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Towards harmonizing natural resources as an area of protection in Life Cycle Impact Assessment

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Abstract

Purpose

In this paper, we summarize the discussion and present the findings of an expert group effort under the umbrella of the United Nations Environment Programme (UNEP)/Society of Environmental Toxicology and Chemistry (SETAC) Life Cycle Initiative proposing natural resources as an Area of Protection (AoP) in Life Cycle Impact Assessment (LCIA).

Methods

As a first step, natural resources have been defined for the LCA context with reference to the overall UNEP/SETAC Life Cycle Impact Assessment (LCIA) framework. Second, existing LCIA methods have been reviewed and discussed. The reviewed methods have been evaluated according to the considered type of natural resources and their underlying principles followed (use-to-availability ratios, backup technology approaches, or thermodynamic accounting methods).

Results and discussion

There is currently no single LCIA method available that addresses impacts for all natural resource categories, nor do existing methods and models addressing different natural resource categories do so in a consistent way across categories. Exceptions are exergy and solar energy-related methods, which cover the widest range of resource categories. However, these methods do not link exergy consumption to changes in availability or provisioning capacity of a specific natural resource (e.g. mineral, water, land etc.). So far, there is no agreement in the scientific community on the most relevant type of future resource indicators (depletion, increased energy use or cost due to resource extraction, etc.). To address this challenge, a framework based on the concept of stock/fund/flow resources is proposed to identify, across natural resource categories, whether depletion/dissipation (of stocks and funds) or competition (for flows) is the main relevant aspect.

Conclusions

An LCIA method - or a set of methods - that consistently address all natural resource categories is needed in order to avoid burden shifting from the impact associated with one resource to the impact associated with another resource. This paper is an important basis for a step forward in the direction of consistently integrating the various natural resources as an Area of Protection into LCA.

1. Introduction

Life Cycle Assessment (LCA) is the compilation of inputs (consumption of resources) and outputs (emissions) and the evaluation of related potential environmental impacts of a product system throughout its life cycle (ISO 2006). Other types of LCA exist, e.g. social LCA, but in this paper, the term LCA refers to environmental LCA. According to the new Life Cycle Impact Assessment (LCIA) framework (Frischknecht and Jolliet 2016), environmental impacts can be expressed on the level of individual impact categories or can be aggregated into so-called damage categories, or Areas of Protection (AoP), including 'Human Health', 'Ecosystem Quality' (sometimes referred to as 'Natural Environment') and 'Natural Resources' (see also EC-JRC 2010; Hauschild and Huijbregts 2015). While the former two are well-established and accepted, the role of the latter in LCA is still debated and there is no consensus on how this AoP should be tackled methodologically (see e.g. EC-JRC 2010; Mancini et al. 2013; Dewulf et al. 2015a). However, the natural environment provides natural resources, i.e. the substances/materials and flows that humans can use (e.g. metals, water, or wind), and changes on these provisions can therefore be considered an environmental impact.

Natural resources play a role in two phases of LCA: as elementary flows in the inventory analysis and as an AoP in LCIA. The focus of this paper is on LCIA methods and the AoP 'Natural Resources' (see Table S1 for naming in different methods). Natural resource consumption inventory flows (e.g. consumption of minerals, fossil fuels, land, or water) may have an impact on the AoP 'Natural Resources', but also on the other AoPs 'Ecosystem Quality' and 'Human Health'. For instance, land use may impact biodiversity (Koellner et al. 2013) and water consumption may cause shortages for irrigation, resulting in human malnutrition (Pfister et al. 2009). This paper does not address such resulting impacts on the AoP 'Ecosystem Quality' and 'Human Health'. Furthermore, emission inventory flows may have an impact on the AoP 'Natural Resources', e.g. emissions to water may decrease freshwater quality and thereby its availability at a specific quality level (Boulay et al. 2011; Bayart et al. 2014). However, these qualitative assessments are a combined assessment of pollution effects causing impacts on humans and ecosystems as well as impacts on resource availability that are not commonly established in LCIA methods.

Existing LCIA methods mainly consider the intrinsic values of human health and ecosystem quality, i.e. their "value by virtue of their pure existence", and the instrumental value of natural resources, i.e. their "utility to humans" (Frischknecht and Jolliet 2016). However, there is little agreement in the scientific community on what exactly is to be protected under the AoP 'Natural Resources' and what kind of metric should be used. Within the

UNEP-SETAC Life Cycle Initiative, it has been argued that the damage to natural resources consists of "the reduced availability of the corresponding type of resource to future generations" (Jolliet et al. 2004). Several approaches have been proposed to account for this, e.g. depletion rates (use-to-stock and use-to-availability ratios) or increased efforts for future generations to access resources in lower quality deposits. On the other hand, some authors claim that short- and medium-term (from a few years to a few decades) *availability* of mineral resources is mainly constrained by socio-economic factors and it is therefore debatable whether natural resource *availability* should be addressed in an environmental assessment (Drielsma et al. 2016). However, changes in the environment's capacity to provide natural resources is clearly an environmental issue, which should be of concern in an AoP 'Natural Resources'.

Although LCIA methods traditionally focused on abiotic natural resource depletion (minerals/metals and fossil fuels) (Weidema et al. 2007), there is no generally accepted impact assessment method (or model) for these natural resource categories and several methods exist concurrently (van der Voet 2013 in Mancini et al. 2013). Methods for other resource categories such as water and soil exist in parallel. In general, no method addressing impacts on natural resources, neither at midpoint nor at endpoint, can be recommended without restrictions (EC-JRC 2011; Hauschild et al. 2013). This paper reviews existing LCIA methods/models addressing natural resources and discusses their conceptual approaches across different natural resource categories. This is an important basis for further method development and moving towards a more consistent assessment within the AoP 'Natural Resources'. This paper is an output of a working group within the task force on crosscutting issues mandated by the UNEP-SETAC Life Cycle Initiative as a part of its flagship activities. It is structured as follows: first, natural resources are defined and categorized for the LCA context; second, existing methods that assess impacts on natural resources are briefly reviewed by resource category; and third, existing approaches are analyzed and discussed across resource categories.

2. Definition and categorization of natural resources

Definition of natural resources

From the discussions of the working group, it was concluded that natural resources are of concern in LCA because of their instrumental value to humans. This focus on the instrumental value is consistent with the definition of the new overall LCIA framework of the UNEP-SETAC Life Cycle Initiative (Frischknecht and Jolliet 2016). The working group acknowledges the complexity of defining natural resources and the existence of different definitions (see e.g. WTO 2010; Fischer-Kowalski and Swilling 2011; Dewulf et al. 2015b). The majority of the group agreed on the following definition of natural resources in LCA, which is compatible with the UNEP-SETAC LCIA framework:

Natural resources are material and non-material assets occurring in nature that are at some point in time deemed useful for humans.

