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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

89   UNEP-SETAC Life Cycle Initiative, it has been argued that the damage to natural resources consists of "the

90   reduced availability of the corresponding type of resource to future generations" (Jolliet et al. 2004). Several

91   approaches have been proposed to account for this, e.g. depletion rates (use-to-stock and use-to-availability

92   ratios) or increased efforts for future generations to access resources in lower quality deposits. On the other

93   hand, some authors claim that short- and medium-term (from a few years to a few decades) *availability* of

94   mineral resources is mainly constrained by socio-economic factors and it is therefore debatable whether natural

95   resource *availability* should be addressed in an environmental assessment (Drielsma et al. 2016). However,

96   changes in the environment's capacity to provide natural resources is clearly an environmental issue, which

97   should be of concern in an AoP 'Natural Resources'.

98   Although LCIA methods traditionally focused on abiotic natural resource depletion (minerals/metals and fossil

99   fuels) (Weidema et al. 2007), there is no generally accepted impact assessment method (or model) for these

100   natural resource categories and several methods exist concurrently (van der Voet 2013 in Mancini et al. 2013).

101   Methods for other resource categories such as water and soil exist in parallel. In general, no method addressing

102   impacts on natural resources, neither at midpoint nor at endpoint, can be recommended without restrictions (EC-

103   JRC 2011; Hauschild et al. 2013). This paper reviews existing LCIA methods/models addressing natural

104   resources and discusses their conceptual approaches across different natural resource categories. This is an

105   important basis for further method development and moving towards a more consistent assessment within the

106   AoP 'Natural Resources'. This paper is an output of a working group within the task force on crosscutting issues

107   mandated by the UNEP-SETAC Life Cycle Initiative as a part of its flagship activities. It is structured as

108   follows: first, natural resources are defined and categorized for the LCA context; second, existing methods that

109   assess impacts on natural resources are briefly reviewed by resource category; and third, existing approaches are

110   analyzed and discussed across resource categories.

111   2. Definition and categorization of natural resources

112   **Definition of natural resources**

113   From the discussions of the working group, it was concluded that natural resources are of concern in LCA

114   because of their instrumental value to humans. This focus on the instrumental value is consistent with the

115   definition of the new overall LCIA framework of the UNEP-SETAC Life Cycle Initiative (Frischknecht and

116   Jolliet 2016). The working group acknowledges the complexity of defining natural resources and the existence

117 of different definitions (see e.g. WTO 2010; Fischer-Kowalski and Swilling 2011; Dewulf et al. 2015b). The

118 majority of the group agreed on the following definition of natural resources in LCA, which is compatible with

119 the UNEP-SETAC LCIA framework:

120 *Natural resources are material and non-material assets occurring in nature that are at some point in time*

121 *deemed useful for humans.*

122 Natural resources include minerals and metals, air components, fossil fuels, renewable energy sources, water,

123 land and water surface, soil, and biotic natural resources such as wild flora and fauna. Natural resources may be

124 distinguished from (primary) raw materials and (primary) energy carriers, which are the result of transformation

125 of natural resources by the primary production sector through operations such as growing, harvesting, mining,

126 and refining (Dewulf et al. 2015b). The World Trade Organization (WTO), for example, does not make this

127 distinction since most resources require some processing before they can be traded or consumed (WTO 2010).

128 However, the WTO also states that "the line of demarcation between natural resources and other goods will

129 always be somewhat arbitrary" (WTO 2010). The WTO distinguishes natural resources from manufactured

130 products (subject to a *substantial* amount of processing) and agricultural goods (cultivated rather than extracted

131 from the natural environment). Also in the LCA context, biotic resources produced by an industrial production

132 process (such as agricultural crops, livestock, fish from aquaculture, or wood from a plantation) are usually not

133 classified as biotic natural resources (Klinglmair et al. 2014). They are produced with natural resource inputs,

134 such as soil and water, and are considered part of the technosphere. Natural biotic resources (and water, surface,

135 and soil) are natural resources and eco-system components (contributing to ecosystem quality) at the same time.

136 Hence, natural biotic resource (or water, surface, or soil) use may have impacts on various AoP, which must be

137 acknowledged by focusing on the issue in question. For instance, fishing would have an impact on the AoP

138 'Natural Resources' when less fish is available as a food source (overfishing), but it could also impact

139 biodiversity (species richness, composition and/or abundance), which would be assessed in the AoP 'Ecosystem

140 Quality'. Such parallel impacts in various AoPs as a consequence of the same environmental intervention are

141 not new in LCA. For example, a toxic emission may have an impact on aquatic organisms (impacts on AoP

142 'Ecosystem Quality') and also enter the human food chain, e.g. by fish consumption (impacts on AoP 'Human

143 Health'). The term 'natural' indicates that the resource is occurring in nature, untransformed by humans.

144 Anthropogenic deposits such as landfills can also be considered sources for secondary resources or raw

145 materials. However, they are neither addressed as inventory flows nor in LCIA. The resource properties do not

146 necessarily get lost when entering the technosphere, but they may be "occupied or "borrowed" by a user within

147   the product system. If it can be recycled afterwards, additional extraction of natural resources can be avoided.

148   Natural resources can provide space (e.g. land area), substances and materials, or sources of energy. While some

149   definitions of natural resources only consider these source functions, others also include sink functions (Dewulf

150   et al. 2015b), i.e. the absorption of emissions in soil, water, and air. In existing LCIA methods, emissions to

151   environmental compartments are considered and the corresponding impacts on humans and ecosystems are

152   covered by the AoPs 'Human Health' and Ecosystem Quality'.

153   **Categorization of natural resources**

154   Natural resources are often categorized as stock, fund, or flow resources (see e.g. Udo de Haes et al. 2002;

155   Klinglmair et al. 2014) according to their renewability and exhaustibility (Table 1).

156   *Stock resources* are considered to exist as a finite amount and are assumed to be non-renewable (they form and

157   concentrate extremely slowly), and are therefore regarded as exhaustible (i.e. they can be used up). Examples

158   are fossil and mineral resource stocks. Whilst individual chemical elements do not disappear and are not

159   exhaustible, in a strict sense, they can be subject to dissipation such that deposits with some minimum level of

160   concentration (useful to humans) may be finite and therefore exhaustible (Dewulf et al. 2015a). In this sense, the

161   problem with the resource consumption is still a stock resource problem, i.e. a depletion or a dissipation

162   problem.

163   *Fund resources* are renewable, i.e. they are continually supplied or re-concentrated once dissipated, but (at least

164   in some cases) also exhaustible if overused (Udo de Haes et al. 2002). The available amount of a fund resource

165   can either be decreased or increased, depending on the ratio of extraction to the renewal rate. Typical examples

166   are fish or wild animals, but the depletion of water bodies such as the Aral Sea can also be considered a fund

167   resource problem.

168   *Flow resources* are non-exhaustible and have a limited availability at a certain time (Udo de Haes et al. 2002),

169   which means that they have to be used as, when, and where they occur. They can be considered renewable when

170   they re-occur at the same location. Examples are solar radiation or run-off from rivers.

171   How to define the boundaries between stocks, funds, and flows, in particular based on regeneration rates, is still

172   an open question.

173   Special cases are land and water surface areas, which are permanently present and usually constant in the total

174   available amount. They cannot be depleted or dissipated but only occupied and as such are non-exhaustible.

175   This does not fit well into the stock/fund/flow classification and has sometimes been kept a separate category

176   besides abiotic and biotic natural resources that have been categorized into stocks/funds/flows (see e.g. Heijungs

177 et al. 1997; Lindeijer et al. 2002). Nonetheless, competition for area has been considered to be a flow resource

178 problem because surface area (just quantity, disregarding quality) cannot be depleted and hence is not lost for

179 future generations (Lindeijer et al. 2002). The issue with land quality or soil properties may be considered to be

180 a fund resource problem because soil properties can be deteriorated (or remediated) such that soil loses (or

181 increases) its usefulness for a certain purpose.

