



HAL
open science

Preparing the ground for an operational handling of long-term emissions in LCA

I. Bakas, M.Z. Hauschild, T.F. Astrup, R.K. Rosenbaum

► **To cite this version:**

I. Bakas, M.Z. Hauschild, T.F. Astrup, R.K. Rosenbaum. Preparing the ground for an operational handling of long-term emissions in LCA. *International Journal of Life Cycle Assessment*, 2015, 20 (10), pp.1444-1455. 10.1007/s11367-015-0941-4 . hal-01360586

HAL Id: hal-01360586

<https://hal.science/hal-01360586>

Submitted on 6 Sep 2016

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Preparing the ground for an operational handling of long-term emissions in LCA**

2 *Ioannis Bakas^{*1}, Michael Z. Hauschild¹, Thomas F. Astrup², Ralph K. Rosenbaum³*

3 ¹ Division for Quantitative Sustainability Assessment, Department of Management Engineering, Technical
4 University of Denmark Kgs. Lyngby, DK-2800

5 ² Department of Environmental Engineering, Technical University of Denmark, Kgs. Lyngby, DK-2800

6 ³ Irstea, UMR ITAP, ELSA-PACT – Industrial Chair for Environmental and Social Sustainability Assessment, 361
7 rue Jean-François Breton, BP 5095, F-34196 Montpellier Cedex 5, France

8 **KEYWORDS:** LCA, landfill, heavy metals, long-term, toxicity.

9 **ABSTRACT**

10 *Purpose.* Currently, there is no meaningful methodology for the estimation of environmental impacts from long-
11 term heavy metal emissions in a Life Cycle Assessment (LCA) context, when an assessment of landfill and mining
12 technologies is performed. In this paper, the aim is to investigate the main issues hindering the standardization of a
13 methodology to account for potential impacts from long-term metal emissions, and to describe the characteristics of
14 a robust framework for an operational impact assessment methodology.

15 *Methods.* In order to demonstrate the issues around potential impacts from long-term emissions in LCA and derive a
16 scientific basis for developing an adequate LCA methodology to address these impacts, a two-part review on metal
17 long-term emissions is performed that a) identifies a suitable time-dependent Life Cycle Inventory (LCI) while
18 underlining the problems in existing emission prediction attempts and b) describes the existing LCA approaches for
19 accounting for toxic potential impacts from these emissions, while explaining the reasons that the identified
20 proposals have not been adopted from the LCA community. These approaches are then compared upon the basis of a
21 common LCI and their differences are highlighted.

* e-mail: ioba@dtu.dk

22 *Results.* A suitable dynamic LCI is identified for landfill emissions, which calculates Ni, Zn, Cd and Pb emissions as
23 a function of time, based on assumed developments of the leachate pH. The results of the application of the different
24 impact assessment methods on that LCI differ by up to 8 orders of magnitude. Therefore, the decision- making
25 process supported by an LCA becomes very confusing. None of the approaches consider future changes in the
26 receiving environment and are not accompanied with any uncertainty considerations.

27 *Conclusions.* In order to move towards a robust environmental assessment of long-term emissions, it is necessary to
28 (i) represent future potential impacts more accurately by estimating time dependent CFs corresponding to changing
29 environmental conditions, (ii) develop more robust estimations by addressing uncertainty and (iii) refer to actual
30 potential impacts, by taking into account the current and future background concentrations.

31 **1 INTRODUCTION**

32 Life Cycle Assessment (LCA) is a decision-support tool aiming at assessing the environmental impacts associated
33 with products or systems (ISO 2006a; ISO 2006b). An important element of LCA is the quantification of emissions,
34 representing an environmental exchange between the product or system and the ecosphere, and the subsequent
35 characterization of the emissions into potential environmental impacts by applying characterization factors (CFs) to
36 the emissions. LCA is widely used in decision-making processes in waste management by assessing integrated
37 waste management systems or comparing different alternatives for treatment of waste (Laurent et al. 2013a; Laurent
38 et al. 2013b). Contrary to product LCA, waste LCA focuses only on the end-of-life stage of products' life cycles. In
39 waste LCA, the technologies involved are relatively limited (corresponding to a chain of waste treatment facilities).
40 The main direct emissions are thus typically caused by a few installations, the location of which is easier to identify
41 as well as the conditions of the receiving environment. This implies that a more site-specific approach is possible,
42 taking into account the local conditions in contrast to the typical situation for product LCAs. A site-specific
43 assessment is also highly relevant in the case of landfills, where the most important leachate impacts are expected to
44 be on a local scale (i.e. within a few km²).

45 Landfilling of waste (from e.g. households, industrial sites, institutions, construction and demolition sites,
46 etc.) constitutes a predominant waste treatment technology globally. However, landfill leachate poses an important
47 environmental concern. The leachate composition has been well investigated for many types of landfills and its
48 heavy metal content comprises one of the major environmental pollutants in waste management (Christensen et al.

49 2001). Besides toxicity, a problematic property of metals is their environmental persistence, which is practically
50 infinite and thus far superior to any organic chemical. In an LCA context, the toxicity potentials of heavy metal
51 emissions have hence been estimated as relatively high compared to other compounds (Huijbregts et al. 2000).
52 Given the high toxic potential, an accurate representation of potential impacts from landfill metal leaching in LCA is
53 essential to ensure the credibility of the tool in assisting informed decision-making, neither ignoring nor
54 overestimating their importance.

55 When trying to estimate the impacts from landfilling in an LCA context, an important characteristic of
56 landfill metal emissions is the very long time horizon of thousands or even hundred thousands of years over which
57 their release takes place in contrast to the other processes in the system which typically emit within minutes to days.
58 The widely used Ecoinvent inventory database defines long-term metal emissions as occurring after 100 years until
59 60000 years from now (“until the next plateau-covering glacial period [in Switzerland] is estimated”) (Hischier et al.
60 2010). During this period small amounts of leachate or run-off containing pollutants (especially heavy metals) are
61 emitted from the landfill to the surrounding soil, aquifer, and eventually the surface water.

62 Apart from leachate from landfills of municipal, inert or hazardous waste, long-term heavy metal emissions
63 can be found in the tailings from mining operations leading to significant environmental burdens (Stüben et al.
64 2001) that are not properly addressed in LCA mainly due to the lack of reliable data (Althaus and Classen 2005) and
65 an appropriate impact assessment methodology. This problem has been underlined and investigated through a
66 sensitivity study that showed the strong dependence of LCA results from mine tailing management on the choice of
67 time frame (Reid et al. 2009). Also the management of radioactive waste can cause long-term leaching of metals
68 (Singh and Hendry 2012), but due to the special properties of radioactive waste, this source of heavy metal
69 emissions is not investigated in this paper, although some of the considerations described below could be relevant.

70 Out of the leachate pollutants from landfills, long-term metal emissions constitute a particularity in the
71 LCA context. Inventory modelling in LCA applies a time-integration principle, according to which all emissions
72 should be treated as a pulse emission occurring at one point in time, whether they in reality occur in different parts
73 of a life cycle or extended over long-time periods (Guinée and Heijungs 1993). The latter case poses problems when
74 emissions occur in relatively low concentrations over very long time periods leading to large cumulated pulse flows.
75 Their impacts are potentially overestimated when the resulting impact scores from emissions in low concentrations
76 integrated over tens of thousands of years, are interpreted in the same way as impact scores for emissions occurring

77 in significantly shorter periods and thus integrated over shorter periods of time which is the case for transportation
78 processes and many industrial processes. There is a “dilution in time” which is important for the observable impacts
79 from the long-term emissions but not represented in the calculated potential impacts in life cycle impact assessment
80 (LCIA).