Natural resources include minerals and metals, air components, fossil fuels, renewable energy sources, water, land and water surface, soil, and biotic natural resources such as wild flora and fauna. Natural resources may be distinguished from (primary) raw materials and (primary) energy carriers, which are the result of transformation of natural resources by the primary production sector through operations such as growing, harvesting, mining, and refining (Dewulf et al. 2015b). The World Trade Organization (WTO), for example, does not make this distinction since most resources require some processing before they can be traded or consumed (WTO 2010). However, the WTO also states that "the line of demarcation between natural resources and other goods will always be somewhat arbitrary" (WTO 2010). The WTO distinguishes natural resources from manufactured products (subject to a *substantial* amount of processing) and agricultural goods (cultivated rather than extracted from the natural environment). Also in the LCA context, biotic resources produced by an industrial production process (such as agricultural crops, livestock, fish from aquaculture, or wood from a plantation) are usually not classified as biotic natural resources (Klinglmair et al. 2014). They are produced with natural resource inputs, such as soil and water, and are considered part of the technosphere. Natural biotic resources (and water, surface, and soil) are natural resources and eco-system components (contributing to ecosystem quality) at the same time. Hence, natural biotic resource (or water, surface, or soil) use may have impacts on various AoP, which must be acknowledged by focusing on the issue in question. For instance, fishing would have an impact on the AoP 'Natural Resources' when less fish is available as a food source (overfishing), but it could also impact biodiversity (species richness, composition and/or abundance), which would be assessed in the AoP 'Ecosystem Quality'. Such parallel impacts in various AoPs as a consequence of the same environmental intervention are not new in LCA. For example, a toxic emission may have an impact on aquatic organisms (impacts on AoP 'Ecosystem Quality') and also enter the human food chain, e.g. by fish consumption (impacts on AoP 'Human Health'). The term 'natural' indicates that the resource is occurring in nature, untransformed by humans. Anthropogenic deposits such as landfills can also be considered sources for secondary resources or raw materials. However, they are neither addressed as inventory flows nor in LCIA. The resource properties do not necessarily get lost when entering the technosphere, but they may be "occupied or "borrowed" by a user within the product system. If it can be recycled afterwards, additional extraction of natural resources can be avoided. Natural resources can provide space (e.g. land area), substances and materials, or sources of energy. While some definitions of natural resources only consider these source functions, others also include sink functions (Dewulf et al. 2015b), i.e. the absorption of emissions in soil, water, and air. In existing LCIA methods, emissions to environmental compartments are considered and the corresponding impacts on humans and ecosystems are covered by the AoPs 'Human Health' and Ecosystem Quality'.

Categorization of natural resources

Natural resources are often categorized as stock, fund, or flow resources (see e.g. Udo de Haes et al. 2002; Klinglmair et al. 2014) according to their renewability and exhaustibility (Table 1).

Stock resources are considered to exist as a finite amount and are assumed to be non-renewable (they form and concentrate extremely slowly), and are therefore regarded as exhaustible (i.e. they can be used up). Examples are fossil and mineral resource stocks. Whilst individual chemical elements do not disappear and are not exhaustible, in a strict sense, they can be subject to dissipation such that deposits with some minimum level of concentration (useful to humans) may be finite and therefore exhaustible (Dewulf et al. 2015a). In this sense, the problem with the resource consumption is still a stock resource problem, i.e. a depletion or a dissipation problem.

Fund resources are renewable, i.e. they are continually supplied or re-concentrated once dissipated, but (at least in some cases) also exhaustible if overused (Udo de Haes et al. 2002). The available amount of a fund resource can either be decreased or increased, depending on the ratio of extraction to the renewal rate. Typical examples are fish or wild animals, but the depletion of water bodies such as the Aral Sea can also be considered a fund resource problem.

Flow resources are non-exhaustible and have a limited availability at a certain time (Udo de Haes et al. 2002), which means that they have to be used as, when, and where they occur. They can be considered renewable when they re-occur at the same location. Examples are solar radiation or run-off from rivers.

How to define the boundaries between stocks, funds, and flows, in particular based on regeneration rates, is still an open question.

Special cases are land and water surface areas, which are permanently present and usually constant in the total available amount. They cannot be depleted or dissipated but only occupied and as such are non-exhaustible. This does not fit well into the stock/fund/flow classification and has sometimes been kept a separate category besides abiotic and biotic natural resources that have been categorized into stocks/funds/flows (see e.g. Heijungs et al. 1997; Lindeijer et al. 2002). Nonetheless, competition for area has been considered to be a flow resource problem because surface area (just quantity, disregarding quality) cannot be depleted and hence is not lost for future generations (Lindeijer et al. 2002). The issue with land quality or soil properties may be considered to be a fund resource problem because soil properties can be deteriorated (or remediated) such that soil loses (or increases) its usefulness for a certain purpose.

<Table 1>

According to the definitions above, only depletion or dissipation of stock and fund resources imply a damage to the resource as such in its available form. Although there is no agreement on how this damage should be assessed, existing methods mainly relate it to potential consequences for future generations (e.g. reduced availability due to depletion or increased efforts for resource extraction). The use of a flow resource may have impacts on its temporary availability and therefore the impact is the consequences of the increased competition for this resource, rather than any lasting impact on the resource itself.

Most existing LCIA methods focus on mineral/metal and fossil fuel natural resources (see Table S1). Water (substance) and land (surface) are generally assessed separately (Klinglmair et al. 2014). Soil can also be assessed as a resource (see e.g. Milà i Canals et al. 2007a; Koellner et al. 2013; Vidal Legaz et al. 2016), and should not be confused with land (surface) use impacts on biodiversity. Table 2 shows a compilation and categorization of natural resources based on Klinglmair et al. (2014), Dewulf et al. (2015a), Goedkoop et al. (2013), and Frischknecht and Büsser Knöpfel (2013). It is specified whether the natural resource consumption potentially causes a stock, fund, or flow resource problem as listed in Table 1. Furthermore, corresponding elementary flows/activities in the *Ecoinvent 2.2* and *3.2* databases (Frischknecht et al. 2007; Ecoinvent 2015) have been added to demonstrate that natural resources in the impact assessment match the resources in the inventory.

<Table 2>

3. Which resources are addressed in current LCIA methods and how?

Most existing methods are restricted to the dissipation or depletion of mineral/metal and fossil fuel natural resources (see Table S1). Exceptions are the differently organized LIME/LIME 2 method (Itsubo et al. 2004; Itsubo and Inaba 2012) and the Stepwise 2006 method (Weidema et al. 2007), which labels other resources as “Human” and “Biotic”. The operational methods covering the widest range of resource categories are thermodynamic accounting methods (CED, CExD, CEENE, SED; see Table 3). The conceptual framework covering the widest range of resource categories is provided by Stewart and Weidema (2005). It focuses on the functionality of resources and relies on two parameters: the ultimate quality limit and the backup technology (Stewart and Weidema 2005). For water and land use, resource specific frameworks were developed within the UNEP-SETAC Life Cycle Initiative (Milà i Canals et al. 2007a; Bayart et al. 2010; Koellner et al. 2013).

Since frameworks and methods have been developed for different resource categories, further analysis of existing methods is also structured along five natural resource categories: (1) minerals/metals and fossil fuels (often referred to as abiotic natural resources), (2) water, (3) land and water surface (4) soil, and (5) biotic natural resources. Air components and renewable energy sources (see Table 2) are only covered in exergy and solar energy methods.