182

183 <Table 1>

184

185 According to the definitions above, only depletion or dissipation of stock and fund resources imply a damage to

186 the resource as such in its available form. Although there is no agreement on how this damage should be

187 assessed, existing methods mainly relate it to potential consequences for future generations (e.g. reduced

188 availability due to depletion or increased efforts for resource extraction). The use of a flow resource may have

189 impacts on its temporary availability and therefore the impact is the consequences of the increased competition

190 for this resource, rather than any lasting impact on the resource itself.

191 Most existing LCIA methods focus on mineral/metal and fossil fuel natural resources (see Table S1). Water

192 (substance) and land (surface) are generally assessed separately (Klinglmair et al. 2014). Soil can also be

193 assessed as a resource (see e.g. Milà i Canals et al. 2007a; Koellner et al. 2013; Vidal Legaz et al. 2016), and

194 should not be confused with land (surface) use impacts on biodiversity. Table 2 shows a compilation and

195 categorization of natural resources based on Klinglmair et al. (2014), Dewulf et al. (2015a), Goedkoop et al.

196 (2013), and Frischknecht and Büsser Knöpfel (2013). It is specified whether the natural resource consumption

197 potentially causes a stock, fund, or flow resource problem as listed in Table 1. Furthermore, corresponding

198 elementary flows/activities in the *Ecoinvent 2.2* and *3.2* databases (Frischknecht et al. 2007; Ecoinvent 2015)

199 have been added to demonstrate that natural resources in the impact assessment match the resources in the

200 inventory.

201

202 <Table 2>

203

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

230 3. methods relating current natural resource consumption to consequences of future extraction of natural

231   resources (e.g. potential increased energy use or costs)

232 4. methods quantifying consumption of exergy or solar energy

233

234 Method types 1 and 4 can be grouped together as "Resource Accounting Methods" (RAM) (Swart et al. 2015).

235 The fact that RAM do not explicitly link used amounts of resources to changes in their availability or

236 provisioning capacity is perceived by many as a drawback. Type 1 methods are not further discussed here.

237 However, the type 1 indicator Cumulative Energy Demand (CED) can serve as a screening indicator for

238 environmental performance (Huijbregts et al. 2010) and is widely applied in practice. Moreover, type 1

239 indicators, such as Material Input per Service-Unit (MIPS), are widely used to calculate material footprints

240 (Saurat and Ritthoff 2013). Type 4 methods are more comprehensive than CED due to the assessment of the

241 quality of energy and the inclusion of non-energetic resources (Bösch et al. 2007). In this paper, they are

242 referred to as "thermodynamic accounting methods".

243 Type 2 methods are based on use-to-availability ratios. However, there are different estimates for resource

244 availability and the terminology differs between different organizations (e.g. the US Geological Service (USGS)

245 and the Committee for Mineral Reserves International Reporting Standards (CRIRSCO)) (Drielsma et al. 2016).

246 Terms such as "reserves" can therefore be misleading (for a comparison of terms, see Table S2). For example,

247 "Ultimately extractable reserve" (Guinée and Heijungs 1995) and "Extractable global resource" (Drielsma et al.

248 2016) both relate to the amount of crustal content that will ultimately be extractable, which constitutes the

249 resource stock relevant for depletion (Guinée and Heijungs 1995). The often used USGS reserve base on the

250 other hand is not a fixed stock but its size is defined by technical, economic, legal, and other factors and hence

251 can increase or decrease (Drielsma et al. 2016). Accordingly, use-to-availability ratios can increase or decrease

252 over time when using a dynamic size such as the USGS reserve base or reserves for availability. In the case of

253 copper, for example, on a global scale exploration success still outpaces annual production (Northey et al.

254 2014). Furthermore, these dynamic sizes underestimate the availability of less explored minerals and metals

255 when compared to well-explored minerals and metals since more exploration efforts increase reserve estimates.

256 Therefore, these methods do not account for dissipation or depletion of a fixed stock and are here labeled use-to-

257 availability ratios (see Table 3). On the other hand, both the ADP$_{Ultimate Reserves}$ (Guinée and Heijungs 1995; van

258 Oers et al. 2002) and the updated version of the AADP methods (Schneider et al. 2015) are examples of use-to-

259 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

290   relationships between ore grade and energy consumption change within a particular sector or jurisdiction over

291   time. While grade-tonnage relationships have been used to evaluate the physical availability of natural

292   resources, cost-tonnage relationships have been used to account for the economic availability (Vieira et al.

293   2016a). For the period from 2000 to 2013, available data shows increasing costs and declining ore grades with

294   increasing cumulative copper produced although the causal relationship between ore grade decrease and surplus

295   costs is unknown and the authors acknowledge that data over a longer period would be desirable (Vieira et al.

296   2016a). Furthermore, as the example of copper shows, technological advances and economies of scale may

297   offset the higher costs of mining lower ore grades (Crowson 2012). However, the long-run need to use lower ore

298   grades and access more remote and more difficult to process deposits, even if it may not be driven by depletion

299   of high grade deposits (West 2011), will eventually lead to increasing opportunity costs, i.e. what society has to

300   sacrifice to get another unit of a mineral or metal (Tilton and Lagos 2007).

3.2. Water

302   In LCIA, impacts from emissions to water have traditionally been captured by impact categories such as

303   (eco)toxicity, acidification, and eutrophication, which are usually connected to the AoP 'Ecosystem Quality'

304   (Boulay et al. 2014). A general framework connecting water use to other AoP, such as the effects of the

305   depletion of water stock and funds on future generations, has been proposed by Bayart et al. (2010). Several

306   methods have been developed that entirely or partially address the different impact pathways outlined in their

307   framework. A review and analysis of methods is presented in Kounina et al. (2013). Some methods quantify

308   water scarcity/stress based on a use-to-availability ratio (similar to Type 2 methods for abiotic natural resources,

309   see 3.1 and Table 4). However, these methods usually assess a pressure on flow water resources accounting for

310   competition amongst different users and they are not connected to the AoP 'Natural Resources'. Pfister et al.

311   (2009) additionally use a future consequences/surplus energy concept, similar to Type 3 methods above (see

312   3.1).

313   The framework for water use by Kounina et al. (2013) (see also Figure S1) follows the reasoning discussed

314   previously: only depletion of (water) stock and fund resources imply a damage to the resource as such in its

315   available form (as surface or groundwater). Fossil groundwater (no or extremely slow replenishment) is the only

316   water stock resource. Slowly replenishing groundwater bodies or stagnant surface water bodies, such as the Aral

317   Sea, can be considered fund resources, since the available amount of water can either be decreased or increased,

318   depending on the ratio of the extraction to renewal rate. Of all water resources (shown in Table 2), only salt

319   water and rainwater are not considered in impact assessments. Whereas sea water can be considered an

320   unlimited resource, brackish/saline water may be a local stock or fund that could be depleted. Rainwater is one

321   of the resources (e.g. together with solar radiation, wind, or soil) that are acquired through land occupation

322   (Ridoutt and Pfister 2010).

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

3.3. Land and Water Surface

325   Land and water surface are finite and usually (the Aral Sea is an example of an exception) constant in total

326   available amount. They cannot be consumed but only occupied, and they become available again for other uses

327   after occupation. Therefore, they can be considered flow resources. The use of a flow resource may have (local)

328   impacts on the temporary availability of, and therefore the competition (among humans and the environment)

329   for, this resource. Therefore, these impacts have not been connected to the AoP 'Natural Resources', but instead

330   to the AoP 'Ecosystem Quality' by several already existing methods assessing land use impacts on biodiversity

331   (see Table 3). Furthermore, land (and water) surface use can be summed up as in the Recipe method at the

332   midpoint level (Goedkoop et al. 2013), and they can be assessed with thermodynamic accounting methods

333   quantifying consumption of exergy or solar energy (type 4, see 3.1). Finally, the Ecological Footprint method

334   quantifies the area necessary to sustain consumption and activities, e.g. of a nation, expressed in units of world-

335   average biologically productive area (Borucke et al. 2013).