81 In LCIA toxic impacts are modelled using steady-state conditions, applying integration over a defined time
82 horizon. Integrating the potential impacts of long-term emissions over a relatively short time horizon like 100 or 500
83 years (as done for e.g. Global Warming Potentials), and thus neglecting impacts from emissions occurring later,
84 potentially leads to an underestimation of their impacts. On the other hand, including them fully through integration
85 over very long or even infinite time horizons would lead to a strong overestimation, as the (perhaps negligible if
86 from very low emission concentrations) potential impacts occurring over a long period of time would be fully
87 attributed to the product as if they were occurring right now (as one large emission) in the same way as an emission
88 from e.g. a waste incinerator. While the latter approach does not account for the “dilution in time” of the impact, the
89 first approach completely neglects the long-term potential impacts. These two extremes present a dilemma for which
90 an operational and accurate solution is needed in LCIA. Some LCIA approaches specifically deal with long-term
91 emissions (Pettersen and Hertwich 2008; Hauschild et al. 2008). However, currently there is no consensus among
92 researchers on a common methodology, which is illustrated by the differences in this perspective of the various
93 LCIA methodologies (Hischier et al. 2010). Moreover, there are no characterization factors available for long-term
94 emissions of metals, which thus have to be represented by the generic characterisation factor for the metal. Further
95 research is called for so that a more accurate representation of long-term emissions is achieved (Hischier et al.
96 2010).

97 In summary, when attempting to integrate this kind of emissions and their potential impacts into an LCA,
98 two main hurdles need to be overcome: 1) estimating/predicting the future emissions in the inventory phase, and 2)
99 characterising the emissions in a meaningful way that puts them into perspective relative to the impacts caused by
100 emissions that occur over a much shorter time. In order to better understand the perspectives for an adequate
101 representation of long-term emissions, a consistent overview of past experience and current practice within the LCA
102 field is needed. This is done through (i) reviewing the status, reliability and common ground of emission prediction
103 methodologies from an LCA perspective, (ii) reviewing the current proposals for characterization of long-term
104 emissions in LCIA, comparing them in terms of the results they provide, and based on that (iii) derive main

105 principles for a scientifically robust framework for an operational impact assessment for potential impacts of long-
106 term emissions in the LCA context.

107 **2. METHODOLOGY**

108 For addressing the aforementioned objectives, a literature review is conducted. Central studies are presented which
109 have been published in peer reviewed journals and that address the issue of long-term emissions from landfills.

110 The first part of the review aims at identifying studies mainly within the waste management field, which
111 can provide a time-dependent life cycle inventory (LCI) for long-term metal emissions from landfills. A
112 scientifically sound study that provides metal emission profiles for Ni, Cd, Zn, and Pb, suitable as an input to an
113 LCI, is selected. The emission profiles correspond to the leaching of these metals from an air pollution control
114 residues (APCR) landfill of a total capacity of 1,000,000 tonnes.

115 The second part maps research within the LCA field to identify the various approaches that have been
116 developed to address the challenges is assessing potential impacts from heavy metals emitted in low quantities but
117 over long periods of time. The review illustrates the current state of the art and analyzes the existing approaches in
118 terms of the perspectives they adopt on future emissions.

119 The results from the two parts of the literature search are combined to form a case study where the different LCA
120 approaches are applied on a selected emission profile of a metal leaching out of an APCR landfill over a long time
121 period. The same CF (or comparative toxicity potential) is used for both short- and long-term emissions, adopted
122 from recent literature which estimates CFs for Ni and Cu with respect to terrestrial ecotoxicity (Owsianiak et al.
123 2013). The CF for Ni is chosen as an emission profile for Ni can be found in literature (Astrup et al. 2006). The
124 available CF is relevant for terrestrial ecotoxicity impacts, but from a nickel emission to air. Thus this CF is
125 corrected for emissions directly to soil using USEtox (Rosenbaum et al. 2008) and the resulting CF is 4.86×10^3
126 $\text{m}^3/\text{kg}_{\text{emitted to soil}} \times \text{day}$.

127 Based on a common emission profile and an identical CF, the existing LCIA approaches can be compared
128 on the same basis. The time dependent emission profile for Ni provides emission quantities per 200 years time steps.
129 This quantity is integrated over 100 years (the first time step is divided in two) and over an infinite time horizon, and
130 the potential impacts in each case are then estimated by multiplying with the CF. The difference between the
131 impacts from the 100 years integration and the infinite time horizon is the impact allocated to a separate impact

132 category, named stored toxicity.

133 The impact is then estimated per time step and discount rates of $\pm 0.01\%$ are applied to future potential
134 impacts. The magnitude of the rates is set to 0.01% as this is shown to correspond to time horizons of up to 100,000
135 years (Hellweg et al. 2003). One positive and one negative discount rate are modelled, in order to account for
136 uncertainties regarding future economic development which determines the level of the compensation required for
137 future damage.

138 Lastly, the emission concentrations in the landfill leachate, provided also by the Ni profile per time step,
139 are compared to the European median background concentration of Ni in soils. The median situation is chosen for
140 demonstrative reasons, but it is not recommended as the background concentrations for metals vary greatly
141 geographically and according to soil types (Zhao et al. 2007). The median Ni extractable concentration in European
142 soils is estimated at 16 mg/kg (Lado et al. 2008). This is used to estimate the background Ni dissolved concentration
143 by using the equations below and the K_{dNi} (280 l/kg) default values found in the USEtox™ multimedia toxicity
144 model (Rosenbaum et al. 2008):

145
$$K_d = \frac{C_{sorbed}}{C_{dissolved}}$$

146 It is also assumed that:

147
$$C_{total} = C_{sorbed} + C_{dissolved}$$

148 where C_{sorbed} (mg/kg_{soil}) is the sorbed metal concentration, $C_{dissolved}$ is the dissolved metal concentration (mg/kg_{soil})
149 and C_{total} is the extractable metal concentration (mg/kg_{soil}). $C_{dissolved}$ is converted into mg/l by using the soil bulk
150 density ρ_{bulk} (mg/l) and the soil water content w (% v/v):

$$C_{dissolved} \left[\frac{mg}{l} \right] = \frac{\rho_{bulk} C_{dissolved} [mg/kg]}{1000 w}$$

151 By combining the above equations, $C_{dissolved}$ can be calculated as:

$$C_{dissolved} \left[\frac{mg}{l} \right] = \frac{C_{total}}{K_d + \frac{1000w}{\rho_{bulk}}}$$

152 The median global bulk density for soils, based on more than 15,000 samples is estimated at 1.4 t/m³ (Batjes 2008)
153 and it is assumed to apply for Europe. The water content value is adopted from the USEtox default value, which is
154 0.2. Therefore, the dissolved median Ni concentration in European soils is estimated at 0.038 mg/l.

155 Only the Ni concentration that is above the background level is transformed into mass and integrated over
156 time, then multiplied with the CF for Ni in order to provide the total actual potential impact.

157 A comparative analysis of the results of the application of the various LCA approaches helps identify the
158 effect that the specific assumptions and perspectives of each approach have on LCA results, thus directly affecting
159 decisions supported by waste LCA. Based on the analysis, a listing is made of the requirements for developing a
160 robust, common framework for addressing long-term emissions in LCA, by combining different characteristics of
161 the existing approaches.

162 **3 MODELLING LONG-TERM EMISSIONS OF HEAVY METALS**

163 Different types of landfills have been investigated in terms of pollutant release from the leachate. Inert landfills such
164 as an APCR landfills tend to be investigated more regarding metal emissions (e.g. Hellweg et al. 2005), while
165 landfills richer in organic matter are normally investigated in terms of organic pollutants (e.g Kjeldsen et al. 2002).
166 Long-term metal emissions are present in all types of landfills but the primary focus for toxicity might change with
167 landfill type. Also the waste composition in the landfill influences the pattern of metal emissions (Bolton and Evans
168 1991). The literature review conducted here is not confined to a specific landfill type in order to be comprehensive
169 and with the overall aim at identifying a time-dependent leachate inventory.