<Table 3>

3.1. Minerals/Metals and Fossil Fuels

A wide range of methods is available for the abiotic natural resource categories minerals/metals and fossil fuels. These methods (and their underlying models and indicators) have been distinguished into four different types in literature (see e.g. Stewart and Weidema 2005; Steen 2006; Rørbech et al. 2014; Swart et al. 2015):

1. methods aggregating natural resource consumption based on mass or energy
2. methods relating natural resource consumption to natural resource stocks or availability

3. methods relating current natural resource consumption to consequences of future extraction of natural resources (e.g. potential increased energy use or costs)
4. methods quantifying consumption of exergy or solar energy

Method types 1 and 4 can be grouped together as “Resource Accounting Methods” (RAM) (Swart et al. 2015). The fact that RAM do not explicitly link used amounts of resources to changes in their availability or provisioning capacity is perceived by many as a drawback. Type 1 methods are not further discussed here. However, the type 1 indicator Cumulative Energy Demand (CED) can serve as a screening indicator for environmental performance (Huijbregts et al. 2010) and is widely applied in practice. Moreover, type 1 indicators, such as Material Input per Service-Unit (MIPS), are widely used to calculate material footprints (Saurat and Ritthoff 2013). Type 4 methods are more comprehensive than CED due to the assessment of the quality of energy and the inclusion of non-energetic resources (Bösch et al. 2007). In this paper, they are referred to as “thermodynamic accounting methods”.

Type 2 methods are based on use-to-availability ratios. However, there are different estimates for resource availability and the terminology differs between different organizations (e.g. the US Geological Service (USGS) and the Committee for Mineral Reserves International Reporting Standards (CRIRSCO)) (Drielsma et al. 2016). Terms such as “reserves” can therefore be misleading (for a comparison of terms, see Table S2). For example, “Ultimately extractable reserve” (Guinée and Heijungs 1995) and “Extractable global resource” (Drielsma et al. 2016) both relate to the amount of crustal content that will ultimately be extractable, which constitutes the resource stock relevant for depletion (Guinée and Heijungs 1995). The often used USGS reserve base on the other hand is not a fixed stock but its size is defined by technical, economic, legal, and other factors and hence can increase or decrease (Drielsma et al. 2016). Accordingly, use-to-availability ratios can increase or decrease over time when using a dynamic size such as the USGS reserve base or reserves for availability. In the case of copper, for example, on a global scale exploration success still outpaces annual production (Northey et al. 2014). Furthermore, these dynamic sizes underestimate the availability of less explored minerals and metals when compared to well-explored minerals and metals since more exploration efforts increase reserve estimates. Therefore, these methods do not account for dissipation or depletion of a fixed stock and are here labeled use-to-availability ratios (see Table 3). On the other hand, both the $ADP_{Ultimate\ Reserves}$ (Guinée and Heijungs 1995; van Oers et al. 2002) and the updated version of the AADP methods (Schneider et al. 2015) are examples of use-to-stock ratios (see Table 3). It is acknowledged that, on the one hand, the ultimate reserves (estimated by multiplying the average concentrations of chemical elements in the earth's crust by the mass of the crust) will never be fully accessible. On the other hand, although the ultimately extractable reserves is the only relevant parameter in terms of depletion of the useful (to humans) geological stock, its estimation is always bound to large uncertainties because it depends on the future development of extraction technologies (Guinée and Heijungs 1995). Table 4 summarizes the issues related to different deposit estimates used for use-to- availability ratios.

<Table 4>

While Guinée and Heijungs (1995) recommend to use crustal content, Schneider et al. (2015) (AADP method) estimate ultimately extractable reserves as a percentage of crustal content. Both papers acknowledge the implicit assumption that the ratio between the two is equal for all resources. If the natural resource is dissipated into concentrations that are below a threshold that allows for recovery, it is lost and the stock decreases.

Type 3 methods relate current resource consumption to potential consequences for future extraction of resources. These methods quantify these potential consequences as: a) additional energy requirements (e.g. Eco-Indicator 99, IMPACT 2002+, and TRACI and TRACI 2); b) additional costs (e.g. EPS 2000/2015, ReCiPe, LIME and LIME 2, Surplus Cost Potential (SCP), and Stepwise2006 (based on additional energy requirements)); or c) additional ore material that has to be dealt with (e.g. Ore Requirement Indicator (ORI) and Surplus Ore Potential (SOP/LC-Impact)). The rationale of type 3 methods is based on the conception that in the long run the effort to extract resources will increase due to declining quality of deposits. Cumulative grade-tonnage relationships have been used to show declining ore grades with increasing cumulative metal produced using the example of copper (see e.g. Gerst 2008; Vieira et al. 2012). However, at the global scale the initial ore grades of new porphyry copper mines have not declined over the past 150 years (Crowson 2012) and there is no apparent decline in the grades of different nickel ores (Mudd and Jowitt 2014). At the more regional scale on the other hand, data for Australia, Canada, and the United States shows a gradual decline of ore grades over time (see e.g. Mudd 2009). This decline also reflects the ageing of mines and the rising share of production from lower-grade ores that became technically accessible with time (Crowson 2012). When lower ore grades are mined, more waste is removed to access the minerals, which generally also leads to increases in energy consumption across mining operations unless investments are made in more efficient processes (EEX 2016). In reality, such investments combined with the closure of old mines and the opening of new mines mean that relationships between ore grade and energy consumption change within a particular sector or jurisdiction over time. While grade-tonnage relationships have been used to evaluate the physical availability of natural resources, cost-tonnage relationships have been used to account for the economic availability (Vieira et al. 2016a). For the period from 2000 to 2013, available data shows increasing costs and declining ore grades with increasing cumulative copper produced although the causal relationship between ore grade decrease and surplus costs is unknown and the authors acknowledge that data over a longer period would be desirable (Vieira et al. 2016a). Furthermore, as the example of copper shows, technological advances and economies of scale may offset the higher costs of mining lower ore grades (Crowson 2012). However, the long-run need to use lower ore grades and access more remote and more difficult to process deposits, even if it may not be driven by depletion of high grade deposits (West 2011), will eventually lead to increasing opportunity costs, i.e. what society has to sacrifice to get another unit of a mineral or metal (Tilton and Lagos 2007).

3.2. Water

In LCIA, impacts from emissions to water have traditionally been captured by impact categories such as (eco)toxicity, acidification, and eutrophication, which are usually connected to the AoP ‘Ecosystem Quality’ (Boulay et al. 2014). A general framework connecting water use to other AoP, such as the effects of the depletion of water stock and funds on future generations, has been proposed by Bayart et al. (2010). Several methods have been developed that entirely or partially address the different impact pathways outlined in their framework. A review and analysis of methods is presented in Kounina et al. (2013). Some methods quantify water scarcity/stress based on a use-to-availability ratio (similar to Type 2 methods for abiotic natural resources, see 3.1 and Table 4). However, these methods usually assess a pressure on flow water resources accounting for competition amongst different users and they are not connected to the AoP ‘Natural Resources’. Pfister et al. (2009) additionally use a future consequences/surplus energy concept, similar to Type 3 methods above (see 3.1).

