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**Impact categories for natural resources and land use :
survey and analysis of existing and proposed methods in
the context of environmental life cycle assessment**

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Contents

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Summary	6
1 Introduction to the report	7
1.1 Background of the report	7
1.2 Organization of the report	7
2 Introduction to the subject	8
2.1 Life cycle assessment	8
2.2 Characterization	8
2.3 The Dutch Environmental 95	8
IMPACT CATEGORIES FOR NATURAL RESOURCES AND LAND USE	10
3.1 Overview of the problem	10
3.2 Survey of existing and proposed methods	10
3.3 Assessment results	10
3.4 Discussion	10
Survey and analysis of existing and proposed methods in the context of environmental life cycle assessment	11
4.2 Survey of existing and proposed methods	11
4.3 Assessment results	11
4.4 Discussion	11
4 Land use	12
5.1 Overview of the problem	12
5.2 Survey of existing and proposed methods	12
5.3 Assessment results	12
5.4 Discussion	12
6 Concluding discussion	13
6.1 Recommended methods for characterization	13
6.2 Future developments	13
Reinout Heijungs	14
Jeroen Guinée	14
Gjalt Huppes	14

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Contents

Summary	6
1 Introduction to the report	7
1.1 Background of the report	7
1.2 Organization of the report	7
2 Introduction to the subject	8
2.1 Life cycle assessment	8
2.2 Characterization	8
2.3 The Dutch <i>Eco-indicator 95</i>	9
2.4 Input-related interventions and impacts	10
3 Extraction of abiotic resources	16
3.1 Overview of the problem	16
3.2 Survey of existing and proposed methods	16
3.3 Assessment results	20
3.4 Discussion	23
4 Extraction of biotic resources	24
4.1 Overview of the problem	24
4.2 Survey of existing and proposed methods	24
4.3 Assessment results	25
4.4 Discussion	27
5 Land use	28
5.1 Overview of the problem	28
5.2 Survey of existing and proposed methods	28
5.3 Assessment results	30
5.4 Discussion	31
6 Concluding discussion	32
6.1 Recommended methods for characterization	32
6.2 Recommended future developments	32
References	39

Summary

This report gives a survey of existing, that is, operational and proposed, methodologies to characterize input-related interventions in life cycle assessment. It therefore addresses the issues of extraction of abiotic and biotic resources and the use of land.

There exists a wide variety of approaches towards characterizing resource extraction and land use. This report assesses each of these approaches on the basis of a number of criteria:

- compatible with the principles of life cycle assessment;
- compatible with a reasonable definition of the associated environmental problem;
- no double counting;
- unambiguous/no arbitrary elements involved;
- operational/easily operational.

It turns out that none of the proposed approaches is completely satisfactory on all these criteria.

We nevertheless suggest the use of some approaches for the long term: *3b*, *3c* or *3d* for abiotic resources and *4a* for biotic resources. For land use we were not able to find a method that is satisfactory on the short term..

The discussion however suggests a number of lines to investigate in future research. Of eminent importance is a clear perception and definition of the environmental problems that are associated with the input-related interventions. A preliminary proposal in terms of three "depletion themes" (reduces availability, loss of biodiversity and damage to life-support) is made.

1 — Introduction to the report

1.1 — Background of the report

The *Japan Environmental Management Association for Industry* (JEMAI) is interested in developing an eco-indicator for use by Japanese industries, to support environmental decision-making with respect to products. The idea behind the eco-indicator is inspired by the Dutch *Eco-indicator 95* that has been described by Goedkoop (1995). JEMAI has identified a number of research needs before being able to adopt the eco-indicator concept. Among these are the incorporation of the impact categories related to resource extraction and land use. JEMAI has commissioned the *Centre of Environmental Science, Leiden University* (CML) to produce an analytic survey of proposed methods to characterize use and/or consumption of natural resources and land.

The present report is the result of this commission. It should be emphasized that CML's activity has concentrated on producing a report on how to include impacts related to resource extraction and land use. The eco-indicator concept itself has not been discussed in detail, although some remarks have been made with respect to it.

1.2 — Organization of the report

The report is structured as follows.

The second chapter introduces a number of central concepts in life cycle assessment, its characterization step, the *Eco-indicator 95*, as well as a number of characteristics that are relevant for addressing resource extraction and land use and their impacts.

Chapters three and four are devoted to the topic of resource extraction of abiotic and biotic resources respectively, and chapter five to that of land use. These chapters consist for a large part of a presentation of existing and proposed, official and "grey", approaches to characterize resource extraction and land use. No effort will be made to distinguish between existing and proposed methods.

The last chapter contains recommendations for now as well as a discussions of future developments.

1.3 — The Dutch *Eco-indicator 95*

The *Eco-indicator 95* is conceived as "an easy-to-use instrument for environmental impact assessment that can be integrated into the design process". It is designed to help designers to assess the environmental impacts of a certain product over its entire life cycle, from the extraction of the raw materials through production, use and transport, to the environmental aspects of a substantial amount of important materials like

2 — Introduction to the subject

2.1 — Life cycle assessment

Life cycle assessment (LCA) is a procedure to compile and assess the environmental aspects of a product function from the cradle to the grave.