170 Heavy metal concentrations in landfill leachate have been extensively monitored and simulated in batch
171 tests for a surveyable time period, usually capped at 100 years (Finnveden et al. 1995; Flyhammar et al. 1998;
172 Kjeldsen and Christophersen 2001). A review of published monitoring and testing results concludes that the leachate
173 metal concentrations within such a short time frame do not pose a great environmental risk (Kjeldsen et al. 2002).
174 This observation fits well with the generally accepted assumption that typically the vast majority of the landfilled
175 waste content of heavy metals remains in the landfill 100 years after the waste deposition (Hauschild et al. 2008).
176 The heavy metal retention in landfills can be explained by mechanisms such as sorption and precipitation (Kjeldsen
177 et al. 2002).

178 On the other hand, the long-term heavy metal concentration in leachate is difficult to predict in a solid way

179 as laboratory simulation is not possible and mathematical models hence cannot be validated for time frames as long
180 as 100,000 to 250,000 years and should, therefore, not be over-interpreted (Finnveden et al. 1995). Theoretically,
181 after the stable methanogenic phase of a landfill rich in organic matter, the oxygen intrusion facilitates metal
182 mobility due to decreasing pH and oxidation to more soluble metal species (Christensen et al. 2000; Bozkurt et al.
183 2000). However, existing experimental work leads to contradictory results even for the medium time frame
184 (Kjeldsen et al. 2002).

185 Given the importance of oxygen intrusion on the landfill chemistry, a modelling approach has been
186 developed based on the oxygen effect (Bozkurt et al. 2000). In order to predict future heavy metal concentrations in
187 the leachate, this model is based on the fact that, after the methanogenic phase of an organic landfill is completed,
188 the subsequent humic phase is characterized by much slower organic carbon degradation which means that oxygen
189 diffuses into the landfilled waste (Bozkurt et al. 2000). The conceptual model is based on an analysis of the main
190 processes governing each landfill phase after the methanogenic phase, with the presence of oxygen considered as the
191 determining factor for metal mobility (Bozkurt et al. 1999).

192 Bozkurt et al. modelled several scenarios in order to determine the total depletion time for organics and
193 metals in the waste mass and the influence of factors such as the type and characteristics of the top cover (Bozkurt et
194 al. 2001). However, no results are presented regarding the quantity of heavy metals leaching out of the landfill as a
195 function of time. Therefore, this work is not suitable for compiling an LCI.

196 Finnveden attempted to produce emission rates for metals contained in a municipal waste landfill based on
197 a collection of mass balance approaches from literature (Finnveden, 1996). The author produced best estimates of
198 emission rates for a surveyable time period (about one century from waste deposition), which may constitute a
199 dynamic LCI. However, the mass balance approach for an infinite time frame, which is in line with the scope of this
200 paper, claims that all metals will eventually leave the landfill. Therefore, this study does not provide a suitable time-
201 dependent LCI.

202 Other attempts to predict the evolution of metal concentrations out of a landfill involve geochemical
203 models. One study attempted a prediction of the evolution of Cu and Cd concentrations in a municipal incineration
204 residues landfill, based on soil infiltration rate, share of macropore flow, and sorption capacity of the waste
205 (Hellweg et al. 2005). With the help of scenarios that determine the presence of these two heavy metals in waste and
206 the use of the geochemical model PHREEQC (Parkhurst and Appelo 1999), the authors tried to predict the

207 development of emission concentrations over the next 20,000 years for Cd and over 100,000 years for Cu. The
208 results of this work could be used in an LCA context, as illustrated in the same study which also presents results of
209 an LCIA. On the other hand, only information for two metals is given and the time frames for the emission
210 development are different for both metals. A different geochemical landfill model, LandSim, has also been
211 employed to predict the depletion of heavy metals (among others) from a typical municipal solid waste landfill over
212 a 20,000-years period, based on a variety of landfill parameters (Slack et al. 2007). Results of the simulation show
213 that heavy metals leach at very low concentrations over a long period of time and that only chromium and mercury
214 at any point in time exceed current drinking water standards proposed by health organizations. Moreover, the results
215 indicated that the heavy metal content remaining inside the waste mass is negligible after 4,000 years. This
216 conclusion contradicts other evidence of literature suggesting long attenuation of heavy metals in landfills but also
217 findings of laboratory tests (Flyhammar et al. 1998; Hyks et al. 2009). Therefore, the reliability of these results for
218 compiling an LCI is questionable.

219 A laboratory test aiming at simulating the landfill leaching process can also be found in literature (Hyks et
220 al. 2009). The test used a column percolation set-up, which applied forced infiltration of eluent in the column, filled
221 with samples from an inert landfill, in order to simulate leaching until high liquid-to solid (L/S) ratios were reached,
222 corresponding to a leaching duration of thousands of years (Hyks et al. 2009). The test was performed on samples
223 from a landfill for municipal solid waste incineration air pollution control residues, up until the L/S ratio reached
224 200-250 l/kg, in order to determine the leaching behaviour of a large variety of heavy metals. The L/S ratio could
225 then be translated into time based on site-specific landfill characteristics (Hjelmar 1990) and in this case, the total
226 simulated duration corresponds to more than 10,000 years. Results of the test showed that less than 3% of the initial
227 heavy metal mass had leached during the simulated time period of 10,000 years. This test cannot, however, be used
228 in the context of LCI as it does not cover the entire leaching time period of a landfill.

229 If a relationship between pH and the liquid-to-solid (L/S) ratio is established for fly ash landfills, it is
230 possible to predict Al, Ca, Cd, Ba, Mg, Ni, Pb, S, Pb, V, and Zn concentrations in the leachate, using pH as a
231 determining factor, as shown in another study (Astrup et al. 2006). Two types of incineration residues (semi-dry and
232 fly ash) were treated in batches while they were either carbonated before or they were in an uncarbonated form. The
233 pH was measured in the batches and for each measurement, the leaching of metals and the liquid-to-solid (L/S) ratio
234 was calculated. In this way, leaching concentrations were able to be connected with the level of pH. The L/S ratio

235 was translated into time based on average Danish environmental conditions. Based on these assumptions, the authors
236 produced emission profiles for the selected heavy metals until an L/S ratio of 5,000 which corresponds to 100,000 to
237 250,000 years. The results show different behaviour for different metals, but also according to the type of residue
238 investigated and the presence of carbonation. Therefore, it is difficult to group metals according to their leaching
239 patterns.

240 The graphs in Figure 1 present the leaching concentration profile over time modelled using the results of
241 Astrup and co-workers for four selected metals and averaged over the two waste streams modelled (non-carbonated
242 fly ash and semi-dry residue). The model has a temporal resolution of 200 years, and therefore this study could
243 easily be used to provide a time dependent LCI for this type of landfills. The total time frame is chosen at the lower
244 end of the range, set at 100,000 years.

245 The extrapolation of information obtained through leaching tests into considerations regarding metal
246 leaching behaviours in real landfills is hindered by restriction posed in the leaching simulations in the laboratory
247 (van der Sloot et al. 1996). However, for the scope of long-term emissions where actual measurements are
248 impossible to obtain, laboratory tests are the only source of information available regarding metal leaching
249 development patterns in the distant future.

250 It is important to notice that for a very long initial stage, the concentrations of leaching metals remain at a
251 low level, but then start to rise, with Ni and Zn reaching their maximum predicted concentrations at the end of the
252 modelling period. This observation has important consequences when assessing potential impacts and monitoring of
253 pollution around landfill sites.

254 **4 STATE OF THE ART IN LCA**

255 The life cycle impact assessment of long-term heavy metal emissions is currently problematic. The uncertainty of
256 including heavy metal long-term emissions in toxicity assessments within LCA has been identified as a problem for
257 quite some time, from both a methodological and case-study perspective (Finnveden and Nielsen 1999; Hauschild et
258 al. 2008; Hirschier et al. 2010). Many LCA studies of solid waste management systems underline the uncertainty in
259 their results stemming from the inability to accurately account for these potential impacts, while others choose to
260 ignore toxicity impacts altogether (Laurent et al. 2013a; Laurent et al. 2013b). The uncertainty discussed relates
261 mainly to modelling uncertainty (both inventory and impact modelling). However, there is also a methodological

262 uncertainty present which is based on the choice of time aggregation principle for the emissions (Finnveden and
263 Nielsen 1999; Udo de Haes et al. 1999).