The framework for water use by Kounina et al. (2013) (see also Figure S1) follows the reasoning discussed previously: only depletion of (water) stock and fund resources imply a damage to the resource as such in its available form (as surface or groundwater). Fossil groundwater (no or extremely slow replenishment) is the only water stock resource. Slowly replenishing groundwater bodies or stagnant surface water bodies, such as the Aral Sea, can be considered fund resources, since the available amount of water can either be decreased or increased, depending on the ratio of the extraction to renewal rate. Of all water resources (shown in Table 2), only salt water and rainwater are not considered in impact assessments. Whereas sea water can be considered an unlimited resource, brackish/saline water may be a local stock or fund that could be depleted. Rainwater is one of the resources (e.g. together with solar radiation, wind, or soil) that are acquired through land occupation (Ridoutt and Pfister 2010).

Methods addressing freshwater use are compiled in Table 3 and in more detail in Table S4.

3.3. Land and Water Surface

Land and water surface are finite and usually (the Aral Sea is an example of an exception) constant in total available amount. They cannot be consumed but only occupied, and they become available again for other uses after occupation. Therefore, they can be considered flow resources. The use of a flow resource may have (local) impacts on the temporary availability of, and therefore the competition (among humans and the environment) for, this resource. Therefore, these impacts have not been connected to the AoP 'Natural Resources', but instead to the AoP 'Ecosystem Quality' by several already existing methods assessing land use impacts on biodiversity (see Table 3). Furthermore, land (and water) surface use can be summed up as in the Recipe method at the midpoint level (Goedkoop et al. 2013), and they can be assessed with thermodynamic accounting methods quantifying consumption of exergy or solar energy (type 4, see 3.1). Finally, the Ecological Footprint method quantifies the area necessary to sustain consumption and activities, e.g. of a nation, expressed in units of world-average biologically productive area (Borucke et al. 2013).

3.4. Soil

Soil mass (3D-quantity), its properties, and related soil functions are important in addition to land surface (2D-quantity). Soil is defined as the top layer of the earth's crust formed by mineral particles, organic matter, water, air and living organisms (EC 2015). Soil functions include storing, filtering, cycling and transforming nutrients, substances, and water, biomass production, harboring biodiversity, carbon storage, being a source of raw materials, and being a physical environment for humans. The main threats to soil are erosion, loss of soil organic matter (SOM), compaction, salinization, acidification, contamination, sealing, landslides, flooding, desertification, and soil biodiversity loss (EC 2006; EC 2012; Stoessel et al. 2016). The variety of soil properties and functions and the variety of threats posed to them indicate the complexity of a holistic assessment of impacts on soil and so far no standardized method for a universal assessment of soil-quality impacts has been created (Garrigues et al. 2012; Vidal Legaz et al. 2016). Furthermore, this complexity corresponds to little agreement on the framework level (EC-JRC 2010; Koellner et al. 2013; Alvarenga et al. 2015). The threats to the resource soil can result in a physical loss of soil (e.g. of arable land by erosion) or in a change of properties (e.g. if SOM is lost) (see Figure S2). However, soil mass and properties can also be preserved or even increased/improved, e.g. by good agricultural practice, and hence fulfill the criteria of a fund resource as defined before. As for water resources, the depletion of these soil fund resources implies a damage to the resource as such in its available form.

Soil assessment methods and models are listed in Table 3 and Table S5. Some of these methods/models are not operational while others are limited to specific countries (Garrigues et al. 2012; Stoessel et al. 2016). They only address partial impacts relevant for soil degradation (e.g. erosion only) and they do not distinguish between different soil management practices (e.g. tillage or nutrient management) or production standards (e.g. organic or integrated production) (Stoessel et al. 2016). Many of the models have excessive data requirements and are therefore difficult to apply, and none of the methods is made compatible to commonly used existing LCIA methods (Stoessel et al. 2016). Globally, operational models are addressing the following impacts: erosion (Núñez et al. 2013; Saad et al. 2013; Scherer and Pfister 2015), loss of SOM (Milà i Canals et al. 2007b: agriculture and forestry only; Brandão and Milà i Canals 2013), compaction (Garrigues et al. 2013), desertification (Núñez et al. 2010), and salinization (Payen et al. 2016). Acidification and contamination are captured with the impact categories ‘Terrestrial Acidification’ and ‘Terrestrial Eco-toxicity’ but these are not connected to the AoP ‘Natural Resources’. There are several multi-criteria indicators to assess changes in soil properties (Cowell and Clift 2000; Oberholzer et al. 2006; Beck et al. 2010), whereby the LANCA approach (Beck et al. 2010) has been operationalized and is used in the method of Saad et al. (2013) and recently by LANCA developers themselves (Bos et al. 2016). Furthermore, there are exergy methods accounting for occupation of land and marine surfaces (Alvarenga et al. 2013; Taelman et al. 2014). Núñez et al. (2013) use the surplus energy concept and estimate the solar energy required to generate one gram of soil lost by erosion. Furthermore, Brandão and Milà i Canals (2013) promote the land’s long-term ability to produce biomass (referred to as biotic production potential (BPP), calculated based on SOM) as an endpoint in the AoP ‘Natural Resources’.

3.5. Biotic Natural Resources

Biotic natural resources have not received much attention yet (Finnveden et al. 2009). These resources are living at least until the moment of extraction from the natural environment and include wood, fish, and other terrestrial and aquatic biomass that can be harvested (Klinglmair et al. 2014). Agricultural crops, livestock, fish from aquaculture, or wood from a plantation are usually not classified as biotic natural resources in LCA (Klinglmair et al. 2014) since they are the output of a technical process and are hence already part of the technosphere. Impacts on habitats of biotic natural resources are assessed in the AoP 'Ecosystem Quality'. Impacts on biotic natural resources that are of concern in the AoP 'Natural Resources' are caused by overharvesting, overfishing, and overhunting. Such overuse of biotic natural resources may also affect the natural regeneration rate of these fund resources, leading to feedback mechanisms that may cause their depletion.

Aggregating methods considering biotic natural resources are Eco-scarcity, IMPACT 2002+, EPS 2000/2015, LIME/LIME 2, and exergy methods. However, in many cases the only biotic natural resource considered is wood as an energy resource. For instance, the IMPACT 2002+ method applies energy use from wood as a stand-alone indicator, because it is not part of the non-renewable energy indicator (Jolliet et al. 2003). In the Eco-scarcity method, "the energy content of energy resources not used for energy production (feedstock energy, such as when hydrocarbons are used as refrigerants or wood is used in a building), is also assessed with a primary energy factor. However, only the consumed proportion should be assessed" (Frischknecht and Büsser Knöpfel 2013). The EPS 2000/2015 method takes a different approach by including the AoP 'Ecosystem Production Capacity', which accounts for the ecosystem capacity to produce crops, wood, fish and meat, and clean water (Steen 1999; Steen 2015). In the LIME/LIME 2 methods, the impacts on forestry, crops, and fishery are linked to the AoP 'Social Assets', and the damages are measured as user costs, in monetary units (Itsubo et al. 2004; Itsubo and Inaba 2012).