The LCA procedure consists of a number of components or elements (Heijungs *et al.*, 1992, Consoli *et al.*, 1993, ISO, 1996). The international standard that is currently being developed (ISO, 1996) will be taken as a reference here. It distinguishes the following elements:

- goal and scope definition, in which the procedure is initiated and a number of major decisions with respect to the set-up of the analysis are taken;
- inventory analysis, in which the environmental interventions (the product system's inputs from and outputs to the environment) are compiled;
- impact assessment, in which the environmental importance of the different inputs and outputs is taken into account;
- interpretation, in which an opinion on the societal importance and the robustness of the previous results is included.

It is important to recognize that there is quite some agreement with respect to the different aspects that are to be addressed (*e.g.*, functional unit, system boundaries, allocation rules, equivalency factors) as well as to the considerations that are supposed to play a role within these, but that there is still a wide range of possibilities with respect to the exact methodologies. Chapters 3 and 4 of this report will illustrate this agreement on general principles and disagreement on operational principles.

2.2 — Characterization

The characterization step of life cycle impact assessment is defined as the step in which the environmental interventions (the product system's inputs from and outputs to the environment) are translated in terms of contributions to a selected number of environmental impact categories. The *SETAC-Europe Working Group on Impact Assessment* (WIA; Udo de Haes, 1996) has described a default classification list of impact categories, which is reproduced below:

- input related categories ("resource depletion or competition")
 - abiotic resources (deposits, funds, flows)
 - biotic resources (funds)
 - land
- output related categories ("pollution")
 - global warming
 - depletion of stratospheric ozone
 - human toxicological impacts
 - ecotoxicological impacts

- photo-oxidant formation
- acidification
- eutrophication (incl. BOD and heat)
- odour
- noise
- radiation
- casualties
- *pro memoria*: flows not followed up to system boundary
 - input related (energy, materials, plantation wood, etc.)
 - output related (solid waste, etc.)

The Working Group proposes an operational method for characterization for only very few impact categories. For most impact categories, there is either no consensus on which method to choose, or there is no appropriate method. It is also recognized that some impact categories may have to be split into a number of subcategories, because the impact category itself can as yet not be addressed. For instance, Guinée *et al.* (1996) divide the impact category ecotoxicological impact into aquatic ecotoxicity and terrestrial ecotoxicity.

The mathematical structure of the characterization step is as follows:

$$\text{impact score}_{\text{category}} = \sum_{\text{type}} \text{equivalency factor}_{\text{category, type}} \times \text{intervention amount}_{\text{type}} \quad (2.1)$$

For instance, if the environmental interventions are atmospheric emission of 12 kg CO₂ and 4 kg CH₄, and if we have adopted the global warming potentials (GWPs; see, e.g., Heijungs *et al.*, 1992a) as equivalency factors for the impact category of global warming, we have the following:

$\text{intervention amount}_{\text{CO}_2} = 12 \text{ kg CO}_2$;

$\text{intervention amount}_{\text{CH}_4} = 4 \text{ kg CH}_4$;

$\text{equivalency factor}_{\text{global warming, CO}_2} = 1 \text{ kg CO}_2\text{-equivalent/kg CO}_2$;

$\text{equivalency factor}_{\text{global warming, CH}_4} = 11 \text{ CO}_2\text{-equivalent/kg CH}_4$;

$\text{impact score}_{\text{global warming}} = (1 \text{ kg CO}_2\text{-equivalent/kg CO}_2 \times 12 \text{ kg CO}_2) + (11 \times 4 \text{ kg CO}_2\text{-equivalent/kg CH}_4) = 56 \text{ kg CO}_2\text{-equivalent}$.

To enable a more concise discussion, the terms to be used in the mathematical expressions will be abbreviated to mere symbols, as much as possible in conformity with the recommendations from SETAC-Europe (Heijungs & Hofstetter, 1996)). Thus the above expression reduces to

$$S_j = \sum_i Q_{ji} \times m_i \quad (2.2)$$

In this equation, m_i represents the intervention amount of type i , which is often a mass, expressed in kg, but which may also be expressed in other units, like m³, m²·yr, *et cetera*. S_j represents the impact score on the j th impact category, and Q_{ji} represents the equivalency factor or characterization factor that connects intervention i to impact category j .

2.3 — The Dutch Eco-indicator 95

The *Eco-indicator 95* is conceived as “an easy-to-use instrument with which environmental aspects can be integrated into the design process” (Goedkoop, 1995, p.5). The idea is that the environmental impacts of a certain product can be approximated by the environmental impacts of the constituting materials plus some environmental impacts due to processing and transport. If the environmental impacts of a substantial amount of important materials (like

aluminium and glass) are known, and if the impacts of the additional processes (like rolling of steel and transport by truck) are known as well, the environmental impact of the product is easy to estimate in many cases.

There is one important aspect that is essential for the eco-indicator concept: easy-to-use requires that the environmental impact is expressed as one single number. The above mentioned characterization results in a set of numbers, one for global warming, one for ozone depletion, *et cetera*. The *Eco-indicator 95* therefore contains a valuation methodology to weight the characterization scores to one environmental index, which is called an eco-indicator. The valuation principle chosen is based on a distance-to-target principle. It is foreseen that the valuation principle of the Dutch *Eco-indicator 97* that is now being developed will be based on a panel procedure instead of a distance-to-target principle.