264 Long-term emissions are currently treated in LCA either by modifications in the inventory modelling or by
265 hybrid methods adopted from other fields such as risk assessment (Hischier et al. 2010). The state of the art in the
266 inventory registration of long-term emissions is represented by Ecoinvent, which is one of the most widely used
267 LCA databases, providing inventories for many processes, including waste management (Frischknecht and Rebitzer
268 2005).

269 The Ecoinvent background report for landfills provides a comprehensive set of arguments for and against
270 inclusion of long-term emissions in the inventories and consequently in impact assessment (Doka 2009), but no
271 consensus is reached by the authors (Hischier et al. 2010).

272 Therefore, Ecoinvent inventories report both short- and long-term emissions from landfills, but their
273 inclusion or not in the impact assessment depends on whether or not the chosen impact assessment methodology
274 allows for it. Impact assessment methodologies such as CML2001, EDIP 97/2003, as well as IMPACT 2002+
275 (Hauschild and Wenzel 1997; Guinée et al. 2001a; Guinée et al. 2001b; Jolliet et al. 2003; Hauschild and Potting
276 2005) can produce differentiated impact assessment results by including or excluding long-term (beyond 100 years)
277 emissions. Other methodologies, such as Ecoindicator 99 and ReCiPe apply social perspectives reflecting the social
278 and environmental values of current generations towards future generations (Goedkoop and Spriensma 2001a;
279 Goedkoop and Spriensma 2001b; Goedkoop et al. 2009). Some of these perspectives include both short- and long-
280 term emissions and apply the same characterization factor for the two emission durations in the impact assessment.

281 A similar approach of differentiated time periods has been developed previously, by distinguishing between
282 two time periods, namely the surveyable time period (set to 100 years corresponding to the end of the methanogenic
283 phase of a typical municipal waste landfill) and the infinite time period (set to the time necessary for all emissions to
284 occur) (Finnveden 1999). The author recommends assessing potential impacts over both time periods in a full LCA,
285 since it should consider impacts from all relevant emissions, instead of the common practice of cutting off emissions
286 occurring after 100 years.

287 Several approaches have been developed beyond the LCI phase in order to tackle the issue of long-term
288 emissions' potential impacts. These approaches aim at developing specific LCIA methodologies that estimate
289 impacts from emissions beyond a point in time (stored toxicity) (Hauschild et al. 2008), or at weighing differently

290 impacts from future emissions compared to current impacts (environmental discounting) (Hellweg et al. 2003). The
291 last methodology presented here functions as an intercept between LCI and LCIA by eliminating emissions beyond
292 a certain threshold. Dynamic LCIA methods that have been developed but do not address specifically emissions
293 during very long time frames are not examined here as the long-term perspective requires a special framework
294 compared to simple time differentiated approaches (Levasseur et al. 2010).

295 **4.1 Stored toxicity**

296 In order to distinguish between potential toxic impacts from short- and long-term emissions, a new impact category
297 has been proposed, which builds upon current Ecoinvent practice: the emissions occurring during the first 100 years
298 of a landfill are treated together with the emissions released from all other processes in the life cycle (Hauschild et
299 al. 2008). The emissions beyond that point in time are classified as belonging to a new impact category, named
300 stored toxicity (or stored human toxicity and stored ecotoxicity), following the EDIP 2003 method (Hauschild and
301 Potting 2005). In order to estimate the potential toxic impacts, emissions inventoried in the stored toxicity categories
302 are characterised in the same way (and based on the same factors) as in the traditional toxicity categories. The
303 characterised results are then normalised based on an area's total annual stored toxicity, which is determined from
304 the mass flow of heavy metals within all waste streams in the year 1994, divided by the area's population. The
305 normalization is performed in order to assess the relative magnitude of the examined system's impact.

306 The proposed stored toxicity approach was applied in an LCA study on landfilled bottom ash and the
307 results showed that stored toxicity impacts are 325 times greater than the highest result in the traditional impact
308 categories spectrum (namely Ecotoxicity_{water}) (Birgisdóttir 2005).

309 This approach, although in line with current practice, is still problematic since the introduced impact
310 category lacks interpretation and weighting factors needed in the comparison with potential impacts in the other
311 categories. However, it provides a first step in separating between (i) emissions occurring within a time period
312 where landfill chemistry, and therefore heavy metal emissions, is well known and monitoring or testing is possible,
313 and (ii) emissions occurring in a distant future where uncertainty in their development is high and no monitoring or
314 testing is possible.

315 **4.2 Environmental discounting**

316 Hellweg and co-workers attempted an application of economic discounting in environmental assessment under the
317 context of LCA (Hellweg et al. 2003). The authors based their analysis on four main arguments for environmental
318 discounting (changes in magnitude of damage, pure time preference, productivity of capital, uncertainties). These
319 arguments, based on the economic theory, can be quantified in order to produce discount rates, applied on potential
320 impacts from future emissions, so that the weight of future impacts is differentiated compared with impacts from
321 emissions occurring instantly.

322 The choice, however, of a discount rate is subjective and very decisive, and in order for it to be meaningful,
323 it needs to be close to 0 ($-1\% \leq r \leq +1\%$). Under a higher positive discount rate, even potential impacts from
324 relatively short-term emissions (below 100 years) would practically disappear. Even in the case of low discount rates
325 the value of the discount rate is the sole most determining factor for the resulting potential impacts, because of the
326 exponential nature of discounting. The choice of a discount rate presupposes the monetization of environmental
327 impacts and depends on assumptions on the development of the future global economy, as well as value choices of
328 the LCA practitioner.

329 The adoption of moral archetypes from Cultural Theory for LCA modelling purposes (Hofstetter et al.
330 2000) could be a guide for selecting an appropriate discount rate according to the selected cultural perspective
331 (Hellweg et al. 2003). However, even within each cultural perspective the subjectivity of the choice is still not
332 eradicated which endangers the objectiveness of decisions supported by an LCA, while it has been shown that the
333 influence of an archetype choice is significant for the overall LCA results (Schryver et al. 2012).

334 **4.3 Background concentrations**

335 Another approach for tackling the issue of long-term emissions has been inspired by the field of risk assessment.
336 According to this, emissions occurring at leachate concentrations that are below the background concentration levels
337 for each heavy metal can be discarded as they cause no effect (Finnveden 1999). Therefore, it has been proposed to
338 cut off emissions of heavy metals that occur after the point in time when their concentrations fall below the
339 background concentrations (Finnveden and Huppes 1995). This approach has inspired studies related to landfill
340 aftercare period and technologies related to an effort for a fast reduction of metal leaching concentrations (Brand et
341 al. 2014).

342 This approach neglects that heavy metal emissions do not necessarily follow a decreasing trend, as

343 illustrated in Figure 1, and that background concentrations might not stay at the same level during the long time
344 frame considered. For some heavy metals, emissions have been shown to decrease steadily and then to increase
345 again in the future (Astrup et al. 2006). On the other hand, heavy metal background concentrations could increase
346 substantially in the future because of accumulation in specific environmental compartments (van der Voet et al.
347 2000).

348 Moreover, this approach could be considered as conflicting with the general LCA principles according to
349 which all emissions should be taken into account whether above or below thresholds (Udo de Haes et al. 1999),
350 although attempts to include background levels in LCIA can be found in literature (Hellweg et al. 2005). This holds
351 in particular in the extreme case of landfill leaching in contaminated soil where landfill emissions could potentially
352 dilute the soil pore water, thus reducing its toxicity to some extent, depending on the affected organisms and the
353 dose-response curves for the leached metal. It could, however be argued that a cut-off determined by the natural
354 background pore water concentration gives a more relevant representation of actual potential toxic impacts resulting
355 from long-term heavy metal emissions than a cut-off at an arbitrarily set time limit or an infinite time horizon, as
356 concentrations of metals below the background level have no toxic effect on the local ecosystems. Due to the natural
357 variation in soil water concentrations of metals, a high degree of site-specificity would be relevant in the modelling
358 (Lado et al. 2008).