3.4. Soil

337   Soil mass (3D-quantity), its properties, and related soil functions are important in addition to land surface (2D-

338   quantity). Soil is defined as the top layer of the earth's crust formed by mineral particles, organic matter, water,

339   air and living organisms (EC 2015). Soil functions include storing, filtering, cycling and transforming nutrients,

340   substances, and water, biomass production, harboring biodiversity, carbon storage, being a source of raw

341   materials, and being a physical environment for humans. The main threats to soil are erosion, loss of soil organic

342   matter (SOM), compaction, salinization, acidification, contamination, sealing, landslides, flooding,

343   desertification, and soil biodiversity loss (EC 2006; EC 2012; Stoessel et al. 2016). The variety of soil properties

344   and functions and the variety of threats posed to them indicate the complexity of a holistic assessment of

345   impacts on soil and so far no standardized method for a universal assessment of soil-quality impacts has been

346   created (Garrigues et al. 2012; Vidal Legaz et al. 2016). Furthermore, this complexity corresponds to little

347   agreement on the framework level (EC-JRC 2010; Koellner et al. 2013; Alvarenga et al. 2015). The threats to

348   the resource soil can result in a physical loss of soil (e.g. of arable land by erosion) or in a change of properties

349   (e.g. if SOM is lost) (see Figure S2). However, soil mass and properties can also be preserved or even

350   increased/improved, e.g. by good agricultural practice, and hence fulfill the criteria of a fund resource as defined

351   before. As for water resources, the depletion of these soil fund resources implies a damage to the resource as

352   such in its available form.

353   Soil assessment methods and models are listed in Table 3 and Table S5. Some of these methods/models are not

354   operational while others are limited to specific countries (Garrigues et al. 2012; Stoessel et al. 2016). They only

355   address partial impacts relevant for soil degradation (e.g. erosion only) and they do not distinguish between

356   different soil management practices (e.g. tillage or nutrient management) or production standards (e.g. organic

357   or integrated production) (Stoessel et al. 2016). Many of the models have excessive data requirements and are

358   therefore difficult to apply, and none of the methods is made compatible to commonly used existing LCIA

359   methods (Stoessel et al. 2016). Globally, operational models are addressing the following impacts: erosion

360   (Núñez et al. 2013; Saad et al. 2013; Scherer and Pfister 2015), loss of SOM (Milà i Canals et al. 2007b:

361   agriculture and forestry only; Brandão and Milà i Canals 2013), compaction (Garrigues et al. 2013),

362   desertification (Núñez et al. 2010), and salinization (Payen et al. 2016). Acidification and contamination are

363   captured with the impact categories 'Terrestrial Acidification' and 'Terrestrial Eco-toxicity' but these are not

364   connected to the AoP 'Natural Resources'. There are several multi-criteria indicators to assess changes in soil

365   properties (Cowell and Clift 2000; Oberholzer et al. 2006; Beck et al. 2010), whereby the LANCA approach

366   (Beck et al. 2010) has been operationalized and is used in the method of Saad et al. (2013) and recently by

367   LANCA developers themselves (Bos et al. 2016). Furthermore, there are exergy methods accounting for

368   occupation of land and marine surfaces (Alvarenga et al. 2013; Taelman et al. 2014). Núñez et al. (2013) use the

369   surplus energy concept and estimate the solar energy required to generate one gram of soil lost by erosion.

370   Furthermore, Brandão and Milà i Canals (2013) promote the land's long-term ability to produce biomass

371   (referred to as biotic production potential (BPP), calculated based on SOM) as an endpoint in the AoP 'Natural

372   Resources'.

3.5. Biotic Natural Resources

374   Biotic natural resources have not received much attention yet (Finnveden et al. 2009). These resources are living

375   at least until the moment of extraction from the natural environment and include wood, fish, and other terrestrial

376 and aquatic biomass that can be harvested (Klinglmair et al. 2014). Agricultural crops, livestock, fish from

377 aquaculture, or wood from a plantation are usually not classified as biotic natural resources in LCA (Klinglmair

378 et al. 2014) since they are the output of a technical process and are hence already part of the technosphere.

379 Impacts on habitats of biotic natural resources are assessed in the AoP 'Ecosystem Quality'. Impacts on biotic

380 natural resources that are of concern in the AoP 'Natural Resources' are caused by overharvesting, overfishing,

381 and overhunting. Such overuse of biotic natural resources may also affect the natural regeneration rate of these

382 fund resources, leading to feedback mechanisms that may cause their depletion.

383 Aggregating methods considering biotic natural resources are Eco-scarcity, IMPACT 2002+, EPS 2000/2015,

384 LIME/LIME 2, and exergy methods. However, in many cases the only biotic natural resource considered is

385 wood as an energy resource. For instance, the IMPACT 2002+ method applies energy use from wood as a stand-

386 alone indicator, because it is not part of the non-renewable energy indicator (Jolliet et al. 2003). In the Eco-

387 scarcity method, "the energy content of energy resources not used for energy production (feedstock energy, such

388 as when hydrocarbons are used as refrigerants or wood is used in a building), is also assessed with a primary

389 energy factor. However, only the consumed proportion should be assessed" (Frischknecht and Büsser Knöpfel

390 2013). The EPS 2000/2015 method takes a different approach by including the AoP 'Ecosystem Production

391 Capacity', which accounts for the ecosystem capacity to produce crops, wood, fish and meat, and clean water

392 (Steen 1999; Steen 2015). In the LIME/LIME 2 methods, the impacts on forestry, crops, and fishery are linked

393 to the AoP 'Social Assets', and the damages are measured as user costs, in monetary units (Itsubo et al. 2004;

394 Itsubo and Inaba 2012).

395 Net Primary Production (NPP) has been used as proxy for damage assessment in the AoP 'Ecosystem Quality'

396 (e.g. Pfister et al. 2009; Taelman et al. 2016), but also as a resource. For instance, Alvarenga et al. (2015)

397 suggest the NPP deficit, which is the assessment of the decrease of biomass availability due to land use, as an

398 indicator for damage assessment in the AoP 'Natural Resources'. They suggest the surplus cost approach, using

399 algae cultivation in the ocean, as the backup technology (Alvarenga et al. 2015).

400 Methods for overfishing were initially developed within the EU LC-impact project, but these are not yet

401 operational on a global scale (Emanuelsson et al. 2014).

4. Discussion

403 Natural resources have been categorized and grouped in many ways, as many LCIA methods (and underlying

404 models and indicators) have been developed for assessing damages to different natural resources. While there

15

405   seems to be agreement in the scientific community that declining environmental provision of natural resources

406   should be assessed, there is not yet an agreement on which indicator describes this best (e.g. use-to-availability

407   approaches, surplus cost/energy/ore). Furthermore, there is not yet a consensus on whether and how the

408   functionality of a resource should be taken into account.

409   **Figure 1** shows the framework suggested for all resource categories. The depletion or dissipation of stock and

410   fund resources implies a declining environmental provision of natural resources. The use of a flow resource does

411   not imply such a damage, but it may deprive others from using the resource, as a result of competition for it.

412   Competition for natural resources (including competition for stock and fund resources) is an issue that has not

413   yet been explicitly addressed in LCA. However, possible consequences of competition, such as crop failures due

414   to lacking irrigation water, may be assessed as impacts. In the case of water, impacts of deprivation have been

415   linked to the AoPs 'Human Health' and 'Ecosystem Quality' (Pfister et al. 2009) (dashed arrows pathway in

416   **Figure 1**). Another possible consequence of competition is indirect land use change, which is of interest in

417   consequential LCIA (Schmidt et al. 2015). However, so far there is no generally established methodological

418   approach to address competition for flow (or fund and stock) resources in LCIA. Since it is debatable to what

419   degree competition is an environmental problem, it is up to discussion whether and how this should be further

420   developed. The same applies for all other pathways not yet established in LCIA, represented by dotted arrows in

421   **Figure 1**.

422   Another issue not yet consistently addressed throughout existing LCIA methods are impacts on resources by

423   other impact categories, such as the effects of global warming on soil productivity. This issue is partly addressed

424   in the IMPACT 2002+ method, in which global warming is listed as a separate impact category, because it is

425   assumed to impact so-called "life supporting functions" (Jolliet et al. 2003). Similar examples are the LIME

426   methods, in which impacts on biotic production is considered (Itsubo et al. 2004; Itsubo and Inaba 2012).