2.4 — Input-related interventions and impacts

A life cycle inventory analysis concentrates on compiling a product system's inputs and outputs of "elementary flows" from and to the environment. The result of the inventory analysis (often called the inventory table) contains a large number of items (the environmental interventions) that represent specified amounts of specified inputs from and outputs to the environment. Output items are, for instance, an atmospheric emission of 23 kg CO₂, an aquatic emission of 1 mg mercury, and a heat release of 120 MJ. Input items are, for instance, the consumption of 2 kg bauxite, the consumption of 3 whales, and the use of 15 m²·yr land for agricultural purposes.

Several characteristics may be observed:

- the specification contains a quantitative ("23 kg") and a qualitative ("atmospheric emission of CO₂") part;
- the quantitative specification is in terms of amounts ("23 kg") and not necessarily in terms of flows or fluxes (like "23 kg·yr⁻¹");
- the quantitative specification is in terms of different types of units ("kg", "species", "m²·yr");
- the qualitative specification may be more or less detailed, ranging from coarse (like "organic compounds to air") to very detailed (like "Hg²⁺ to the Baltic Sea").

These characteristics give rise to a number of concepts that are sometimes discussed in connection with LCA, characterisation, or input-related interventions and impacts.

Units and magnitudes

An LCA most often focuses on an arbitrarily chosen functional unit of product, such as "10 loaves of bread" or "10 m² floor covering". There is no connection with actual consumption or production levels, and the fact that the functional unit is an amount and not a flow or flux (like "10 loaves of bread per day") explains the units of the interventions. Moreover, it introduces a certain degree of unspecificity: we are interested in 10 loaves of bread of a certain type, without specifying at which time at which place the bread is exactly produced or consumed. These facts make that LCA can not aim to predict actual environmental impacts, but rather deals with environmental interventions in a generic way. For instance, the release of a toxic substance is interpreted in terms of intrinsic potential harmfulness, thereby neglecting specific information like the background concentration of the same and other toxic substances, the number of people that are living in the vicinity of the point of release, *et cetera*. For resources, it means that we do not aim to tell that this product is responsible for logging a specific tree, or for the death of the penultimate elephant.

Lack of spatial differentiation

Related to the above point, it means that there is in general – as a default – no spatial differentiation in the characterization. In LCA, it is seldom specified if a chemical is released indoor or outdoor, in urban or in rural areas, or in tropic or in arctic zones. The same applies to the input-related interventions, although it is clearly felt that use of water in the Middle East might represent a more serious environmental problem than use of water in Bangladesh.

What is the input precisely?

We see that the inputs are theoretically expressed as the “ore” and not as the useful “material” that can be obtained from the ore. For instance, the inventory table lists bauxite, elephants and trees instead of aluminium, ivory and wood. On the other hand, many inventory tables specify the material of concern, like “iron in ore”. Consequently, most available lists of equivalency factors are expressed in terms of iron, copper, *et cetera*.

Categorizations of inputs

It may be observed that the resources may be categorized in different ways.

Some resources are of an abiotic origin (like ores), while others are of a biotic origin (like elephants and trees) (Heijungs *et al.*, 1992). There are also resources which are not living but which originate from living organisms (like fossil fuels). Their categorization is sometimes biotic and sometimes abiotic.

Another categorization is that into renewable and non-renewable resources (Fava *et al.*, 1993; in that text the terms flow resources and stock resources are used for renewable and non-renewable resources respectively). Renewable resources coincide more or less (but not completely) with the biotic ones, and non-renewable resources coincide ones more or less with the abiotic ones.

A third categorization is that into deposit resources, fund resources and flow resources (Finnveden, 1996). Deposits resources are resources that can only be depleted because they do not regenerate; for instance mineral ores. Fund resources are those resources that can be used or depleted, since they possess the capability of regeneration. So far, there is a large correspondence with the renewability criterion. The new element is introduced by separately considering flow resources, which are resources that can only be used, not depleted, like solar radiation and wind. It should be emphasized that the meaning of the term flow by Fava *et al.* (1993) corresponds to Finnveden's (1996) funds and flows, while Fava's stock resources correspond to Finnveden's deposits. The only exception is land, which Fava *et al.* categorize under stocks, whereas it has a separate place in Finnveden's scheme.

Finally, the set of resources is sometimes divided into two or more categories on the basis of functional characteristics. Energy carriers and non-energetic resources is one instance of such a functional categorization (Baumann *et al.*, 1992). Another instance is that into production functions, regulation functions, information functions and carrier functions (Sas *et al.*, 1996; actually this distinction was only proposed in the context of biotic resources). Production functions, for instance relate to the production of matter for food, construction, *et cetera*, to the production of genetic information, and to the production of energy carriers like wood. Regulation functions relate to the absorbing capacity of the environment for waste material and maintaining the life support function, *e.g.*, with respect to the large cycles of C, N and water and the climatic structures. The information function relates to how we appreciate the existence of nature, and the carrier function to the substrate of our human condition, in particular soil and water surface.

This report uses the categorization abiotic resources, biotic resources and land to enable a clear discussion in Chapters 3, 4 and 5 respectively.

Use versus consumption and depletion versus competition

A distinction can be made between use and consumption of materials and land (Finnveden, 1996). Use then means an "occupation" which is of an intrinsically limited duration. For instance, a certain area of land may be used for a certain time, and the same applies to a certain amount of copper. On the other hand, consumption denotes a final act, with an associated permanency. For instance, a certain amount of available energy may become less available or a tree may be cut.