359 **5 COMPARISON OF DIFFERENT METHODS DEALING WITH LONG-TERM EMISSIONS**

360 The LCA methods described above differ in many aspects: (i) the approaches to handling the short- and long-term
361 emissions; (ii) the respect of the time equity principle; (iii) the inclusion of subjective (value) choices in the
362 accounting of potential impacts. To investigate the importance of these differences, the different LCA approaches
363 are applied on the same emission profile of Ni leaching out of an air pollution control (APC) residues landfill. Based
364 on the assumptions on the initial content of the landfill, Ni will have leached out in about 73,000 years. The cut-off
365 of emissions after 100 years, the adoption of an infinite time horizon, the handling of emissions in a separate “stored
366 toxicity” impact category, the concept of environmental discounting and the estimation of potential impacts only
367 from emissions above the background concentrations, are all applied on the Ni profile.

368 The CF used for the analysis is estimated at $4.86 \times 10^3 \text{ m}^3/\text{kg}_{\text{emitted to soil}} \times \text{day}$ and it represents the impact on
369 terrestrial ecotoxicity from an emission of Ni to soil.

370 The results of the application are shown in Figure 2. The lowest impact given by the cut-off of emissions at
371 100 years, and the highest impact from the negative discount rate differ by approximately eight orders of magnitude.
372 The stored ecotoxicity approach (which is practically the difference between the cut-off and the infinite time horizon
373 approaches) gives an impact around five orders of magnitude higher than the results of the cut-off approach,
374 demonstrating the significance of long-term emissions against short-term. The use of a negative discount rate, which
375 gives a higher importance to impacts occurring in the future, provides the highest results. The difference between
376 impacts with a small positive and a small negative discount rate is about five orders of magnitude, highlighting the
377 importance of the choice of discount rate, which relies on subjective criteria. The second lowest overall impact is
378 produced by the inclusion of emissions only above the background concentrations. This is because the pattern of the
379 emission profile for Ni shows a sharp increase in the leached metal only after 35,000 years and exceeding the
380 background Ni concentration after 55,000 years approximately.

381 A similar pattern would result from the comparison of the methods for emissions of other metals, as only
382 the magnitude would change (based on different emission levels, CFs, and background concentrations). Therefore, it
383 is safe to say that the cumulative effect of the choice of LCIA approach towards long-term emissions from all metals
384 leaching out of the landfill would be much higher.

385 If the results from this comparison are put in the context of a full LCIA, the selection of method becomes
386 critical as it would potentially lead to very different decisions supported by the corresponding LCA study. For
387 example, the infinite time horizon method would lead to a dominance of toxicity impact categories over the full
388 LCIA profile (Hauschild et al. 2008).

389 **6 DISCUSSION**

390 The prediction of the development of emissions over time for heavy metals in landfills is shown to be difficult due
391 to hindering factors such as (i) the complexity and dynamics of landfill chemistry where many processes and the
392 waste characteristics (waste composition) influence heavy metal mobility, (ii) many different parameters (e.g. pH,
393 organic matter in the deposit) that govern metal kinetics and (iii) the inherent uncertainty when attempting to predict
394 future conditions in landfills determining the chemicals behaviour for very long time periods. Due to this
395 complexity, there is little common ground among the different methods reviewed. No study has been identified that
396 has made comprehensive use of all information available regarding the governing mechanisms of metal mobility –

397 instead the studies tend to focus on a selected few of these mechanisms and adopt them in the construction of a
398 prediction model.

399 In the LCA domain, the use of predictions of long-term emissions is limited, as the current state-of-the-art
400 either uses emissions from robust models or laboratory findings that extend to the first 100 years after deposition or
401 uses mass balance calculations to estimate the aggregated emissions over infinite time horizons. The proposed
402 approaches to account for potential impacts from long-term emissions present some interesting insights but carry
403 individual, inherent problems. An overall conclusion is that a distinction in the way potential impacts are calculated
404 for short- and long-term emissions is required.

405 None of the approaches considers the changes in environmental conditions or ecosystem equilibrium when
406 estimating future potential impacts. The CF used is the same for short- and long-term emissions, although the
407 environmental compartments receiving long-term emissions are bound to change if such long time perspectives are
408 investigated. Currently, the predominant approaches for integrating emissions over time does not allow for a time-
409 differentiated CF, although that would increase accuracy. For example, fluctuations in the soil pH would change
410 drastically the metal mobility (Richards et al. 2000), increasing or decreasing their toxic potential. The presented
411 dynamic inventory allows for investigating impacts in every future point in time and paves the way for
412 investigations regarding changing over time soil properties that influence the calculations of metal toxicity.

413 The comparison of existing LCIA approaches on the same metal emission profile shows that the resulting
414 predicted potential toxic impacts differ quite substantially, thus leading to very different assessments of the toxicity
415 potential of landfill leachate. The common practice in LCA, of cutting off emissions after 100 years, is problematic
416 as it ignores the vast majority of potential impacts, regardless of the selected approach towards long-term emissions
417 as shown in Figure 2 and supported by other studies (Huijbregts et al. 2001). However, given the importance of
418 heavy metal emissions in the total toxicity-related impacts, it is essential that a robust, accurate, and realistic
419 approach is developed so that properly informed decisions can be made based on the LCA results. A robust
420 approach needs to include an accompanying module on uncertainty in both the prediction of emissions (LCI) and the
421 subsequent toxicity modelling (LCIA), which, although very complex, is essential for putting the impact assessment
422 results into context and avoiding their over-interpretation.

423 In order to produce an accurate representation of potential impacts from long-term emissions, the changes
424 in the receiving environment need to be investigated and possibly reflected in a time-dependent toxicity CF for each

425 metal being emitted. This should be based on a modelling of the temporal changes in landscape properties over long-
426 term time frames of the environmental compartments receiving the emissions (mainly soil) and the response of the
427 exposed ecosystems, which would result in time dependent fate, exposure, and effect calculations. Site-specificity is
428 also crucial, as soil properties that affect metal toxicity, such as pH or soil organic matter, vary across the globe.

429 On the other hand, the handling of long-term emissions should be realistic, so that only real potential toxic
430 impacts are taken into account. The inclusion of background concentrations (Birgisdóttir 2005) in a comparison with
431 the emission concentrations would disregard emissions that actually dilute existing background levels in the
432 environment. These considerations should reflect the fact that metal emissions from landfills occur over long time
433 frames but in relatively low concentrations. These low concentrations are not currently considered, due to the
434 predominant practices of integrating emissions over time. The evolution of background levels with time can be
435 addressed by modelling different scenarios (Hellweg et al. 2005). As the background levels have a significant effect
436 on the amount of emissions contributing to toxicity, a spatially differentiated approach is required in order to capture
437 the natural variations in soil concentrations of metals in different regions (e.g. Shacklette and Boerngen 1984;
438 Herselman et al. 2005; Lado et al. 2008)

439 Some of these method elements may challenge traditional axioms of LCA specifically and sustainability in
440 general. The time equity principle, essential to the sustainability concept aiming to preserve equal development
441 chances for current and future generations, according to which all emissions from a system should be treated equally
442 regardless of the point in time at which they occur, is one of them. This principle functions well in relatively short
443 time frames (one day, one year or even a decade) since the internal and external conditions that determine the
444 potential impacts from an emission do not change substantially. However, in extreme conditions, when emissions
445 occur over a very long time frame, the time equity principle cannot hold, since the conditions determining the
446 estimation of the impacts are bound to change. Therefore, emissions occurring in different time periods should be
447 treated differently in an LCA context, by modifying accordingly the associated CFs. Some existing approaches in
448 LCIA already challenge the equity principle by explicitly applying discounting in future impacts, or differentiating
449 between impacts within a surveyable time period and future impacts (Hellweg et al. 2003; Hauschild et al. 2008).
450 Likewise, the common practice in LCA to ignore impacts from emissions occurring after a specific time frame,
451 without adequate scientific argumentation, clearly violates the time equity principle.