427

428   <Figure 1>

429

430   Apart from thermodynamic accounting methods, currently there is no all-inclusive method available to assess

431   impacts for all natural resource categories altogether, nor are methods, proposed for different natural resource

432   categories, able to consistently assess these impacts across methods.

433   **Type 2 methods: scarcity and dissipation/depletion**

434 Use-to-availability ratios are concepts that are widely used in LCIA methods. They may account for dissipation

435 or depletion of stock and fund resources and for pressure on flow resources (see **Figure 1**). Concerning minerals

436 and metals, it is especially important to discuss the denominator in the ratio (see section 3.1 and Table 4).

437 Methods using a dynamic size such as the USGS reserves for availability do not account for dissipation or

438 depletion of a fixed stock and might therefore be misleading. However, estimating the geological stock relevant

439 for dissipation or depletion (i.e. the amount of crustal content that will ultimately be extractable) is also bound to

440 large uncertainties because it depends on the future development of extraction technologies. The two approaches

441 taken for estimating fixed stocks are (i) setting the full crustal content as the availability of the resource

442 (although it will never be fully accessible), and (ii) setting the ultimately extractable resource amount as a

443 percentage of crustal content. Both approaches implicitly assume that the ratio between the crustal content and

444 the ultimately extractable amount is equal for all minerals and metals.

445 Withdrawal-to-availability and consumption-to-availability ratios have been used to assess water stress or water

446 scarcity. They usually consider the flow resource surface water. However, where the calculated ratio is larger

447 than one, groundwater bodies (stocks or funds) or large surface water bodies (funds) are being depleted as

448 assessed in the method by Pfister et al. (2009). Another issue concerning water availability (to humans) is

449 whether the demand of ecosystems should be considered, and if so how large this demand is (different methods

450 provide values from 35 to 80%) (Boulay et al. 2015).

451 A special case of a use-to-availability ratio to assess scarcity is the distance-to-target ratio. The Eco-scarcity

452 method is based on this concept using the "current flow" of an environmental pressure (e.g. an emission) and the

453 "critical flow" representing the political target in a weighting step (Frischknecht and Büsser Knöpfel 2013).

454 Efforts to include carrying capacity or planetary boundaries in LCIA have introduced a (distance-to-target)

455 normalization against carrying capacity-based references calculated with scientifically estimated thresholds for

456 different impact categories (Bjørn and Hauschild 2015).

457 Finally, it should be noted that physical availability may not be the dominating factor when referring to

458 environmental impacts. For instance, for minerals/metals and fossil fuels, greenhouse gas emissions and the

459 climate effect these emissions produce may be of more environmental concern than the availability of these

460 resources (Mudd and Ward 2008; McGlade and Ekins 2015).

461 **Type 3 methods: declining quality and consequent future efforts**

462 Stewart and Weidema (2005) defined two key variables when modelling impacts on natural resources: ultimate

463 quality limit and backup technology. The ultimate quality limit is the limit differentiating whether a material is

17

464 reusable with a lower functionality, or rendered unavailable (Stewart and Weidema 2005). Backup technology

465 refers to both the technology applied to recycle a material and the alternative technology applied when reaching

466 the ultimate quality limit, *i.e.* when the material is lost (Stewart and Weidema 2005). Common examples are the

467 desalination of water and the consumption of shale gas and oil sands. It has been discussed whether future

468 efforts (use of backup technologies) of current resource dissipation should be part of the impact assessment or

469 part of the inventory (Finnveden 2005). However, type 3 methods seem to understand these future efforts as a

470 proxy for quantifying the difficulty to access natural resources in the future and hence for quantifying an impact

471 on natural resource provision.

472 The concept of long-term increasing efforts to access natural resources, as a result of declining quality, has been

473 investigated for several natural resource categories. It has first been applied to minerals/metals and fossil fuels.

474 The decision about which deposits of different quality (e.g. ore grade concentration) are extracted (or defined as

475 extractable) depends (among other factors) on production costs. This is the reason why some LCIA methods use

476 increasing future extraction costs as an endpoint unit. Furthermore, it is generally true that more energy is

477 needed to exploit lower grade ores with the same technology. This is the reason why some methods use

478 increasing energy demand for future extraction as an endpoint unit. Technological advances and economies of

479 scale have offset higher costs of mining lower ore grades in the past and assumptions of increased costs and

480 energy consumption of future resource extraction are highly uncertain. However, since LCA is indicating

481 potential impacts for comparison on a common scale, these methods might still be used to account for declining

482 resource quality. Type 3 methods differ in assumptions, e.g. concerning discount rates to calculate future costs.

483 Even within the ReCiPe method for instance, different characterization factors calculated with different discount

484 rates are provided. However, the fundamental principle (declining quality leading to increasing efforts for

485 resource extraction) remains the same. A backup technology approach assessing surplus costs or energy has also

486 been proposed for water (Pfister et al. 2009) and for biotic natural resources (net primary production)

487 (Alvarenga et al. 2015). Some future effort methods for mineral resources avoid a translation into additional

488 costs or energy requirements and account for potentially increasing ore requirements per mineral/metal

489 extracted. This potential future burden is not related to a backup technology that might be used but to physical

490 mass that may have to be dealt with. There are no similar methods like this last subtype of future effort methods

491 for other natural resource categories.

492 **Type 4 methods: thermodynamic accounting**

18

493   Thermodynamic accounting methods or methods quantifying consumption of exergy or solar energy are able to

494   capture the widest range of natural resource categories (see Table 3). As they consider the consumed quantities,

495   they could be helpful in resource efficiency calculations. However, these methods do not link exergy

496   consumption to changes in availability or provisioning capacity of the natural resource (mineral, water, land

497   etc.) that is consumed.

498   **Quality, functionality, recycling, substitutability**

499   The UNEP-SETAC Life Cycle Initiative overall framework acknowledges the instrumental value of natural

500   resources, which also depends on their quality and related functionality. Natural resources and (raw) materials

501   are lost if the required qualities for their functionality are lost (e.g. through dissipation). However, these

502   properties may be restored or even enhanced further through recycling and upcycling efforts. If this is not

503   possible, the material may either be used for other purposes or it is lost. However, even when a material is "lost"

504   to humans, its functionality may be replaced by other materials made from other natural resources.

505   Stewart and Weidema (2005) suggest a conceptual framework focusing on the functionality of natural resources.

506   Methodologically, this approach implies that the quality and functionality of the input and output flows of a

507   production system need to be recorded in the LCI in order to assess whether a natural resource is lost at its

508   functionality level (Stewart and Weidema 2005). This issue has, for example, been addressed for water where

509   water qualities needed for different uses were categorized (Boulay et al. 2011; Bayart et al. 2014).

510   The use of secondary/recycled and treated materials can lower the demand for natural resources (**Figure 1**). This

511   use is typically modeled in the inventory phase. However, whether the use of recycled materials or the output of

512   recyclable materials should get the environmental credits depends on the allocation modeling choice

513   (Frischknecht 2010). Existing methods only roughly consider material quality, if at all, assuming "functional

514   equivalence" of the substituted material. By contrast, the exergy efficiency approach explicitly considers both

515   the quality of input and output materials. However, exergy might not be the only relevant quality criteria. For a

516   proper inclusion of such criteria, metrics for quality and functionality would need to be defined and recorded in

517   life cycle inventories.

518   Another aspect leading to the reduction of resource availability by reducing resource quality is the impact on

519   natural resources caused by emissions, such as the pollution of groundwater bodies.

520   **Research needs**

521 In order to further improve impact assessment in the AoP 'Natural Resources', the discussion on whether

522 resources should be a part of environmental LCA should be replaced by debates about 1) how environmental

523 issues (we suggest natural provisioning capacity) can best be assessed and 2) how other aspects (e.g. short-term

524 (market) availability) can be assessed in a complementary way. The integration of different resource categories

525 into an AoP 'Natural Resources' involves some major challenges. While the distinction of stocks, funds, and

526 flows is helpful, these categories still have to be better defined based on regeneration rates. Furthermore, a

527 deeper discussion on whether and how impacts from competition for resources should be integrated in LCIA is

528 needed. In addition, if ecosystem-relevant resources (land, soil, water, and biotic natural resources) and others

529 (minerals/metals and fossil fuels) are to be assessed with a common unit within the same AoP, impact modelling

530 has to be adapted.