Related to this is the distinction between depletion and competition (Finnveden, 1996). Depletion indicates a situation that a certain commodity is unavailable for future generations, while competition indicates the situation that the commodity is unavailable for everyone at the same time.

Clearly, resources that are only used (like solar energy) can not be depleted: only competition is at stake. Resources that can be consumed (like fossil fuels) can of course be depleted, but competition may also be relevant, although it will often be dominated by depleting impacts (Finnveden, 1996). More generally, the scheme of Figure 2.1 arises in connection with the previous point.

	use	consumption
depletion	—	deposits, funds ¹
competition	flows, funds	—

¹ Only those funds for which the annual consumption exceeds the annual regeneration (non-sustainably harvested funds, see Finnveden (1996)) can be depleted.

FIGURE 2.1. The relationship between use/consumption, depletion/competition, and deposits/funds/flows.

Müller-Wenk (1997) introduces the distinction into destructive use (like combustion of oil), dissipative use (like the case of zinc) and non-dissipative use (like the case of gold). The situation of dissipative use is often – but not necessarily – connected to pollution-related problems, like ecotoxicity.

A framework for discussion

Following SETAC-Europe's state-of-the-art (Udo de Haes, 1996), a framework has been proposed for discussing impacts of output-related interventions. It builds on the earlier attempts in terms of "levels of sophistication" (Fava *et al.*, 1993), but with the hierarchical "levels" redefined as independent "dimensions" and the "sophistication" redefined as more neutral "information". There are four such dimensions of information:

- effect information;
- fate information;
- background level information;
- spatial information.

Each characterization methodology can be defined as coordinates in the 4-space that is spanned by these four dimensions. For instance, the recent CML-RIVM-proposal for characterizing toxic releases (Guinée *et al.*, 1996) has the following characteristics:

- it is somewhere on the +side of the effect dimension, since it is based on toxicological data, and not on simple rules or political standards; on the other hand it is not on the extreme +side, since the toxicological data is often based on extrapolated single-species toxicity data;
- it is quite on the +side of the fate information, since a multi-media model is incorporated;
- it is on the -side of the background level dimension, since background levels nowhere enter the characterization model;
- it is quite on the -side of the spatial dimension, since the only differentiation that is included is that between four emission compartments: air, surface water, industrial soil and agricultural soil.

It should be emphasized that the change from sophistication to information implies that being on the +side is not obligatory.

Udo de Haes (1996) furthermore assumes that the dimensions of information can also be used to categorize characterization methodologies for input-related interventions. Effect information should consider the extent to which a good measure of impact is included and fate information should consider the extent to which regeneration processes are included. Background levels could represent use levels and spatial information could allow to distinguish between a resource here and a resource there.

Safeguard subjects and areas for protection

Many texts on impact assessment elaborate a number of impact categories "top-down", that is, they first define a number of safeguard subjects (Steen & Ryding, 1993; Müller-Wenk, 1997) or areas for protection (Consoli *et al.*, 1993) and choose with that in mind a set of impact categories that are to be addressed during characterization. Common sets of subjects/areas are:

- biodiversity, production, human health, resources, aesthetic values (Steen & Ryding, 1993);
- human health, ecological health, resources (Fava *et al.*, 1993).

We may observe that many subjects/areas are directly and indirectly affected by many types of impacts. For instance, toxic releases directly affect human health, but they do so also indirectly, through decrease in crop production. It is difficult to define a consistent (that is, complete and independent) set of safeguard subjects or areas for protection, and to indicate an unambiguous relation with a consistent set of impact categories. Consoli *et al.* (1993) make an attempt for this (see their text on *classification*), with obvious shortcomings, for instance in defining direct and indirect connections.

The exact meaning (and therefore content) of the different safeguard subjects differs from text to text. For instance, while most authors share the reduced availability of biotic resources under the safeguard subject of resources, Müller-Wenk (1997) puts it under ecosystem health (or rather: ecosystems). The exact perception of the environmental problems that are associated with extraction of resources and use of land is decisive for the way it is operationalized. In the next chapters, we will see that this perception differs to quite some degree among LCA-theorists.

Characterization in relation to valuation

In §2.2, characterization was defined in terms of providing an interpretation of environmental intervention into environmental impact categories. Although there is agreement on a default classification list, it may be interesting to analyze in some more detail the procedure.

By introducing the difference between characterization and valuation, and therefore by introducing the default classification list, we have decomposed this part of the impact assessment into two parts:

- a more or less objective part, in which natural scientific knowledge is used to approach impact categories (characterization);
- a more or less subjective part, in which normative play a dominant role (valuation).

It is clear that the words "more or less" are required here: the choice of impact categories to be approached and to some extent the way they are operationalized is subjective. Moreover, the subjective valuation may be guided through contemplation of quite objective information on the state of the environment, the foreseen trends, and the environmental mechanisms that come into play.

The present set-up has been built, more or less, bottom-up. That is, we started with an inventory that produced environmental interventions, we were able to characterize these into a number of impact scores, and a final aggregation was left to be performed on the basis of societal judgment. The fact that some of the impact categories are so abstract that they are difficult to value is then ignored or sometimes repaired by the introduction of normalization.