452 On the other hand, the involvement of background concentrations is not consistent with the general rule in

453 LCA of treating emissions in the same way whether above or below thresholds (Udo de Haes et al. 1999). However,
454 such an approach is necessary for producing more realistic future estimates for potential toxic impacts, but also for
455 addressing the fact that long-term emissions typically emit in low concentrations but over very long time periods.
456 Overall, it is time a consensus was reached for the issue of long-term emissions in LCA. The complexity of
457 emissions prediction, the diversity of approaches, and the inherent uncertainty lead most practitioners to ignore long-
458 term emissions altogether. On the other hand, policy makers tend to undervalue or ignore future potential impacts
459 due to pure time preference (Harvey 1994), which is not supported by environmental ethics (Hellweg et al. 2003).
460 These two factors cause a significant misrepresentation of potential toxic impacts in LCA studies involving long
461 term emissions of metals.

462

463 **COMPLIANCE WITH ETHICAL STANDARDS**

464 Our research does not involve any human or animal participants.

465

466 **REFERENCES**

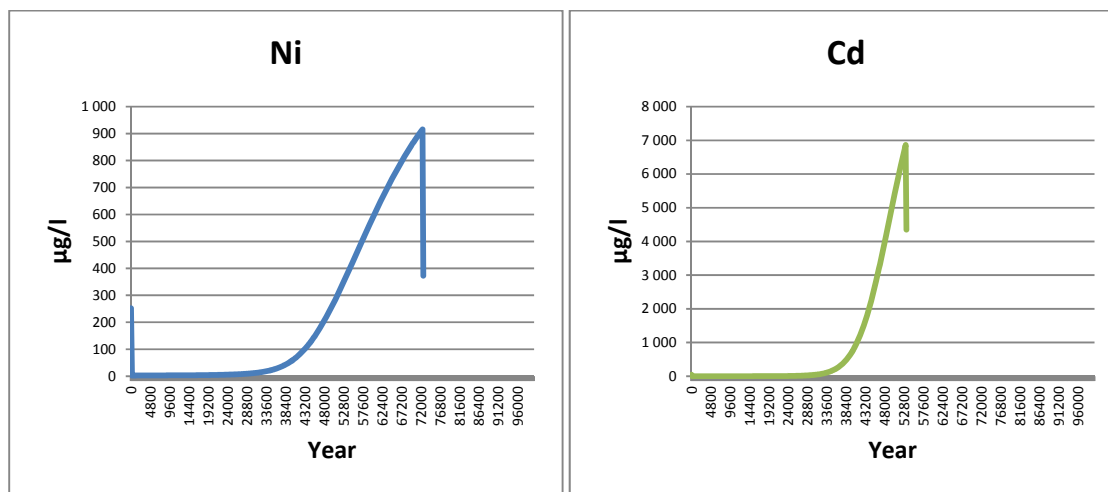
- 467 Althaus H, Classen M (2005) Life Cycle Inventories of Metals and Methodological Aspects of Inventorying
468 Material Resources inecoinvent. *Int J Life Cycle Assess* 10:43–49.
- 469 Astrup T, Mosbaek H, Christensen TH (2006) Assessment of long-term leaching from waste incineration air-
470 pollution-control residues. *Waste Manag* 26:803–14. doi: 10.1016/j.wasman.2005.12.008
- 471 Batjes NH (2008) ISRIC-WISE Harmonized Global Soil Profile Dataset (Ver. 3.1). Rep. 2008/2, ISRIC - World Soil
472 Information, Wageningen (with dataset)
- 473 Birgisdóttir H (2005) Life cycle assessment model for road construction and use of residues from waste incineration.
474 Technical University of Denmark
- 475 Bolton KA, Evans LJ (1991) Elemental composition and speciation of some landfill leachates with particular
476 reference to Cadmium. *Water, Air and Soil Pol* 60: 43-53
- 477 Bozkurt S, Moreno L, Neretnieks I (2000) Long-term processes in waste deposits. *Sci Total Environ* 250:101–21.
- 478 Bozkurt S, Moreno L, Neretnieks I (1999) Long-term fate of organics in waste deposits and its effect on metal
479 release. *Sci Total Environ* 228:135–52.
- 480 Bozkurt S, Sifvert M, Moreno L, Neretnieks I (2001) The long-term evolution of and transport processes in a self-
481 sustained final cover on waste deposits. *Sci Total Environ* 271:145–68.

- 482 Brand E, de Nijs T, Claessens J, Dijkstra J, Comans R, Lieste R (2014). Development of emission testing values to
483 assess sustainable landfill management on pilot landfills. National Institute of Public Health and the
484 Environment, Bilthoven, the Netherlands
- 485 Christensen AG, Fischer EV, Nielsen HN, Nygaard T, Østergaard H, Lenschow SR, Sørensen H, Fuglsang IA,
486 Larsen TH (2000) Passive soil vapor extraction of chlorinated solvents using boreholes. The Second
487 International Conference on Remediation of Chlorinated and Recalcitrant Compounds, Monterey, California,
488 May 22-25, 2000
- 489 Christensen T, Kjeldsen P, Bjerg P, Jensen DL, Christensen JB, Baun A, Albrechtsen H-J, Heron G (2001)
490 Biogeochemistry of landfill leachate plumes. *Appl Geochemistry* 16:659–718.
- 491 Doka G (2009) Life Cycle Inventories of Waste Treatment Services. ecoinvent report No. 13. Swiss Cent. Life
492 Cycle Invent. Dubend.
- 493 Finnveden G (1996). Solid Waste Treatment Within the Framework of Life Cycle Assessment - Metals in Municipal
494 Solid Waste Landfills. *Int J LCA* 1 (2) 74-78 (1996)
- 495 Finnveden G (1999) Methodological aspects of life cycle assessment of integrated solid waste management systems.
496 *Resour Conserv Recycl* 26:173–187.
- 497 Finnveden G, Huppes G (1995) Life Cycle Assessment and Treatment of Solid Waste. Proceedings of the
498 International Workshop, Stockholm, Sweden. AFR-Report 98. Stock. Sweden AFR, Swedish EPA
- 499 Finnveden G, Albertsson A-C, Berendson J, Eriksson E, Höglund LO, Karlsson S, Sundqvist J-O (1995) Solid waste
500 treatment within the framework of life cycle assessment. *J Cleaner Prod* 3 (4) 189-199
- 501 Finnveden G, Nielsen PH (1999) Long-Term Emissions from Landfills Should Not be Disregarded. *Int J Life Cycle*
502 *Assess* 4:125–126.
- 503 Flyhammar P, Tamaddon F, Bengtsson L (1998) Heavy metals in a municipal solid waste deposition cell. *Waste*
504 *Manag Res* 16:403–410. doi: 10.1177/0734242X9801600502
- 505 Frischknecht R, Rebitzer G (2005) The ecoinvent database system: a comprehensive web-based LCA database. *J*
506 *Clean Prod* 13:1337–1343. doi: 10.1016/j.jclepro.2005.05.002
- 507 Goedkoop M, Heijungs R, Huijbregts M, De Schryver A, Struijs J, van Zelm R (2009) ReCiPe 2008; A life cycle
508 impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint
509 level - Report I: Characterisation. Minist. van VROM, Den Haag
- 510 Goedkoop M, Spriensma R (2001a) The Eco-indicator 99; A damage oriented method for Life Cycle Impact
511 Assessment - Methodology Annex. PRé Consult. Amersfoort, Netherlands
- 512 Goedkoop M, Spriensma R (2001b) The Eco-indicator 99; A damage oriented method for Life Cycle Impact
513 Assessment - Methodology Report. PRé Consult. Amersfoort, Netherlands
- 514 Guinée J, Heijungs R (1993) A proposal for the classification of toxic substances within the framework of life cycle
515 assessment of products. *Chemosphere* 26:1925–1944.
- 516 Guinée JB, Gorrée M, Heijungs R, Huppes J, Kleijn R, de Koning A, van Oers A, Sleswijk AW, Suh S, Udo de
517 Haes HA, de Bruijn H, van Duin R, Huijbregts MAJ, Lindeijer E, Roorda AAH, van der Ven BL, Weidema B
518 (2001a) Life cycle assessment; An operational guide to the ISO standards. Minist. Housing, Spat. Plan.
519 Environ. Cent. Environ. Sci. (CML), Den Haag Leiden, Netherlands