5. Conclusions

531

532 The environment's capacity to provide natural resources of a useful quality with instrumental value to humans is

533 what should be protected under the AoP 'Natural Resources'. However, we know neither how technological

534 developments influence future accessibility nor what the needs of future generations are. While it is true that

535 because of the instrumental value the issue of concern is actually the functionality of a natural resource,

536 information on the functionality and substitutability of resources is mostly incomplete, especially with regard to

537 the future consumption of resources. Therefore, for the time being, it makes sense to devote time to the

538 assessment of environmental provisioning capacity of natural resources. Thereby, the concept of

539 stock/fund/flow resources is helpful, across natural resource categories, in identifying whether

540 depletion/dissipation (of stocks and funds) or competition (for flows) is the main relevant issue. The former has

541 been of primary interest for the AoP 'Natural Resources' and accordingly the damage has been described as a

542 reduced availability of, or as a more onerous access to, natural resources in the future (see e.g. Udo de Haes et

543 al. 2002; Jolliet et al. 2004; Bayart et al. 2010). Two main types of methods/models have been used to account

544 for this: 1) use-to-stock/availability methods focus mainly on the quantitative availability; 2) future effort

545 methods focus more on resource quality and corresponding efforts to make the resource usable. Both method

546 types have been used for several resource categories, but no set of methods is yet available to consistently

547 capture all natural resource categories, except for exergy and solar energy methods. However, the fact that

548 exergy and solar energy methods do not explicitly link exergy consumption to changes in availability or

549 provisioning capacity of the natural resource (mineral, water, land etc.) that is consumed may be considered to

550 be a drawback.

551 An LCIA method - or a set of methods - that consistently addresses all natural resource categories is needed in

552 order to assess the AoP 'Natural Resources' in a comprehensive manner and to avoid burden shifting from

553 impacts on one resource to impacts on another resource. This paper reviewed existing LCIA methods/models

554 addressing natural resources and discussed their conceptual approaches across different natural resource

555 categories, which is an important prerequisite for a step in this direction.

556

563

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798   **7. Tables**

799   **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

800

801

802 **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

803 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

34

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

809 **Table 4** Metal/mineral deposits used for use-to-availability ratios according to terminology used by the CML-IA

810 method (Guinée and Heijungs 1995), by the US Geological Service (USGS), and by the Committee for Mineral

811 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

812

813 **8. Figure Captions**

814 **Figure 1** Impact pathways from use of different natural resource types to areas of protection; "competition for

815 resource" means that there is not enough provided to match the demand of all users (including the environment);

816 "within renewability rate" means that the fund resource is used in way that it is not depleted in the long term and

817 that there is no competition; the dashed arrow shows the pathway of how indirect effects of competition have

818 been assessed; the dotted arrows show pathways not yet established in LCIA methods (it is up to discussion

819 whether and how they should be established)
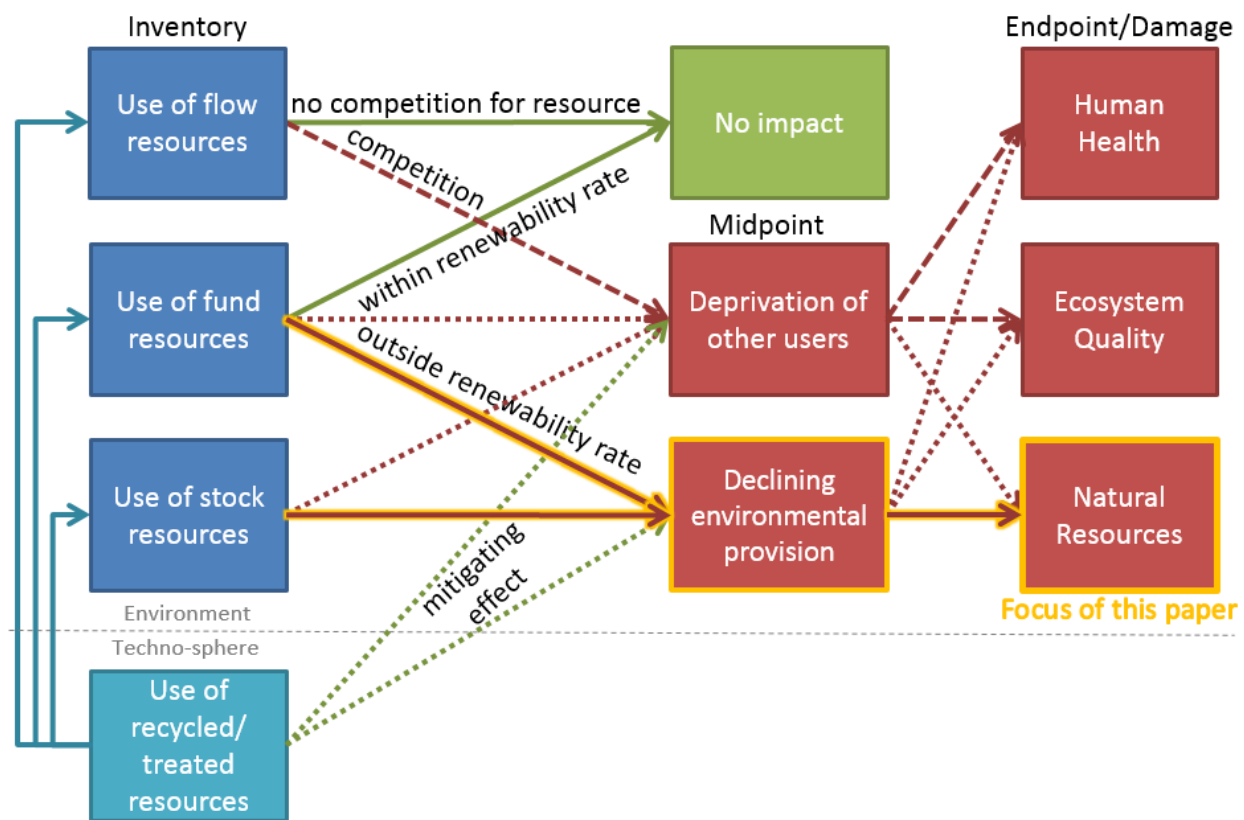
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9. Figures

823   Figure 1 (created with Microsoft Power Point)

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

SUPPLEMENTARY MATERIAL

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Tables

Figures

Abbreviations

AoP   Area of Protection
LCA   Life Cycle Assessment
LCIA   Life Cycle Impact Assessment

Areas of Protection in current LCIA methods

Most LCIA methods currently associate the final impact pathway damages to the three AoPs 'Human Health', 'Ecosystem Quality', and 'Natural Resources' (Table S1). Exceptions are the EPS 2000, the LIME, and the Stepwise method:

The EPS 2000 method has an additional AoP called "Ecosystem Production Capacity", assessing the effect of decreased yields of crop, fish and meat, wood, and freshwater associated with the production capacity of ecosystems (Steen 1999). This includes biotic resources produced by an industrial production process, which – as discussed before – in the LCA context are usually not considered to be natural resources.

The IMPACT 2002+ method models impacts of climate change on life supporting functions as a separate AoP (Jolliet et al. 2003). This has been kept for the IMPACT World+ method and water impacts is another optional reporting category (Impact World+ 2016).

The LIME/LIME 2 method is organized in four AoP grouped in two categories: 'Human Life/Human Society' includes the AoPs 'Human Health' and 'Social Assets'; 'Ecosystem' includes the AoPs 'Biodiversity' and 'Primary Production' (of ecosystems) (Itsubo et al. 2004; Itsubo and Inaba 2012). Social assets cover the impact on agricultural products, forests, marine products, mineral resources, and fossil fuels measured in monetary units (Itsubo and Inaba 2012). It could be considered the equivalent to the AoP "Natural Resources" in other methods although – as in the AoP "Ecosystem Production Capacity" of the EPS 2000 method – biotic resources produced by an industrial production process are included.