There is an increasing tendency to reverse this state of affairs. Braunschweig *et al.* (1996) provide an extensive discussion in what might be called the top-down approach. First a number of safeguard subjects is defined. These are defined in such a way that they are supposed to be accessible to the human value-setting system. Then, working backwards, impact categories are defined that can be linked to these safeguard subjects. Finally, this leads to requirements to the type of information that the inventory analysis is expected to provide.

It should also be emphasized that the structure of the impact assessment is and will be constructed as a compromise between ideal considerations and practical limitations, and therefore as a compromise between the bottom-up approach and the top-down approach. This implies that, although we would like to calculate impact scores on the level of perceptible safeguard subjects, we are bound to calculate scores at some intermediate place in the cause-effect chain. For instance, although we would like to assess the consequences of greenhouse gases for human health, we cannot even assess these gases in terms of climate change. The only thing that is currently available with sufficient accuracy is radiative forcing. However, this is difficult to perceive in a normative valuation. The trick that is assumed to solve this, is that the impact category radiative forcing is declared to be an indicator for consequences further down the causal chain, and hence also for the threat to human health.

In the context of resource extraction and land use, the subjective choice of impact categories is of particular interest. It turns out that the environmental problems that are associated with resource depletion and land use may be perceived in many different ways. Consider, for instance, the extraction of a certain animal. One may attribute a kind of human rights to animals, and thereby operationalize an impact category. But one may also look at the function for mankind of the species at hand. One may also approach it from the angle of ecosystem stability, thereby for instance concentrating on the role in the food chain. The important thing is that all these perceptions of the value of an animal lead to different sets of impact categories and different methods for operationalization.

The question of validation

In describing methods for characterizing resource extraction and land use, it is tempting to look for "scientific evidence" in the same way as characterization models for global warming, toxicity or acidification has to some extent been scientifically validated. It should be made clear that this is impossible (Guinée & Heijungs, 1995; Finnveden *et al.*, 1996). Since one can prove that mercury is more toxic and more persistent than CO, it is plausible that equivalency factors for toxic impacts for mercury should be higher than for CO. One can also – to some extent – prove that the reserve of manganese is larger than that for tin, and that the societal demand is larger as well. But does this imply that the equivalency factors for resource depletion for tin should be higher than for manganese? There are many reasons to doubt so. This of course depends strongly on the way the depletion problem is perceived. It makes a large difference if human welfare is the safeguard subject that relates to depletion, or if it is the life-support function that may be derived from ecosystem health. Also, the sustainability perspective may make a large difference. For instance, one might argue that depletion of fossil fuels is not a severe problem because future generations may employ renewable energy sources. But one might argue as well that this poses an unfair duty to future generations. All in all, it is clear that a characterization method for resource extractions and land use is much less objective and scientific than characterization methods for most output-related impact categories.

The next three chapters give an overview of a number of methods for characterizing the impacts associated with the extraction of abiotic resources, biotic resources and land use. The section thereafter assesses these methods on the basis of a number criteria. This reports uses the following criteria:

- compatible with the principles of life cycle assessment;
- compatible with a reasonable definition of the associated environmental problem;
- no double counting;
- unambiguous/no arbitrary elements involved;
- operational/easily operational.

Of course, one may disagree with these criteria. But the authors feel that one must be clear in defining the assessment criteria.

3 — Extraction of abiotic resources

3.1 — Overview of the problem

Of the three intervention types that are considered in this report (extraction of abiotic resources, extraction of biotic resources and land use), extraction of abiotic resources is the most intensely studied one in the context of LCA. This may be explained by LCA's historic roots in energy analysis, where there was an obvious desire to aggregate different energy carriers into one single score.

The environmental problem that is associated with the extraction of abiotic resources is nowadays interpreted in different ways. Corresponding to these different interpretations, several characterization methods have been proposed; see §3.2. This section will be concerned with discussing the aspects that are to be considered in connection with abiotic resources.

The extraction of abiotic resources is responsible for a large number of environmental problems. Major categories are:

- The impacts connected with mining and/or purification; these impacts will not be considered in this report, because it is presumed that the production of (dangerous) waste, the release of (polluting) substances and the use of energy and materials has found a proper place somewhere else in the LCA (*cf.* Heijungs & Guinée, 1996).
- The impacts connected with landscape occupation and/or exploitation; these impacts will be considered in Chapter 5 on "land use".
- The impacts connected with the reduced availability of the resource; this will be the main focus of this chapter.

Even with the above limitation in scope in mind, there is a wide array of aspects that might be considered. We mention the following:

- The depletion of the reserve.
- The loss of use options for future generations.
- The increase of environmental impacts of mining in future because the easily accessible ones will be depleted first.

Depending on the exact perception of the depletion problem, a wide array of characterization methods may be developed. The discussion in §3.4 and §6.2 will go into the question of sensibility.

3.2 — Survey of existing and proposed methods

Fairly recent overviews of characterization methods for extraction of abiotic resources are provided by Finnveden (1994), Lindfors *et al.* (1995), Finnveden (1996) and, to a lesser extent, Guinée & Heijungs (1995). Their overviews have been reproduced here, supplemented with a number of more recently published proposals.