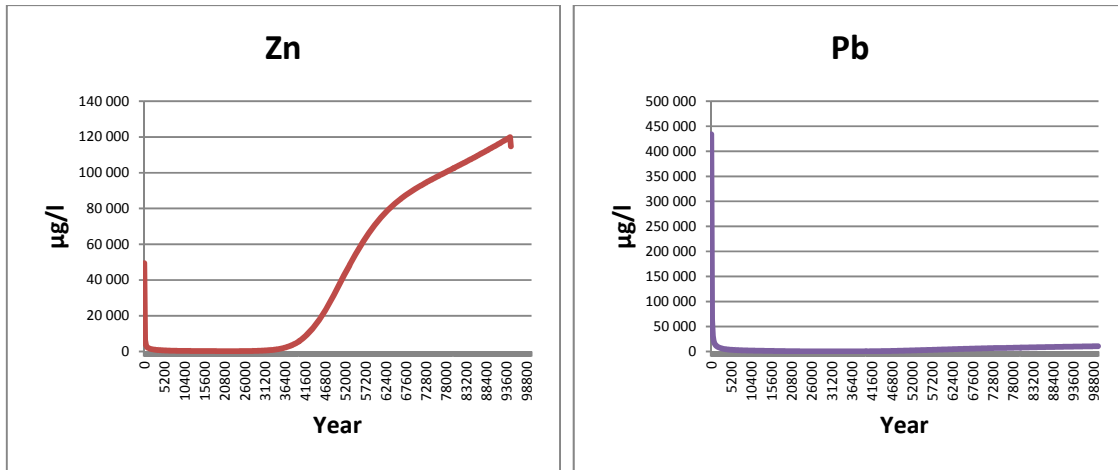
- 520 Guinée JB, Gorrée M, Heijungs R, Huppés J, Kleijn R, de Koning A, van Oers A, Sleeswijk AW, Suh S, Udo de
521 Haes HA, de Bruijn H, van Duin R, Huijbregts MAJ, Lindeijer E, Roorda AAH, van der VenBL, Weidema B
522 (2001b) Life cycle assessment; An operational guide to the ISO standards - Part 3: Scientific Background.
523 Minist. Housing, Spat. Plan. Environ. Cent. Environ. Sci. (CML), Den Haag Leiden, Netherlands
- 524 Harvey CM (1994) The reasonableness of non-constant discounting. *J Public Econ* 53:31–51.
- 525 Hauschild M, Olsen SI, Hansen E, Schmidt A (2008) Gone...but not away—addressing the problem of long-term
526 impacts from landfills in LCA. *Int J Life Cycle Assess* 13:547–554. doi: 10.1007/s11367-008-0039-3
- 527 Hauschild MZ, Potting J (2005) Background for spatial differentiation in LCA impact assessment: The EDIP03
528 methodology. *Environ. Proj. No. 996. Inst. Prod. Dev. Tech. Univ. Denmark*
- 529 Hauschild MZ, Wenzel H (1997) *Environmental Assessment of Products. Vol. 2: Scientific background.* Chapman
530 & Hall, London, Weinheim, New York
- 531 Hellweg S, Hofstetter TB, Hungerbühler K (2003) Discounting and the Environment; Should Current Impacts be
532 Weighted Differently than Impacts Harming Future Generations? *Int J Life Cycle Assess* 8:8–18.
- 533 Hellweg S, Hofstetter TB, Hungerbühler K (2005) Time-dependent life-cycle assessment of slag landfills with the
534 help of scenario analysis: the example of Cd and Cu. *J Clean Prod* 13:301–320. doi:
535 10.1016/j.jclepro.2004.02.016
- 536 Herselman JE, Steyn CE, Fey MV (2005) Baseline concentration of Cd, Co, Cr, Cu, Pb, Ni and Zn in surface soils
537 of South Africa. *S Afr J Sci* 101:509-512
- 538 Hirschier R, Weidema B, Althaus H-J, Bauer C, Doka G, Dones R, Frischknecht R, Hellweg S, Humbert S,
539 Jungbluth N, Köllner T, Loerincik Y, Margni M, Nemecek T (2010) Implementation of Life Cycle Impact
540 Assessment Methods;ecoinvent report No. 3, v2.2. Swiss Cent. Life Cycle Invent. Dübend.
- 541 Hjelmar O (1990) Leachate from land disposal of coal fly ash. *Waste Manag Res* 8:429–449.
- 542 Hofstetter P, Baumgartner T, Scholz RW (2000) Modelling the Valuesphere and the Ecosphere : Integrating the
543 Decision Makers ' Perspectives into LCA. *Int J Life Cycle Assess* 5:161–175.
- 544 Huijbregts M a, Guinée JB, Reijnders L (2001) Priority assessment of toxic substances in life cycle assessment. III:
545 Export of potential impact over time and space. *Chemosphere* 44:59–65.
- 546 Huijbregts MAJ, Thissen U, Guinée JB, Jager T, Kalf D, Van de Meent D, Ragas AMJ, Sleeswijk AW, Reijnders L
547 (2000) Priority assessment of toxic substances in life cycle assessment. Part I: Calculation of toxicity
548 potentials for 181 substances with the nested multi-media fate, exposure and effects model USES -LCA.
549 *Chemosphere* 41:541–573.
- 550 Hyks J, Astrup T, Christensen TH (2009) Long-term leaching from MSWI air-pollution-control residues: leaching
551 characterization and modeling. *J Hazard Mater* 162:80–91. doi: 10.1016/j.jhazmat.2008.05.011
- 552 ISO (2006a) Environmental management:—life cycle assessment— principles and framework. *Int Stand Organ*
553 Geneva 14040:2006.
- 554 ISO (2006b) Environmental management—life cycle assessment— requirements and guidelines. *Int Stand Organ*
555 Geneva 14044:2006.