Net Primary Production (NPP) has been used as proxy for damage assessment in the AoP 'Ecosystem Quality' (e.g. Pfister et al. 2009; Taelman et al. 2016), but also as a resource. For instance, Alvarenga et al. (2015) suggest the NPP deficit, which is the assessment of the decrease of biomass availability due to land use, as an indicator for damage assessment in the AoP 'Natural Resources'. They suggest the surplus cost approach, using algae cultivation in the ocean, as the backup technology (Alvarenga et al. 2015).

Methods for overfishing were initially developed within the EU LC-impact project, but these are not yet operational on a global scale (Emanuelsson et al. 2014).

4. Discussion

Natural resources have been categorized and grouped in many ways, as many LCIA methods (and underlying models and indicators) have been developed for assessing damages to different natural resources. While there seems to be agreement in the scientific community that declining environmental provision of natural resources should be assessed, there is not yet an agreement on which indicator describes this best (e.g. use-to-availability approaches, surplus cost/energy/ore). Furthermore, there is not yet a consensus on whether and how the functionality of a resource should be taken into account.

Figure 1 shows the framework suggested for all resource categories. The depletion or dissipation of stock and fund resources implies a declining environmental provision of natural resources. The use of a flow resource does not imply such a damage, but it may deprive others from using the resource, as a result of competition for it. Competition for natural resources (including competition for stock and fund resources) is an issue that has not yet been explicitly addressed in LCA. However, possible consequences of competition, such as crop failures due to lacking irrigation water, may be assessed as impacts. In the case of water, impacts of deprivation have been linked to the AoPs 'Human Health' and 'Ecosystem Quality' (Pfister et al. 2009) (dashed arrows pathway in **Figure 1**). Another possible consequence of competition is indirect land use change, which is of interest in consequential LCIA (Schmidt et al. 2015). However, so far there is no generally established methodological approach to address competition for flow (or fund and stock) resources in LCIA. Since it is debatable to what degree competition is an environmental problem, it is up to discussion whether and how this should be further developed. The same applies for all other pathways not yet established in LCIA, represented by dotted arrows in **Figure 1**.

Another issue not yet consistently addressed throughout existing LCIA methods are impacts on resources by other impact categories, such as the effects of global warming on soil productivity. This issue is partly addressed in the IMPACT 2002+ method, in which global warming is listed as a separate impact category, because it is assumed to impact so-called "life supporting functions" (Jolliet et al. 2003). Similar examples are the LIME methods, in which impacts on biotic production is considered (Itsubo et al. 2004; Itsubo and Inaba 2012).

<Figure 1>

Apart from thermodynamic accounting methods, currently there is no all-inclusive method available to assess impacts for all natural resource categories altogether, nor are methods, proposed for different natural resource categories, able to consistently assess these impacts across methods.

Type 2 methods: scarcity and dissipation/depletion

Use-to-availability ratios are concepts that are widely used in LCIA methods. They may account for dissipation or depletion of stock and fund resources and for pressure on flow resources (see **Figure 1**). Concerning minerals and metals, it is especially important to discuss the denominator in the ratio (see section 3.1 and Table 4). Methods using a dynamic size such as the USGS reserves for availability do not account for dissipation or depletion of a fixed stock and might therefore be misleading. However, estimating the geological stock relevant for dissipation or depletion (i.e. the amount of crustal content that will ultimately be extractable) is also bound to large uncertainties because it depends on the future development of extraction technologies. The two approaches taken for estimating fixed stocks are (i) setting the full crustal content as the availability of the resource (although it will never be fully accessible), and (ii) setting the ultimately extractable resource amount as a percentage of crustal content. Both approaches implicitly assume that the ratio between the crustal content and the ultimately extractable amount is equal for all minerals and metals.

Withdrawal-to-availability and consumption-to-availability ratios have been used to assess water stress or water scarcity. They usually consider the flow resource surface water. However, where the calculated ratio is larger than one, groundwater bodies (stocks or funds) or large surface water bodies (funds) are being depleted as assessed in the method by Pfister et al. (2009). Another issue concerning water availability (to humans) is whether the demand of ecosystems should be considered, and if so how large this demand is (different methods provide values from 35 to 80%) (Boulay et al. 2015).

A special case of a use-to-availability ratio to assess scarcity is the distance-to-target ratio. The Eco-scarcity method is based on this concept using the "current flow" of an environmental pressure (e.g. an emission) and the "critical flow" representing the political target in a weighting step (Frischknecht and Büsser Knöpfel 2013). Efforts to include carrying capacity or planetary boundaries in LCIA have introduced a (distance-to-target) normalization against carrying capacity-based references calculated with scientifically estimated thresholds for different impact categories (Bjørn and Hauschild 2015).

Finally, it should be noted that physical availability may not be the dominating factor when referring to environmental impacts. For instance, for minerals/metals and fossil fuels, greenhouse gas emissions and the climate effect these emissions produce may be of more environmental concern than the availability of these resources (Mudd and Ward 2008; McGlade and Ekins 2015).

Type 3 methods: declining quality and consequent future efforts

Stewart and Weidema (2005) defined two key variables when modelling impacts on natural resources: ultimate quality limit and backup technology. The ultimate quality limit is the limit differentiating whether a material is reusable with a lower functionality, or rendered unavailable (Stewart and Weidema 2005). Backup technology refers to both the technology applied to recycle a material and the alternative technology applied when reaching the ultimate quality limit, *i.e.* when the material is lost (Stewart and Weidema 2005). Common examples are the desalination of water and the consumption of shale gas and oil sands. It has been discussed whether future efforts (use of backup technologies) of current resource dissipation should be part of the impact assessment or part of the inventory (Finnveden 2005). However, type 3 methods seem to understand these future efforts as a proxy for quantifying the difficulty to access natural resources in the future and hence for quantifying an impact on natural resource provision.

The concept of long-term increasing efforts to access natural resources, as a result of declining quality, has been investigated for several natural resource categories. It has first been applied to minerals/metals and fossil fuels. The decision about which deposits of different quality (e.g. ore grade concentration) are extracted (or defined as extractable) depends (among other factors) on production costs. This is the reason why some LCIA methods use increasing future extraction costs as an endpoint unit. Furthermore, it is generally true that more energy is needed to exploit lower grade ores with the same technology. This is the reason why some methods use increasing energy demand for future extraction as an endpoint unit. Technological advances and economies of scale have offset higher costs of mining lower ore grades in the past and assumptions of increased costs and energy consumption of future resource extraction are highly uncertain. However, since LCA is indicating potential impacts for comparison on a common scale, these methods might still be used to account for declining resource quality. Type 3 methods differ in assumptions, e.g. concerning discount rates to calculate future costs. Even within the ReCiPe method for instance, different characterization factors calculated with different discount rates are provided. However, the fundamental principle (declining quality leading to increasing efforts for resource extraction) remains the same. A backup technology approach assessing surplus costs or energy has also been proposed for water (Pfister et al. 2009) and for biotic natural resources (net primary production) (Alvarenga et al. 2015). Some future effort methods for mineral resources avoid a translation into additional costs or energy requirements and account for potentially increasing ore requirements per mineral/metal extracted. This potential future burden is not related to a backup technology that might be used but to physical mass that may have to be dealt with. There are no similar methods like this last subtype of future effort methods for other natural resource categories.