Proposal 3a

It is sometimes proposed to aggregate abiotic resources on the basis of their mass (Baumann *et al.*, 1992):

$$S_{3a} = \sum_i m_i \quad (3.1)$$

Some authors propose to distinguish a number of subcategories within this procedure, so that the equation becomes a set of equations rather than a single equation:

$$\begin{aligned} S_{3a1} &= \sum_{i \in C_1} m_i \\ S_{3a2} &= \sum_{i \in C_2} m_i \\ &\dots = \dots \end{aligned} \quad (3.2)$$

Examples of sets C_j of subcategories are (Lindfors *et al.*, 1995):

- renewable versus non-renewable;
- deposits and funds versus flows;
- reversible use versus irreversible use.

Proposal 3b

Several authors propose to aggregate abiotic resources, or at least energy carriers, in energetic terms (Baumann *et al.*, 1992; Van den Berg *et al.*, 1995). The procedure to be followed is

$$S_{3b} = \sum_i \varepsilon_i \times m_i \quad (3.3)$$

where ε_i is the specific energy (or: energy content) of the indicated energy carrier, *e.g.*, 36 MJ·m⁻³ for natural gas. A variety of interpretations of this energy content exists. Examples are:

- only non-renewable energy carriers versus also wood and other renewables, sometimes even solar energy;
- only energy carriers when used for energy conversion versus also energy carriers when used for producing plastics or other products.

It is also possible to distinguish a number of subcategories according to the above criteria; see *proposal 3a* for some examples.

Proposal 3c

It is often proposed to weight an abiotic resource with a measure of the available reserve (Heijungs *et al.*, 1992a):

$$S_{3c} = \sum_i \frac{m_i}{R_i} \quad (3.4)$$

Here R_i denotes the reserve of the abiotic resource measured in the same unit as the extracted amount m_i . For instance, natural gas is measured in m³ and coal in kg. Several choices for the reserve are possible (Guinée & Heijungs, 1995; see Heijungs *et al.*, 1992b for another categorization):

- the reserve base;
- the economic reserve;
- the ultimate reserve;
- the ultimately extractable reserve.

A choice between these types of reserves may be inspired by theoretical considerations, *e.g.*, the desire to include or exclude the present state of mining technology, but it may also be inspired by considerations with respect to data availability and/or data quality.

Proposal 3d

A modification to the above approach is one in which the global annual extraction of the resource (the production P_i) is introduced as well. The most frequent encountered form (Fava *et al.*, 1993; Guinée & Heijungs, 1995) is

$$S_{3d} = \sum_i \frac{m_i}{R_i} \times \frac{P_i}{R_i} \quad (3.5)$$

but alternative forms like

$$S_{3d'} = \sum_i m_i \times \frac{P_i}{R_i} \quad (3.6)$$

could be envisaged as well. Of course, the same range of possibilities for the choice of the reserve exists. For renewable abiotic resources (like fossil fuels), the annual production P may be corrected for the annual regeneration of that reserve, although the correction may be negligible in practice.

Proposal 3e

Some authors use the entropy or the exergy of a resource as a measure of aggregation, thereby interpreting the availability of a resource in terms of low entropy. Entropy is a thermodynamic quantity that may be interpreted as a measure of randomness of the system. The entropy of a metal in a high quality ore is low, the entropy of the same metal dispersed around the world is high. Exergy is a quantity that refers to the amount of available or useful energy. The energy that can be obtained from a body, by combustion, by heat transfer, or by any other means, depends on the state of the surroundings. For instance, a heat reservoir of 20° C can be used to release energy only if the surroundings have a temperature that is lower than 20° C. Exergy can thus be said to correct energy according to its quality. It can, however, also be used to indicate the resource quality of a non-energetic resource.

Finnveden & Östlund (1996) propose the exergy measure for abiotic resources. Their expression can be written as

$$S_{3e} = \sum_i \varepsilon_i \times m_i \quad (3.7)$$

where ε_i is the specific exergy (or: exergy content) of the resource that is indicated by i . Expressions for the specific exergy may be constructed from the partial molar chemical exergy and the Gibb's free energy for the formation of the compound (see Finnveden & Östlund (1996)).

Blonk *et al.* (1996) consider more than only the exergy of the resource: they also take into account the energy and material requirements of the extraction and purification process, and the exergy that is carried with outputs other than the one of interest, like tailings.

Ayres & Ayres (1996) apply the exergy concept at an even broader way. They perform an exergy analysis of the full product system, so of the entire life cycle. In this way they deliberately use exergy as a measure for the entire functioning of the life cycle, to account for extraction of resources as well as formation of waste and harmful pollutants.

Proposal 3f

Hauschild (1996) describes a method which they themselves do not wish to call characterization. They use the terms normalization and valuation instead. Nevertheless, it can in the present context be regarded as a characterization methodology. It must be emphasized that their proposal is in Danish, and that our Danish is probably insufficient to fully understand and appreciate the approach. The following exegesis is therefore somewhat speculative. An English translation is scheduled to appear in a few months (Hauschild & Wentzel, 1997).

The approach is based on a "normalization" of the product's resource use on the basis of the annual production per capita of that resource. The "normalized" scores are next "valuated" by dividing by the depletion time of the resource. All together, the approach amounts to the following:

$$S_{3f,i} = \frac{m_i}{T \times R_i / W} \quad (3.8)$$

where W is the world population and T is the duration of the functional unit. Aggregation of the different S_i for the different resources into one overall depletion score is not recommended.

Proposal 3g

Starting from a completely different point of view are approaches that translate depletion of resources into future impacts on one or more other impact categories. Several methods have been elaborated.