The Stepwise method does not only consider natural resources but also man-made biotic resources and human resources: "human resources are the available labor force with its different productive abilities, biotic resources are the natural or manipulated biota with its inherent or artificially enhanced abilities to grow and propagate, and abiotic resources are the natural or manufactured raw materials or catalysts for human or biotic production" (Weidema et al. 2007). Accordingly, impacts on resource productivity include the impacts on human health, which indirectly have an impact on human productivity, and the impacts on agricultural production from global warming and photochemical ozone (Weidema et al. 2007).

Table S1: Areas of Protection (AoP) in various LCIA methods; despite different names, the resource-AoPs are usually restricted to mineral and fossil fuels

| Method | AoPs | | | | Natural Resources | Connected Impact Categories |
	Humans	Ecosystem	Natural Resources	Other	Endpoint unit	
Eco-Indicator 99 (Goedkoop and Spriensma 2001)	Human Health	Ecosystem Quality	Mineral and Fossil Resources	-	MJ surplus energy	- Resource concentration (Minerals & Fossils)
EPS 2000 (Steen 1999)	Human Health	Biodiversity	Abiotic Resources	Ecosystem Production Capacity		
ILCD (EC-JRC 2012)					Cost increase in $ (from ReCiPe 2008)	Resource depletion – mineral, fossils and renewables
IMPACT 2002+ (Jolliet et al. 2003)	Human Health	Ecosystem Quality	Resources	Climate change (Impact on life support functions)	MJ surplus energy	- Non-renewable energy - Mineral extraction
LC-Impact (http://www.lc-impact.eu/about-lc-impact)	Human Health	Ecosystem Quality	Resources		kg_{ore}/kg_x	- Mineral resources depletion
LIME2 (Itsubo and Inaba 2012)	*Human Society:* Human Health	*Ecosystem:* Biodiversity	*Human Life:* Social Assets	*Ecosystem:* Primary Production	Social cost: Yen	- Farm products - Land - Marine products - Energy - User cost (of mineral resource consumption)
ReCiPe (2008) (Goedkoop et al. 2013)	Human Health	Ecosystems	Resources	-	Cost increase in $	- Resource concentration (Minerals & Fossils)
Stepwise (2006) (Weidema et al. 2007)	Human Well-Being	Ecosystems	*Resource productivity:* - Natural resources	*Resource productivity:* - Human resources - Biotic resources	€$_{2003}$	- Non-renewable energy - Mineral extraction
TRACI 2					MJ surplus energy (from Eco-Indicator 99)	- Resource concentration (Fossils)

Table S2: Definitions of different resource deposits

	CML-IA (Guinée and Heijungs 1995)	USGS	Definition	CRIRSCO/ (Drielsma et al. 2016)	Definition
Stable estimates	Ultimate reserves		"Ultimate reserves are estimated by multiplying the average concentrations of chemical elements in the earth's crust by the mass of the crust. […] ultimate reserves cannot be extracted completely, as some locations will be inaccessible […]" (Guinée and Heijungs 1995)	Crustal content	"Crustal content represents the total amount of an element in a given layer of the Earth's crust." (Drielsma et al. 2016)
	Ultimately extractable reserves		"Those reserves that can ultimately be technically extracted may be termed the ultimately extractable reserves. Between the ultimate reserve and the ultimately extractable reserve there is likely to be a substantial difference. **In terms of depletion, the ultimately extractable reserve is the only relevant reserve parameter.** However, data on this type of reserve are unavailable and will never be exactly known because of their dependence on future technological developments." (Guinée and Heijungs 1995)	Extractable global resource	"Extractable global resource is the amount of crustal content that will ultimately prove extractable by humans." (Drielsma et al. 2016)
Dynamic estimates		Resources	"A concentration of identified naturally occurring mineral in or on the earth's crust in such form and amount that economic extraction is currently or potentially feasible. However resource estimates are based on current knowledge and are continually revised in the context of technological changes and shifts in prices and costs." (Schneider et al. 2015)		
	Reserve base	Reserve base	"The reserve base is that part of an identified resource that meets specified minimum physical and chemical criteria related to current mining practice. It encompasses that fraction of the resources with a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics." (Guinée and Heijungs 1995)	Mineral resource	"Mineral resource is a concentration or occurrence of solid material of economic interest in or on the Earth's crust in such form, grade or quality, and quantity that there are reasonable prospects for eventual economic extraction." (Drielsma et al. 2016)
	Economic reserves	Reserves	"The economic reserve is that part of the reserve base that can be economically extracted at the time of determination." (Guinée and Heijungs 1995)	Mineral reserve	"Mineral reserve is the economically mineable part of a measured and/or indicated mineral resource." (Drielsma et al. 2016)

Abbreviations: CML: Centre of Environmental Science, Leiden University; IA: Impact Assessment; CRIRSCO: Committee for Mineral Reserves International Reporting Standards; USGS: United States Geological Service

Table S3: Basic concepts of abiotic resources in LCIA methods; based on Rørbech et al. (2014) and literature indicated in Table 3

Method	Model concept	Unit
Type 2a: Use-to-stock		
CML-IA: ADP$_{Ultimate\ Reserve}$	Use-to-stock ratios based on present production and ultimate reserves in the upper crust of the earth	kg Sb-eq
AADP$_{Update}$	Use-to-stock ratios based on present extraction and the extractable geologic stock + the anthropogenic stock: the extractable geologic stock is estimated on the basis of the resources in the upper continental crust	kg Sb-eq
Type 2b: Use-to-availability		
CML-IA: ADP$_{Reserve\ Base}$/ILCD	Use-to-stock ratios based on present production and the reserve base (resources that have a reasonable potential for becoming economically and technically available)	kg Sb-eq
CML-IA: ADP$_{(Economic)\ Reserve}$	Use-to-stock ratios based on present production and part of the reserve base which could be economically extracted or produced at the time of determination	kg Sb-eq
AADP	Use-to-availability ratios based on present extraction and the USGS "Resources" (see Table S2) + the anthropogenic stock	kg Sb-eq
LIME & LIME 2	Midpoint: Fossil fuels and Mineral resources	MJ/kg Sb-eq
EDIP 97 & 2003	Economic availability based on economic reserves per person	Person Reserves
Eco-scarcity	Based on ratio of current flow (pollutant load/resource extraction) and critical flow, which is determined by political targets	-
Type 3: Future consequences		
Eco-Indicator 99	Surplus energy representing assumed additional energy requirements for extraction and processing of low grade deposits in the future	MJ
IMPACT 2002+	Surplus energy representing assumed additional energy requirements in future, similar to EI99, with the addition of including the extractable energy content of resources used destructively (fossils and uranium) to the surplus energy of these	MJ
TRACI & TRACI 2	Based on Eco-indicator 99	MJ
Stepwise	Difference between the current energy requirement for extraction and an assumed future energy requirement for extraction from lower grade ores	EUR$_{2003}$
EPS 2000	Future extraction costs related to mining of average earth crust composition with existing technologies, but using renewable energy sources only	ELU
ReCiPe	Marginal increase in future extraction costs relative to current extraction costs (assumed that future ore concentrations decline when cumulative production increases)	$
LIME & LIME 2	Endpoint: User cost (AoP Human Life/Society)	Yen
ORI	Ore requirement indicator: present (i.e. current observed) annual change in ore requirements per kg of metal content	kg/year
SOP/LC-Impact	Surplus Ore Potential: assumed extra amount of ore produced in the future per unit of mineral extracted based on cumulative grade-tonnage relationships	kg$_{ore}$/kg$_x$
SCP	Surplus Cost Potential: assumed surplus cost in the future per unit of mineral extracted based on cumulative grade-tonnage relationships	USD$_{2013}$/ kg$_x$
Type 4: Advanced accounting/Thermodynamic losses		
CExD	Cumulative Exergy Demand: total removal of exergy from nature embedded in processed material (including slags and tailing), as exergy difference between the material and a defined reference state in the natural environment, to society	MJ$_{ex}$-eq
CEENE	Cumulative Exergy Extraction from the Natural Environment: total extraction of exergy from nature embedded in target resources, as the exergy difference between a resource and a defined reference state in the natural environment, to society	MJ$_{ex}$-eq
SED	Solar Energy Demand: total direct and indirect solar energy requirements needed to provide a product or service	MJ$_{se}$-eq