Type 4 methods: thermodynamic accounting

Thermodynamic accounting methods or methods quantifying consumption of exergy or solar energy are able to capture the widest range of natural resource categories (see Table 3). As they consider the consumed quantities, they could be helpful in resource efficiency calculations. However, these methods do not link exergy consumption to changes in availability or provisioning capacity of the natural resource (mineral, water, land etc.) that is consumed.

Quality, functionality, recycling, substitutability

The UNEP-SETAC Life Cycle Initiative overall framework acknowledges the instrumental value of natural resources, which also depends on their quality and related functionality. Natural resources and (raw) materials are lost if the required qualities for their functionality are lost (e.g. through dissipation). However, these properties may be restored or even enhanced further through recycling and upcycling efforts. If this is not possible, the material may either be used for other purposes or it is lost. However, even when a material is "lost" to humans, its functionality may be replaced by other materials made from other natural resources.

Stewart and Weidema (2005) suggest a conceptual framework focusing on the functionality of natural resources. Methodologically, this approach implies that the quality and functionality of the input and output flows of a production system need to be recorded in the LCI in order to assess whether a natural resource is lost at its functionality level (Stewart and Weidema 2005). This issue has, for example, been addressed for water where water qualities needed for different uses were categorized (Boulay et al. 2011; Bayart et al. 2014).

The use of secondary/recycled and treated materials can lower the demand for natural resources (**Figure 1**). This use is typically modeled in the inventory phase. However, whether the use of recycled materials or the output of recyclable materials should get the environmental credits depends on the allocation modeling choice (Frischknecht 2010). Existing methods only roughly consider material quality, if at all, assuming "functional equivalence" of the substituted material. By contrast, the exergy efficiency approach explicitly considers both the quality of input and output materials. However, exergy might not be the only relevant quality criteria. For a proper inclusion of such criteria, metrics for quality and functionality would need to be defined and recorded in life cycle inventories.

Another aspect leading to the reduction of resource availability by reducing resource quality is the impact on natural resources caused by emissions, such as the pollution of groundwater bodies.

Research needs

In order to further improve impact assessment in the AoP ‘Natural Resources’, the discussion on whether resources should be a part of environmental LCA should be replaced by debates about 1) how environmental issues (we suggest natural provisioning capacity) can best be assessed and 2) how other aspects (e.g. short-term (market) availability) can be assessed in a complementary way. The integration of different resource categories into an AoP ‘Natural Resources’ involves some major challenges. While the distinction of stocks, funds, and flows is helpful, these categories still have to be better defined based on regeneration rates. Furthermore, a deeper discussion on whether and how impacts from competition for resources should be integrated in LCIA is needed. In addition, if ecosystem-relevant resources (land, soil, water, and biotic natural resources) and others (minerals/metals and fossil fuels) are to be assessed with a common unit within the same AoP, impact modelling has to be adapted.

5. Conclusions

The environment’s capacity to provide natural resources of a useful quality with instrumental value to humans is what should be protected under the AoP ‘Natural Resources’. However, we know neither how technological developments influence future accessibility nor what the needs of future generations are. While it is true that because of the instrumental value the issue of concern is actually the functionality of a natural resource, information on the functionality and substitutability of resources is mostly incomplete, especially with regard to the future consumption of resources. Therefore, for the time being, it makes sense to devote time to the assessment of environmental provisioning capacity of natural resources. Thereby, the concept of stock/fund/flow resources is helpful, across natural resource categories, in identifying whether depletion/dissipation (of stocks and funds) or competition (for flows) is the main relevant issue. The former has been of primary interest for the AoP ‘Natural Resources’ and accordingly the damage has been described as a reduced availability of, or as a more onerous access to, natural resources in the future (see e.g. Udo de Haes et al. 2002; Jolliet et al. 2004; Bayart et al. 2010). Two main types of methods/models have been used to account for this: 1) use-to-stock/availability methods focus mainly on the quantitative availability; 2) future effort methods focus more on resource quality and corresponding efforts to make the resource usable. Both method types have been used for several resource categories, but no set of methods is yet available to consistently capture all natural resource categories, except for exergy and solar energy methods. However, the fact that exergy and solar energy methods do not explicitly link exergy consumption to changes in availability or provisioning capacity of the natural resource (mineral, water, land etc.) that is consumed may be considered to be a drawback.

An LCIA method - or a set of methods - that consistently addresses all natural resource categories is needed in order to assess the AoP 'Natural Resources' in a comprehensive manner and to avoid burden shifting from impacts on one resource to impacts on another resource. This paper reviewed existing LCIA methods/models addressing natural resources and discussed their conceptual approaches across different natural resource categories, which is an important prerequisite for a step in this direction.

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7. Tables

Table 1 Classification of potential resource problems according to renewability and exhaustibility of resources

	Renewability	Exhaustibility
Potential stock problem	non-renewable	exhaustible
Potential fund problem	renewable	exhaustible
Potential flow problem	re-occurring or permanently present	non-exhaustible

Table 2 Compilation and categorization of natural resources based on Klinglmair et al. (2014), Dewulf et al. (2015a), Goedkoop et al. (2013), and Frischknecht and Büsser Knöpfel (2013), including the corresponding elementary flows in the *Ecoinvent 2.2* and *3.2* databases (Frischknecht et al. 2007; Ecoinvent 2015)

Resource Categories		**Resource(s)**	**Stock/Fund/Flow resource problem**	**Resources in inventory according to *Ecoinvent 2.2 and 3.2***
Minerals and metals	Aggregates	Rock	Stock	e.g. Granite, Shale…
		Gravel	Stock/Fund	Gravel, in ground
		Sand	Stock/Fund	Sand, unspecified, in ground
		Clay	Stock/Fund	Clay, bentonite, in ground; Clay, unspecified, in ground
		Minerals	Stock	e.g.Anhydrite, Dolomite…
	Elements	Metals	Stock	e.g. Copper, Gold…
		Elements in water	Stock	Bromine, Iodine, Magnesium
		Elements in air	Stock	Krypton, Xenon
Radioactive elements		Uranium (and others)	Stock	Uranium, in ground
Air components		Air components	Stock	Carbon dioxide, Nitrogen, Oxygen, Argon-40
Fossil fuels	Coal	Peat	Stock	Peat, in ground
		Brown coal	Stock	Coal, brown, in ground
		Black coal	Stock	Coal, hard, unspecified, in ground
	Oil & gas[a]	Petroleum	Stock	Oil, crude, in ground
		Natural gas	Stock	Gas, natural, in ground
(Abiotic) renewable energy sources		Solar power	Flow	Energy, solar, converted
		Wind power	Flow	Energy, kinetic (in wind), converted
	Hydropower	Potential	Fund/Flow	Energy, potential (in hydropower reservoir), converted
		Wave power	Flow	
		Tidal power	Flow	
		Geothermal power	Flow/Fund	Energy, geothermal, converted
Water	Salt water	Sea water	Flow/Fund	Water, salt, ocean
		Brackish/saline water	Stock/Fund	Water, salt, sole
	Freshwater	Surface water	Flow/Fund	Water: river, lake, cooling, turbine use, unspecified
		Groundwater	Fund/Flow	Water, well, in ground
		Fossil groundwater	Stock	Water, well, in ground
		Water in air	Flow/Fund	Water, in air
Land and water surface		Land surface	Flow (competition for area)	Land occupation/transformation (various categories)
		Water surface	Flow (competition for area)	Land occupation/transformation: inland waterbody, lake, river, wetland, unspecified
		Sea(bed) surface	Flow (competition for area)	Land occupation/transformation: seabed
Soil[b]		Soil	Fund	
Biotic natural resources	Flora: terrestrial	Wild plants/wood	Fund	Energy, gross calorific value, in biomass, Wood: hard, primary forest, soft, unspecified
	Flora: aquatic	Wild aquatic flora	Fund	Energy, gross calorific value, in biomass
	Fauna: terrestrial	Game	Fund	Energy, gross calorific value, in biomass
	Fauna: aquatic	Wild fish, seafood…	Fund	Energy, gross calorific value, in biomass