Steen & Ryding (1993) characterize resources by considering the environmental impacts of sustainable mining processes. For metals, for instance, the sustainable process is defined as mining with renewable energy sources, under the assumption of a sustainable ore grade that is one-tenth of the present ore grade.

Joliet & Crettaz (1996) follow an unreferenced source "(Weidema, 1995)", in which the energy that is required to bring resources back into their initial state is proposed. For minerals, for instance, the energy that is required to concentrate the metal from the average concentration in the earth crust to the average concentration in ores.

Blonk *et al.* (1996) propose to consider the future claim on the key resources energy and land. So, they, in addition to exergy (proposal 3e), translate resource extraction into land use. The claim on energy is operationalized as

$$S_{3g1} = \sum_i \frac{\rho_i - \rho'_i}{\rho'_i} \frac{k_i}{\rho_i} m_i \quad (3.9)$$

Here ρ_i denotes the present ore grade of material i and ρ'_i the future ore grade. It is proposed to use a time horizon of fifty years. The factor k_i is a constant that measures the relationship between the claim on energy and the ore grade, which seems to be 0.4 MJ/kg for many metals. The ore grades in the future may be modelled, for instance by CAG models that model the crustal abundance of ores.

The second impact category for Blonk *et al.* (1996) is the future claim on land:

$$S_{3g2} = \sum_i (n_r - n_a)_i \times T_i \times a_i \quad (3.10)$$

In this equation, a_i represents the size of the area of type i that is affected by the extraction activity, although it is also suggested that the increased land claim after, say, 50 years should be used in the equation. Furthermore, N_a represents the quality of the actual land use and N_r

the quality of the land in an unaffected state, the reference value (see also Chapter 5, proposal 5d). Finally, T represents the time period of the quality loss.

Proposal 3h

Müller-Wenk (1997) approaches the extraction of abiotic resources from the side of the safeguard subject (which is called resources, and which does not reflect extractions of biotic resources). He gives the following equation:

$$S_{3h} = \sum_i \frac{P_i(0)}{R_i(0)} - \left[\frac{P_i(1)}{R_i(0)} \right] (1+k_i) \quad (3.11)$$

In this equation, $\frac{P_i(0)}{R_i(0)}$ denotes the depletion time of the i th resource at a certain time, while

the same quantity with (1) instead of (0) denotes the depletion time in the next year. The reserve is meant to encompass both the natural reserve as well as the "technostock", which is defined as the "resource stocked in the technosphere". Finally, k_i expresses the yearly improvement of resource productivity, for instance, due to more efficient electricity production. It is not indicated where the functional unit enters the equation. The same equation is in particular investigated for energetic resources.

3.3 — Assessment results

It appears that there is a wide choice of methods for characterizing extraction of abiotic resources. It is important to observe that the choice of method is of more than theoretical interest. Different methods may lead to surprisingly large differences in the results. Finnveden (1994) showed that for an example product, a refrigerator, the use of coal contributes 28% to the total score according to one method while it contributes 0.02% according to another method. Uranium contributes 0.03% and 67% respectively. Thus, different optimization strategies will result from the use of different methods. Similarly, a comparison between alternative products will with one method favour a certain alternative, while it will disfavour that alternative under another method.

Several authors give arguments why their proposal is to be favoured to that of others. For instance, Guinée & Heijungs (1995) argue that aggregation on a mass basis is incorrect for reasons of dimensional arbitrariness, and Fava *et al.* (1993) argue that an energetic measure is not an adequate basis for impact assessment. Other texts are less clear in rejecting certain ideas, either because their main purpose is to give an overview (*e.g.*, Finnveden, 1996), or because they concentrate on postulating one particular proposal (*e.g.*, Blonk *et al.*, 1996).

A choice between the methods is to be based on an assessment on the different criteria that were listed in §3.1.

proposal	compatible with LCA-principles	depletion problem defined in a reasonable	no double counting	unambiguous /no arbitrary elements involved	(easily) operational
3a	+	- [1]	+	- [2]	+
3b	+	+/- [3]	+	- [4]	+
3c	+	? [5]	+	+/- [6]	+/- [7]
3d	+	? [8]	+	+/- [9]	+/- [10]
3e	+	- [11]	+/- [12]	- [13]	+/- [14]
3f	? [15]	? [16]	+	+/- [17]	- [18]
3g	+	? [19]	+	- [20]	- [21]
3h	- [22]	- [23]	+	- [24]	- [25]

Explanatory arguments

- [1] It is questionable whether aggregation of materials in mass terms represents a good indication of the environmental problem of depletion. The extraction of 1 kg of a very rare material would in that case be equally serious as the extraction of 1 kg of an abundant material. This is usually not what people think of when speaking about resource depletion.
- [2] Aggregation in mass terms contains one very arbitrary element, namely the choice for mass. One could have chosen volume or number of molecules as well.
- [3] As long as only energy carriers are characterized in this way, the proposal is quite defensible. But when non-energy carriers are excluded, and when energetic materials that are not exclusively used as a source of energy are included, one obtains strange results. For instance, building materials with a zero energy content are excluded, while inflammable building materials are included.
- [4] The energy-content of a material is not fixed, as it depends on the circumstances. For instance, engineers distinguish between upper heating value and lower heating value. And Einstein's introduction of the rest energy of a material body gives a still substantially different result.
- [5] Depending on the definition of the depletion problem, it is sometimes argued that not only the reserve, but also the societal interest in the resource is important. This view would disfavour this proposal (as well as some others). See also [8].
- [6] The arbitrary element that may be involved is the choice for the type of reserve used in the calculation. Some choose the proven reserve, while others choose the ultimate reserve.
- [7] The reserve of many resources is not accurately known. This applies especially for more speculative measures, such as the ultimate reserve. On the other hand, lists have been constructed for this purpose (see Heijungs, 1992a).
- [8] Depending on the definition of the depletion problem, it is sometimes argued that it is only the reserve that is important, and not the societal interest in the resource, at least from the viewpoint of the environment. This view would disfavour this proposal (as well as some others). See also [5].
- [9] See [6].