Abbreviations: ADP: Abiotic Depletion Potential, AADP: Anthropogenic stock extended Abiotic Depletion Potential, CEENE: Cumulative Exergy Extraction from the Natural Environment, CExD: Cumulative Exergy Demand, ELU: environmental load unit, ORI: Ore Requirement Indicator, SED: Solar Energy Demand, SOP: Surplus Ore Potential
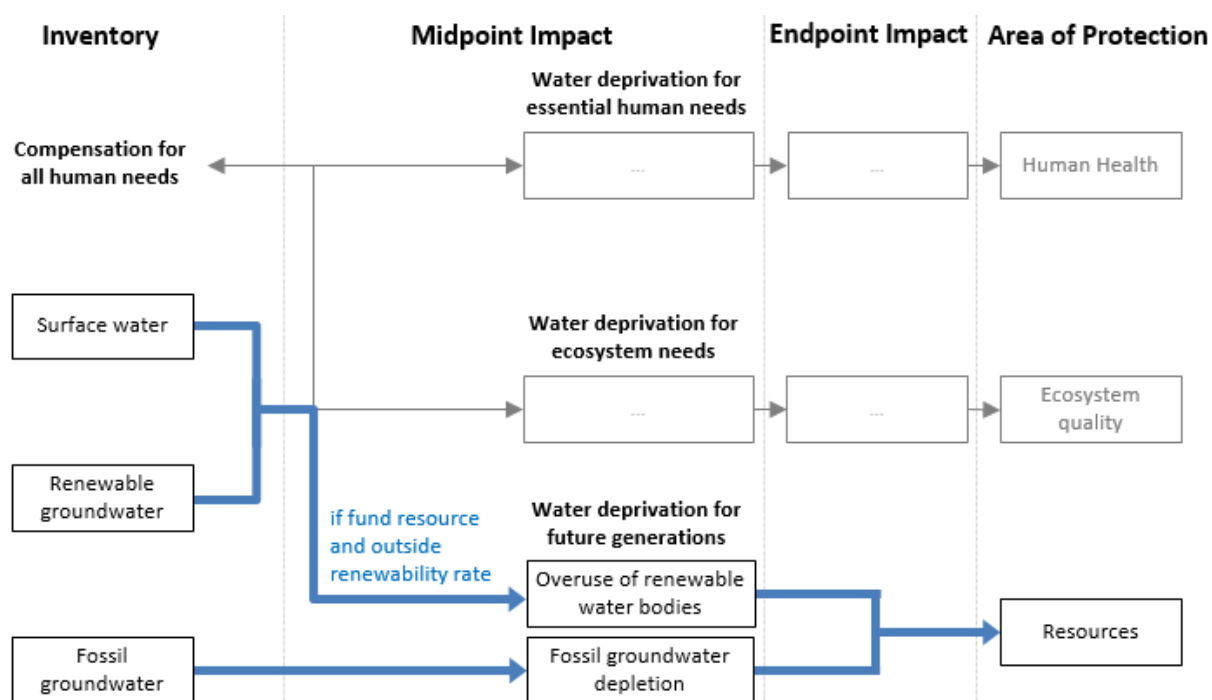
Figure S1: Cause-effect chains from the (water) inventory to the AoP according to Kounina et al. (2013)

Table S4: Methods and underlying models addressing freshwater use at midpoint and at endpoint for the AoP 'Natural Resources'; based on Kounina et al. (2013), water methods available in SimaPro 8, and literature indicated

Method	Model concept	Unit
Thermodynamic accounting/Exergy		
(Bösch et al. 2007)	Potential exergy is applied on potential energy in water used to run a hydroelectric plant	MJ/m^3
	The chemical exergy value for water from Szargut (2005) was attributed to freshwater. Seawater is a reference species and does not feature exergy.	MJ/MJ
Midpoint		
Eco-scarcity (Frischknecht and Büsser Knöpfel 2013)	Based on withdrawals to availability	unitless: m^3 (unavailable to other users)/ m^3 (used)
WSI (Pfister et al. 2009)	Based on withdrawals to availability (WaterGap)	unitless: m^3 (unavailable to other users)/ m^3 (used)
WDI (Berger et al. 2014)	Based on withdrawals to availability (WaterGap)	unitless: m^3 (unavailable to other users)/ m^3 (used)
WFN Water Scarcity (Hoekstra et al. 2012)	Fraction between consumed (referred to as blue water footprint) and available water (all runoff water, of which 80% is subtracted to account for environmental water needs)	unitless: m^3 (unavailable to other users)/ m^3 (used)
(Boulay et al. 2011)	Stress (α) based on CU/Q90 (WaterGap) for different sources and qualities (categories i): $\sum_i(\alpha_i \cdot V_{i,in}) - \sum_i(\alpha_i \cdot V_{i,out})$ With and without ("simplified") inclusion of quality	H$_2$O equivalent
WII (Bayart et al. 2014)	Quality index (**not available at global level**, focused on targets that should be met to ensure good ecological status of natural water bodies) combined with WSI $\sum_i(W_i \cdot Q_{W_i} \cdot WSI_i) - \sum_j(R_j \cdot Q_{R_j} \cdot WSI_j)$	m^3
(Milà i Canals et al. 2009)	Specifically for resources, ADP (CML) **no regionalized characterization** Surplus energy proposed with desalination as backup technology	Sb-equivalents
Regulation and Quality		
FWRP & WPP (Saad et al. 2013)	Based on the LANCA tool (see Table S5) FreshWater Regulation Potential (FWRP): groundwater recharge potential Water Purification Potential (WPP): physiochemical filtration potential and mechanical filtration potential Further impact in (Saad et al. 2013): Erosion Regulation Potential	mm year^{-1} cmol$_c$ kg$_{soil}$$^{-1}$ cm day^{-1}
Endpoint resources		
Water Depletion (Pfister et al. 2009)	Fraction of water depleted per water amount used (WaterGap)	unitless: m^3 (depleted)/m^3 (used)
(Pfister et al. 2009)	Surplus energy with desalination as ultimate backup technology	MJ

Land use change

e.g. agricultural inputs
Fertilizer	Herbicides
Pesticides	Heavy Metals
Water	Salts
Machinery	...

Land use (occupation)

Other impact categories

Changes to soil
(and flora and fauna but not listed here)

Impacts from prevention of potential/natural state of flora and fauna (soil neglected)

Impacts on soil

Access loss

Mass loss

Change of properties

Physical	Physical	Physical	Chemical	Biological
Sealing	Erosion	Compaction	Salinization	Change in soil biodiversity
Flooding	Landslides	Change in SOM	Acidification	
		Change in water content	Contamination	
		Desertification	Change in nutrient content	

Impacts on soil functions

Changes in...

