In spite of that, there is a clear convergence in the comparison between the different LCA-based approaches and the planetary boundaries. With all the approaches, the estimated impact related to climate change and photochemical ozone formation are overcoming up to 10 times the safe operating space. The global normalisation set reports also an overcoming in land use and freshwater eutrophication (seven and three times respectively). These impact categories were also popping up in the EU-27 domestic set and in the global set calculated with the extended environmental I/O approach.

Notwithstanding the current exercise could be considered just a preliminary attempt to quantify, in an LCA framework, the extent to which planetary boundaries are exceed, this is anyway an important step toward the identification of the main knowledge gaps towards a more robust quantification thereof.

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List of abbreviations and definitions

7^{th} EAP	7^{th} Environmental Action Programme
AC	Acidification
AGAGE	Advanced Global Atmospheric Gases Experiment
BoP	Basket of Products
CF(s)	Characterisation Factor(s)
CIENSIN	Center for International Earth Science Information Network
CN	Combined Nomenclature
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CTUe/CTUh	Comparative Toxic Unit (ecotoxicity and human toxicity)
EC-JRC	European Commission's Joint Research Centre
ECCAD	Emissions of atmospheric Compounds and Compilation of Ancillary Data
EDGAR	Emission Database for Global Atmospheric Research
EEA	European Environment Agency
EU-27	European Union 27 Member States
EUTF	Freshwater EUTrophication
EUTM	Marine EUTrophication
EUTT	Terrestrial EUTrophication
FAO	The Food and Agriculture Organization of the United Nations
FRWTOX	FReshWater ecotoxicity
GEIA	Global Emissions InitiAtive
GDP	Gross Domestic Product
GHG	GreenHouse Gas
GTAP	Global Trade Analysis Project
GWP	Global Warming Potential
HDI	Human Development Index
HFCs	Hydrofluorocarbures
HS	Harmonized commodity description and coding System
HMs	Heavy Metals
HTOXC	Human TOXicity, Cancer effects
HTOXNC	Human TOXicity, Non-Cancer effects
IAEA-PRIS	International Atomic Energy Agency's Power Reactor Information System
IEA	International Energy Agency
IFA	International Fertilizer Association
ILCD	International Reference Life Cycle Data System
IR	Ionising Radiation
I/O	Input/Output tables
ISO	International Standard Organisation
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LU	Land Use
LULUCF	Land Use, Land-Use Change and Forestry
MFH	Multi-Family House
MREEIOT	Multi-Regional Environmental Extended Input Output Tables
NASA	National Aeronautics and Space Administration
NF(s)	Normalisation Factor(s)
NMVOC	Non-Metal Volatile Organic Compounds
NO_x	Nitrogen Oxides
NR	Normalisation Reference
ODP	Ozone Depletion Potential
OECD	Organization for Economic Co-operation and Development
OPT	One Planet Thinking

PBs	Planetary Boundaries
PBL	Planbureau voor de Leefomgeving (Netherlands Environmental Assessment Agency)
PFCs	Perfluorocarbons
POF	Photochemical Ozone Formation
POP	Persistent Organic Pollutant
RD-E-MM	Resources Depletion, Energy carriers, Mineral and Metals
RADD	RAdioactive Discharges Database
RIPM	Particulate Matter and Respiratory Inorganics
SETAC	Society for Environmental Toxicology and Cchemistry
SFH	Single Family House
UNDESA	United Nations Department of Economic and Social Affairs
UNDP	United Nations Development Programme
UNEP	United Nations Environment Programme
UNEP/SETAC LCI	UNEP/SETAC Life Cycle Initiative
UNFCCC	United Nations Framework Convention on Climate Change
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
UN-SDG	United Nations Sustainable Development Goals
UN WPP	United Nations World Population Prospects
USGS	United States Geological Survey
WD	Water Depletion
WNA	World Nuclear Association

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