[a] Including unconventional oil and gas such as shale gas

[b] A special case is the consideration of volumes needed to dispose waste in the Ecological Scarcity method

Table 3 Natural resource coverage by method; based on Klinglmair et al. (2014), Rørbech et al. (2014), Hauschild and Huijbregts (2015), and literature indicated

Method/Model	*History/Comment*	*Literature*	Minerals & metals	Radioactive elements[c]	Air components	Fossil fuels[d]	(Abiotic) renewable energy sources[e]	Water	Land & water surface	Soil	Biotic natural resources
USE-TO-STOCK/USE-TO-AVAILABILITY											
Metals/Minerals and Fossil Fuels											
CML-IA: $ADP_{Ultimate\ Reserve}$ $ADP_{Reserve\ Base}$/ILCD $ADP_{(Economic)\ Reserve}$	 Use-to-stock Use-to-availability 2002, Use-to-availability	 (Guinée and Heijungs 1995) (van Oers et al. 2002) (van Oers et al. 2002)	48	Yes	-	4	-	-	-	-	-
AADP $AADP_{Update}$	Use-to-availability Use-to-stock[f]	(Schneider et al. 2011) (Schneider et al. 2015)	10 35	- -	- -	- -	- -	- -	- -	- -	- -
EDIP 97/2003	Use-to-availability	(Potting and Hauschild 2005)	29	Yes	-	4	Partial[g]	-	-	-	Wood: energy
Eco-scarcity (2013) (Switzerland)	1990, 1997, 2006	(Frischknecht and Büsser Knöpfel 2013)	Yes	Yes	-	4	5	Yes	Yes	-	Wood: energy
Water											
Boulay et al.		(Boulay et al. 2011)	-	-	-	-	-	Yes	-	-	-
Milà i Canals et al.	CML approach (ADP)	(Milà i Canals et al. 2009)	-	-	-	-	-	Yes	-	-	-
WDI		(Berger et al. 2014)	-	-	-	-	-	Yes	-	-	-
WFN Water Scarcity		(Hoekstra et al. 2012)	-	-	-	-	-	Yes	-	-	-
WII		(Bayart et al. 2014)	-	-	-	-	-	Yes	-	-	-
WSI/Pfister et al.		(Pfister et al. 2009)	-	-	-	-	-	Yes	-	-	-
Biotic Natural Resources											
Emanuelsson et al.	OF & OB (see Table S6)	(Emanuelsson et al. 2014)	-	-	-	-	-	-	-	-	Fish
Langlois et al.		(Langlois et al. 2014)	-	-	-	-	-	-	-	-	Fish
FUTURE CONSEQUENCES											
Eco-Indicator 99	1995	(Goedkoop and Spriensma 2001)	12	-	-	4	-	-	(Yes AoP EQ)	-	-
EPS 2000/2015	1996	(Steen 1999) (Steen 2015)	67	Yes	-	3[h]	-	Yes[i]	-	-	(Crops), wood, fish & meat[j]
IMPACT 2002+		(Jolliet et al. 2003)	13	Yes	-	5	-	-	(Yes	-	Wood: energy

[c] Uranium

[d] Peat, Brown coal, Black coal, Petroleum, Natural gas, Sulfur

[e] Solar, Wind, Water, Geothermal

[f] The resource stocks ultimately available for human use in the long-term are estimated on the basis of the resources in the upper continental crust

[g] Factors only provided for wood and freshwater at a global level(Hauschild and Huijbregts 2015)

[h] Only one coal category

[i] In AoP 'Ecosystem Production Capacity'

[j] In AoP 'Ecosystem Production Capacity'

Method/Model	*History/Comment*	*Literature*	Minerals & metals	Radioactive elements[c]	Air components	Fossil fuels[d]	(Abiotic) renewable energy sources[e]	Water	Land & water surface	Soil	Biotic natural resources
									AoP EQ)		
LC-Impact	see SOP		51[k]	Yes	-	-	-	(Yes, AoP HH & EQ)	(Yes AoP EQ)	-	-
LIME LIME 2		(Itsubo et al. 2004) (Itsubo and Inaba 2012)	Yes	-	-	Yes	-	-	(Yes, changes in NPP, AoP EQ)	-	Forest resources consumption
ORI		(Swart and Dewulf 2013)	9	-	-	-	-	-	-	-	-
Pfister et al.		(Pfister et al. 2009)	-	-	-	-	-	Yes	-	-	-
ReCiPe (2008)	Based on CML-IA (midpoint only) + EI99 (endpoint only)[l]	(Goedkoop et al. 2013)	19	Yes	-	6	-	Yes (Midpoint)	(Yes AoP EQ)	-	-
SCP		(Vieira et al. 2016a)	12[m]	Yes	-	-	-	-	-	-	-
SOP/LC- Impact		(Vieira et al. 2016b)	58[n]	Yes	-	-	-	-	-	-	-
Stepwise 2006	Based on EDIP 2003 and IMPACT 2002+	(Weidema et al. 2007)	Yes	Yes	-	Yes	-	-	(Yes AoP EQ)	-	-
TRACI TRACI 2	Fossil fuel assessment based on Eco-Indicator 99	(Bare et al. 2003) (Bare 2011)	-	-	-	Yes	-	-	(US only AoP EQ)	-	-
LOSS OF USEFUL PROPERTY											
Thermodynamic Accounting											
CEENE		(Dewulf et al. 2007) (Taelman et al. 2014)	53	Yes	Yes	4	Yes	Yes	Yes (incl. sea surface)	-	Wood
CExD		(Bösch et al. 2007)	57	Yes	Yes	6	5	Yes	-	-	Wood
Exergy NPP		(Alvarenga et al. 2013)	-	-	-	-	-	-	Exergy/NPP	-	Exergy/NPP
SED		(Rugani et al. 2011)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	-	Yes
Soil											
BPP	Based on SOM	(Brandão and Milà i Canals 2013)	-	-	-	-	-	-	-	SOM	-
Compaction		(Garrigues et al. 2013)	-	-	-	-	-	-	-	Pore volume loss	-
Desertification		(Núñez et al. 2010)	-	-	-	-	-	-	-	Desertification (includes erosion)	-
Erosion		(Núñez et al. 2013)	-	-	-	-	-	-	-	Erosion	-
Erosion and P-loss		(Scherer and Pfister 2015)	-	-	-	-	-	-	-	Erosion & P-loss	-
ERP	Using the LANCA tool (Beck et al. 2010)	(Saad et al. 2013)	-	-	-	-	-	-	-	Erosion	-
LANCA		(Beck et al. 2010; Bos et al. 2016)	-	-	-	-	-	-	-	Several indicators	-
Salinization		(Payen et al. 2016)	-	-	-	-	-	-	-	Salinization	-
SOM		(Milà i Canals et al. 2007b)	-	-	-	-	-	-	-	SOM	-