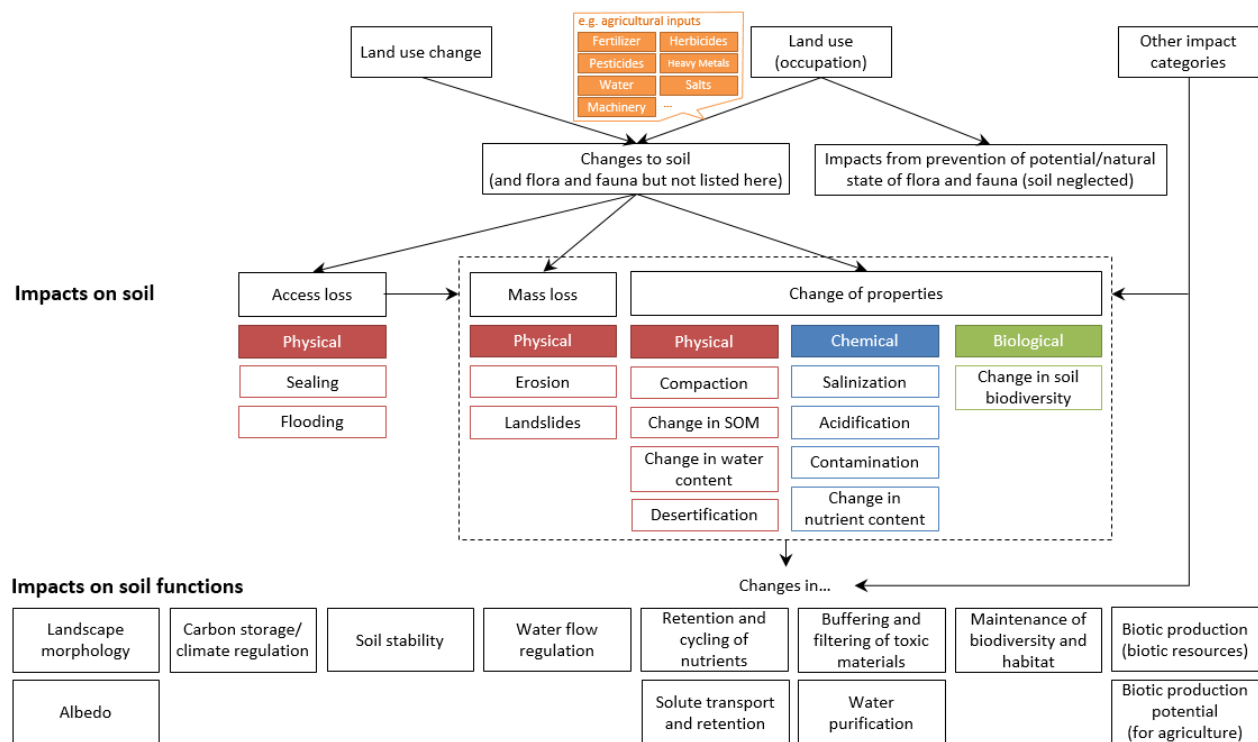| Landscape morphology	Carbon storage/ climate regulation	Soil stability	Water flow regulation	Retention and cycling of nutrients	Buffering and filtering of toxic materials	Maintenance of biodiversity and habitat	Biotic production (biotic resources)
Albedo				Solute transport and retention	Water purification		Biotic production potential (for agriculture)

Figure S2: Impacts on soil and soil functions; own graphic based on (Cowell and Clift 2000), (Garrigues et al. 2012), (Koellner et al. 2013), (Núñez et al. 2013), and (Stoessel et al. 2016)

Table S5: Methods and underlying models addressing impacts from land use on soil as a natural resource; based on Garrigues et al. (2012), (Stoessel et al. 2016), and literature indicated

Method	Model concept	Unit
Land stress		
Land Stress Index (Pfister et al. 2011)	The local NPP of the natural reference vegetation is divided by a global maximal NPP as indicator for land quality No impact on soil as a resource assessed	unitless
Erosion and/or soil fertility		
Achten et al. (2009)	Midpoint: soil fertility (cation exchange capacity (CEC) and base saturation (BS) of the topsoil) and soil structure (SOM of the topsoil and soil compaction) Endpoint: Ecosystem Functional Quality and Ecosystem Structural Quality **Practical application seems complicated**	
Erosion (Núñez et al. 2013)	Land occupation only; surplus energy concept: combines the inventory flow soil loss (based on USLE) with the local available soil reserves and the solar energy factor of soil (around 24 MJ of solar energy is required to generate a gram of soil lost by erosion)	$MJ_{se} \, m^2 \, year^{-1}$
ERP (Saad et al. 2013)	Based on LANCA (see below) Erosion Regulation Potential (ERP): measured in tons of soil eroded per hectare per year, representing the capacity of a land surface to resist water erosion Further impacts in (Saad et al. 2013): Freshwater regulation potential Water purification potential	$t \, ha^{-1} \, year^{-1}$
P-loss due to erosion (Scherer and Pfister 2015)	Method developed for phosphorus loss; includes soil loss due to erosion based on USLE and loss of P (fertility) due to this erosion	$g \, P \, m^{-2} \, year^{-1}$
Loss of Soil Organic Carbon/Matter (SOC/SOM)		
SOM (Milà i Canals et al. 2007b)	SOM as sole indicator of soil quality Only for application in agriculture and forestry; impacts not directly involving SOM, such as acidification and salinization, are excluded. SOM does not influence erosion (probably the most important impact globally), via structural aggregate stability, enough to represent it fully	Impact: Mg C year
SOC/BPP (Brandão and Milà i Canals 2013)	SOC (constant conversion from/to SOM) as indicator of soil quality and its long-term ability to produce biomass (Biotic Production Potential BPP)	CF_{trans}: kg C year m^{-2} CF_{occ}: kg C year $m^{-2} \, year^{-1}$
Compaction		
(Garrigues et al. 2013)	Loss of pore volume due to use of agricultural machines	$m^3 \, ha^{-1} \, crop^{-1}$
(Stoessel et al. 2016)	Yield loss due to compaction (caused by agricultural machines)	% yield loss
Salinization		
(Feitz and Lundie 2002)	Soil salinization from irrigation practices Based on the relationship between the sodium adsorption ratio (SAR) and the electrolyte concentration (EC) **Model has to be adapted to particular sites**	

Leske and Buckley (2004)	Total salinity potential for different compartments (atmosphere, surface water, natural surfaces, and agricultural surfaces) **Relevant for South African conditions**	
Desertification		
Desertification (Núñez et al. 2010)	Considers aridity, water erosion, aquifer overexploitation, and fire risk	dimensionless
Multi-criteria indicators		
(Cowell and Clift 2000)	Soil quantity and quality, many factors discussed; three impact categories: erosion, change in organic matter, compaction **not operational**	
LANCA (Beck et al. 2010) (Bos et al. 2016)	Based on methods of Baitz (2002) and the framework of (Milà i Canals et al. 2007a) Indicator values are calculated outside the LCA software site-specifically and then included into the LCA software in form of indicator value flows for practical reasons If specific data is not available the tool provides data on country-level	
SALCA-SQ Oberholzer et al. (2006)	Nine indicators **High data requirement** **Calibrated for Swiss farms only**	
Thermodynamic accounting/Exergy		
(Wagendorp et al. 2006)	Solar Exergy Dissipation (SED) **not operational**	
(Alvarenga et al. 2013)	Biomass (NPP) and area occupation	$CF_{natural}$: MJ_{ex} MJ^{-1} $CF_{human-made}$: MJ_{ex} m^{-2} $year^{-1}$
(Taelman et al. 2014)	Occupation of the marine environment	MJ_{ex} m^{-2} $year^{-1}$

Abbreviations: BPP: Biotic Production Potential; NPP: Net Primary Production; occ: Occupation; SOC: Soil Organic Carbon; SOM: Soil Organic Matter; trans: transformation; USLE: Universal Soil Loss Equation

Table S6: Methods and underlying models addressing biotic natural resources

Method	Model concept	Unit
Fish		
(Emanuelsson et al. 2014)	Lost Potential Yield (LPY) Units of lost yield per current yield from biomass stock x during year y averaged over a time period T	unitless (yield/yield)
	Overfishing through fishing mortality (OF) Ratio of actual yield (fishing mortality) to maximum sustainable yield minus 1	unitless (kg/kg)
	Overfishedness of Biomass (OB) Ratio of optimal biomass size (size of the spawning stock at maximum sustainable yield) to actual biomass size minus 1.	unitless (size/size)
(Langlois et al. 2014)	Species level Ratio of fished mass to maximum sustainable yield (per year) resulting in a maximum potential regeneration time in years (extended formula for overexploitation)	years
	Ecosystem level Ratio of extracted organic matter (C) to Net Primary Productivity in tonnes of organic C (per year) resulting in the time in years required to regenerate the amount of biomass removed from the sea at the ecosystem level	years
HANPP		
(Alvarenga et al. 2015)	Midpoint CF = $HANPP_{LUC}$ = Natural potential NPP - Actual NPP	kg dry matter m^{-2} year^{-1}
	Endpoint Backup technology of producing seaweed at 14.50 $ per kg dry matter: CF = $HANPP_{LUC}$ x 14.50	$ m^{-2} year^{-1}

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