- 556 Jolliet O, Margni M, Charles R, Humbert S, Payet J, Rebitzer G, Rosenbaum RK (2003) IMPACT 2002+: A New
557 Life Cycle Impact Assessment Methodology. *Int J Life Cycle Assess* 8:324–330.
- 558 Kjeldsen P, Barlaz MA, Rooker AP, Baun A, Ledin A, Christensen TH (2002) Present and Long-Term Composition
559 of MSW Landfill Leachate: A Review. *Crit Rev Environ Sci Technol* 32:297–336. doi:
560 10.1080/10643380290813462
- 561 Kjeldsen P, Christophersen M (2001) Composition of leachate from old landfills in Denmark. *Waste Manag Res*
562 19:249–256. doi: 10.1177/0734242X0101900306
- 563 Lado LR, Hengl T, Reuter HI (2008) Heavy metals in European soils: A geostatistical analysis of the FOREGS
564 Geochemical database. *Geoderma* 148:189–199. doi: 10.1016/j.geoderma.2008.09.020
- 565 Laurent A, Bakas I, Clavreul J, Bernstad A, Niero M, Gentil E, Hauschild MZ, Christensen TH (2013) Review of
566 LCA studies of solid waste management systems - Part I: Lessons learned and perspectives. *Waste Manag.*
567 doi: 10.1016/j.wasman.2013.10.045
- 568 Laurent A, Clavreul J, Bernstad A, Bakas I, Niero M, Gentil E, Christensen TH, Hauschild MZ (2013) Review of
569 LCA studies of solid waste management systems - Part II: Methodological guidance for a better practice.
570 *Waste Manag.* doi: 10.1016/j.wasman.2013.12.004
- 571 Levasseur A, Lesage P, Margni M, Deschênes L, Samson R (2010) Considering time in LCA: dynamic LCA and its
572 application to global warming impact assessments. *Environ Sci Technol* 44:3169–74. doi: 10.1021/es9030003
- 573 Owsianiak M, Rosenbaum RK, Huijbregts M a J, Hauschild MZ (2013) Addressing geographic variability in the
574 comparative toxicity potential of copper and nickel in soils. *Environ Sci Technol* 47:3241–50. doi:
575 10.1021/es3037324
- 576 Parkhurst DL, Appelo CAJ (1999) User's Guide to PHREEQC (Version 2)--A Computer Program for Speciation,
577 Batch-Reaction, One Dimensional Transport, and Inverse Geochemical Calculations. *Water Resour Investig*
578 *Rep* 99–4259.
- 579 Pettersen J, Hertwich EG (2008) Critical Review: Life-Cycle Inventory Procedures for Long-Term Release of
580 Metals. *Environ Sci Technol* 42:4639–4647.
- 581 Reid C, Bécaert V, Aubertin M, Rosenbaum RK, Deschênes L (2009) Life cycle assessment of mine tailings
582 management in Canada. *J Clean Prod* 17:471–479. doi: 10.1016/j.jclepro.2008.08.014
- 583 Richards BK, Steenhuis TS, Peverly JH, McBride MB (2000) Effect of sludge-processing mode , soil texture and
584 soil pH on metal mobility in undisturbed soil columns under accelerated loading. *Environ Pollut* 109:327–346.
- 585 Rosenbaum RK, Bachmann TM, Gold LS, Huijbregts MAJ, Jolliet O, Juraske R, Koehler A, Larsen HF, MacLeod
586 M, Margni M, McKone TE, Payet J, Schuhmacher M, Meent D, Hauschild MZ (2008) USEtox—the UNEP-
587 SETAC toxicity model: recommended characterisation factors for human toxicity and freshwater ecotoxicity
588 in life cycle impact assessment. *Int J Life Cycle Assess* 13:532–546. doi: 10.1007/s11367-008-0038-4
- 589 Schryver AM, Humbert S, Huijbregts MAJ (2012) The influence of value choices in life cycle impact assessment of
590 stressors causing human health damage. *Int J Life Cycle Assess* 18:698–706. doi: 10.1007/s11367-012-0504-x
- 591 Shacklette HT, Boerngen JG (1984) Element Concentrations in Soils and Other Surficial Materials of the
592 Conterminous United States. US Geological Survey Professional Paper 1270

- 593 Singh SP, Hendry MJ (2012) Solid-Phase Distribution and Leaching Behaviour of Nickel and Uranium in a
594 Uranium Waste-Rock Piles. *Water, Air, Soil Pollut* 224:1360. doi: 10.1007/s11270-012-1360-9
- 595 Slack RJ, Gronow JR, Hall DH, Voulvoulis N (2007) Household hazardous waste disposal to landfill: using
596 LandSim to model leachate migration. *Environ Pollut* 146:501–9. doi: 10.1016/j.envpol.2006.07.011
- 597 Stüben D, Berner Z, Kappes B, Puchelt H (2001) Environmental monitoring of heavy metals and arsenic from Ag-
598 Pb-Zn mining: a case study over two millennia. *Environ Monit Assess* 70:181–200.
- 599 Udo de Haes HA, Jolliet O, Finnveden G, Hauschild MZ, Krewit W, Mueller-Wenk R (1999) Best Available
600 Practice Regarding Impact Categories and Category Indicators in Life Cycle Impact Assessment. Backgr. Doc.
601 Second Work. Gr. Life Cycle Impact Assess. SETAC-Europe. p 9
- 602 Van der Sloot HA, Comans RNJ, Hjelmar O (1996). Similarities in the leaching behaviour of trace contaminants
603 from waste, stabilised waste, construction materials and soils. *Sci Total Environ* 178:111-126
- 604 Van der Voet E, Guinée JB, Udo de Haes HA (2000) Heavy Metals: A Problem Solved? Kluwer, Dordrecht-Boston-
605 London
- 606 Zhao FJ, McGrath SP, Merrington G (2007) Estimates of ambient background concentrations of trace metals in soils
607 for risk assessment. *Environ Pollut* 148:221–9. doi: 10.1016/j.envpol.2006.10.041
- 608
- 609



610

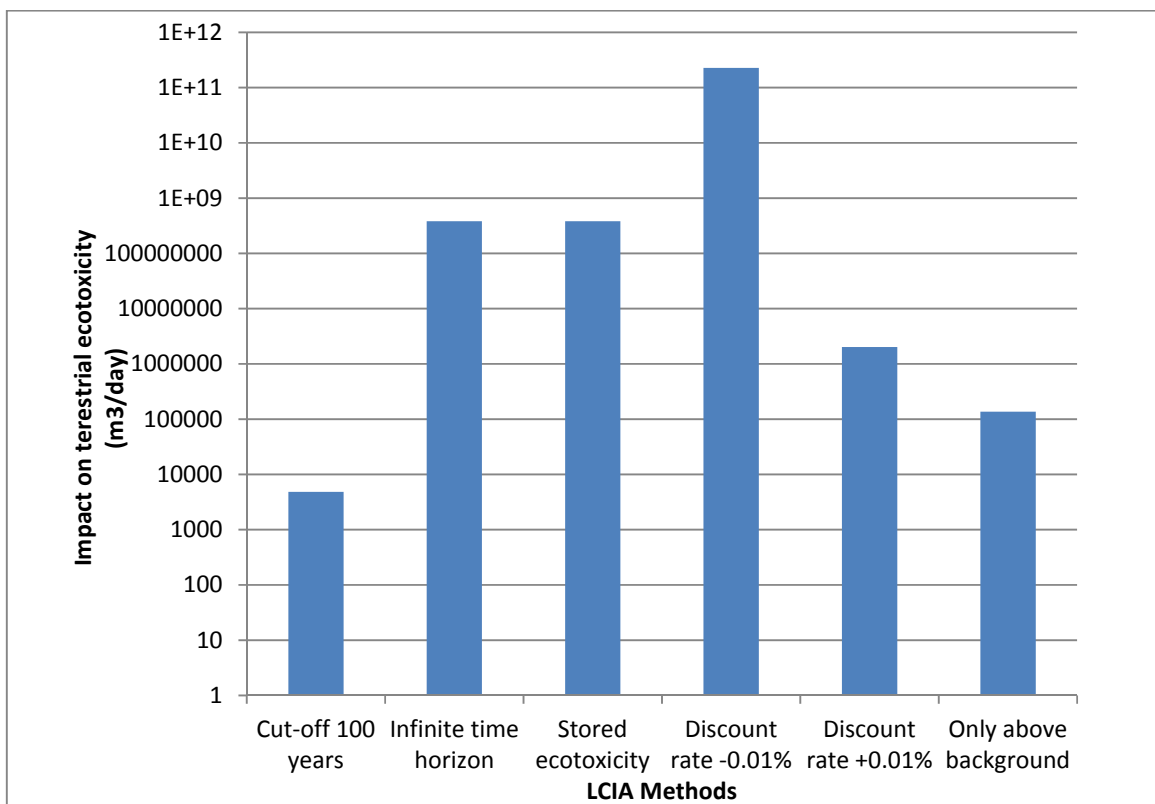


611

612 Figure 1. Development in average leaching concentrations for four heavy metals over 100,000 years (based on
 613 Astrup et al., 2006). *Note:* The proposed patterns do not fully cover the time frame of 100,000 years, as the metal
 614 content in the waste is depleted earlier, except for Pb.

615

616



617

618 **Figure 2** Assessment of the terrestrial ecotoxicity impact for a given emission pattern of Ni leaching out of an APC
619 residues landfill, applying five different approaches towards handling of long-term emissions

620