[k] Currently being expanded
[l] The midpoint and endpoint of mineral resources are new in ReCiPe
[m] Currently being expanded
[n] Currently being expanded

Method/Model	*History/Comment*	*Literature*	Minerals & metals	Radioactive elements[c]	Air components	Fossil fuels[d]	(Abiotic) renewable energy sources[e]	Water	Land & water surface	Soil	Biotic natural resources
Biotic Natural Resources											
Emanuelsson et al.	LPY (see Table S6)	(Emanuelsson et al. 2014)	-	-	-	-	-	-	-	-	Fish
HANPP		(Alvarenga et al. 2015)	-	-	-	-	-	-	-	-	NPP

Abbreviations: (A)ADP: (Anthropogenic stock extended) Abiotic Depletion Potential, BPP: Biotic Production Potential, CEENE: Cumulative Exergy Extraction from the Natural Environment, CExD: Cumulative Exergy Demand, EQ: Ecosystem Quality, ERP: Erosion Resistance Potential, HANPP: Human Appropriation of Net Primary Production, NPP: Net Primary Production, ORI: Ore Requirement Indicator, P: Phosphorous, SCP: Surplus Cost Potential, SED: Solar Energy Demand, SOM: Soil Organic Matter, SOP: Surplus Ore Potential, URR: Ultimate recoverable resource, WDI: Water Depletion Index, WFN: Water Footprint Network, WII: Water Impact Index

Table 4 Metal/mineral deposits used for use-to-availability ratios according to terminology used by the CML-IA method (Guinée and Heijungs 1995), by the US Geological Service (USGS), and by the Committee for Mineral Reserves International Reporting Standards (CRIRSCO) as reported in Drielsma et al. (2016)

Metal/mineral deposits	Advantages	Disadvantages
- (Economic) reserves (CML/USGS)/ Mineral reserves (CRIRSCO) - Reserve base (CML/USGS)/ Mineral Resources (CRIRSCO) - Resources (USGS)	- Based on identified deposits	- Dynamic sizes, no stable indicators - Underestimates extractable metals and minerals (especially if less explored)
Ultimately extractable reserves (CML)/ Extractable Global Resource (Drielsma)	- Relevant for depletion of useful (to humans) geological stock - (Theoretically) fixed stock	- Depends on future technological developments, highly uncertain estimations
Ultimate Reserves (CML)/ Crustal content (Drielsma)	- Fixed stock - Data available	- Not relevant for depletion of useful (to humans) geological stock because part of it is not accessible

8. Figure Captions

Figure 1 Impact pathways from use of different natural resource types to areas of protection; "competition for resource" means that there is not enough provided to match the demand of all users (including the environment); "within renewability rate" means that the fund resource is used in way that it is not depleted in the long term and that there is no competition; the dashed arrow shows the pathway of how indirect effects of competition have been assessed; the dotted arrows show pathways not yet established in LCIA methods (it is up to discussion whether and how they should be established)

9. Figures

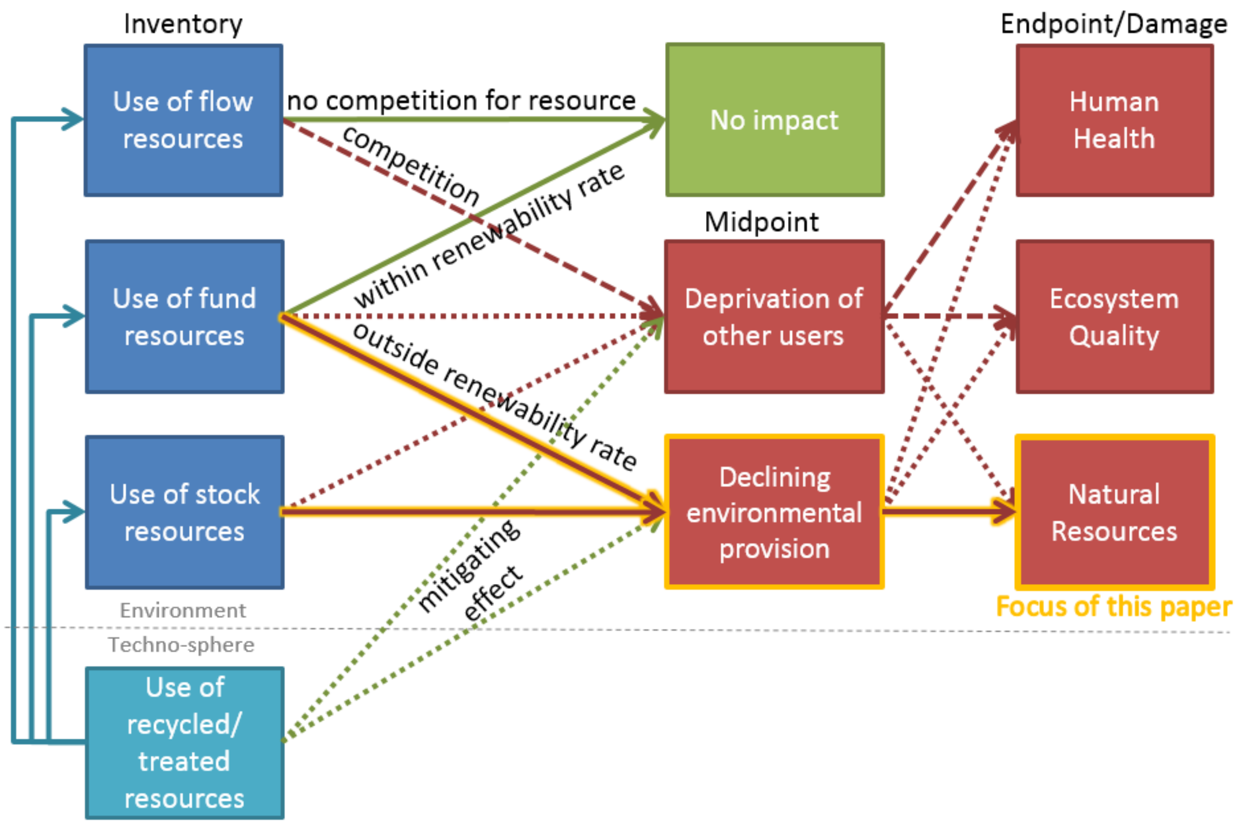

Figure 1 (created with Microsoft Power Point)