- [10] See [7]; for a list, see Guinée (1995).
- [11] For energy carriers, it is defensible that exergy measures the quality of the energy and thereby the availability of energy. For non-energetic resources and for resources that have an energy-content but that are largely not used for energy conversion, it may be observed that exergy measures the availability of another entity than that of interest.
- [12] The exergy concept may be introduced in LCA in different ways. Some of the present approaches include in one or another way emissions, wastes and coproducts in the calculation, flows which are already accounted for in other ways in LCA. This easily introduces a double counting of emissions, wastes and coproducts.
- [13] The concept of exergy requires a reference level, a zero exergy level. There are certain conventions for this, but these remain conventions with some degree of arbitrariness.
- [14] Exergy calculations seem to be laborious; on the other hand, Ayres & Ayres (1996) provide an extensive list.
- [15] This proposal can to some extent be said to violate the prevailing LCA-structure. The method transforms an extraction of a resource into a number on the basis of the reserve, but does not use the transformed result for interpretation into a common denominator (a depletion score). It keeps separate all individual resources, and leads to a somewhat unbalanced valuation procedure: aggregated impact categories, like acidification and global warming, must be weighted along with unaggregated interventions, like copper and zinc.
- [16] See [5]. Although the societal interest in the resource has been incorporated in the derivation of the method, it is absent in the equation.
- [17] See [6].
- [18] See [7]. We are not aware of a list.
- [19] By considering the depletion problem as the fact that there will be more impacts in future, it is implied that the reserve as such does not represent any environmental value. This attitude is at least not generally accepted.
- [20] There quite a few arbitrary elements involved in this approach. We mention the fact that depletion is translated into future impacts, while the same could be done for health impacts (increased care), acidification (increased agricultural efforts), global warming (increased coastal management), and many other impact categories. We also mention the time horizon that is used to assess the future, the expected ore grades at that time, the impacts that will arise by the then prevailing technology, *et cetera*.
- [21] All the elements that were mentioned in [19] do not only involve value choices, but also imply data problems. Especially future ore grades and future impacts may be difficult to estimate.
- [22] It is unclear how the interventions that are associated to a functional unit fit into the approach.
- [23] In principle, one may indeed argue that the "technostock" is a relevant quantity in characterization. There is, however, a large difference in degree of availability of these economic reserves, which is not accounted for in this proposal. Stored aluminium is a direct available reserve, aluminium in aircrafts is not because it belongs to an airline company that does not want to sell it, and aluminium in dump sites is although economically available, perhaps not technically easy to obtain. It is therefore unclear what the depletion time of the economic reserve signifies.
- [24] Again, the choice for which measure of reserve is used is debatable. One other arbitrary element here is the time period of one year that is used to determine the stock change.
- [25] The geologic reserves are not very well known, neither is the economic reserve, and

neither is the yearly increase in resource productivity. This latter factor may also be application-dependent.

3.4 — Discussion

From the previous section, we conclude that there is no method that is good on all criteria. Especially the criteria with respect to a reasonable definition of the depletion problem, the absence of arbitrary elements and the degree of operationalization are often problematic. Proposals 3b, 3c and 3d are perhaps to be preferred for the moment. The choice for an approach to be elaborated in future is more difficult.

It appears that a good definition of the environmental problem is crucial. So, the question is raised what exactly constitutes the environmental problem or problems that is or that are related to the extraction of abiotic resources. Important aspects for this problem definition, such as the abundance (for example measured by the reserve) and the societal importance (for example measured by the annual production), refer to the importance of having possibilities for deriving material welfare. But there are more aspects to be considered in defining the problem of depletion. Firstly, the proven reserve is for some minerals constant for a number of decades already. Mining companies have an obvious interest in confining their exploration activities, for reasons of budget constraints, but also for reasons of pushing up prices by proclaiming an artificial scarcity. Next, there is the argument of substitution. Solar energy may well replace fossil energy to an ever larger extent, for purely economic reasons. It might even be argued that the scarcity of fossil fuels compels us to use even more fossil fuels for the speedier development of solar alternatives. A third argument requires a more economic argumentation. With resources, their functionality in relation to consumption is ultimately what may create the depletion problem. Hence, this functionality should somehow play a role. Usually, the functionality is expressed in prices, as it is the functionality that creates the demand. In general, an adequate pricing scheme can take care of intergenerational justice and leave future generations as well off as current ones in respect to the resource use in question. High prices now with savings and investments helping raise future welfare, can compensate for lower amounts of physical resources at future times (Baumol & Oates, 1975, Chapter 5). The pricing system as it is then may reflect more or less the "right" price already and there is no environmental externality to compensate for. Hence no characterization would be needed. This of course holds for priced resources only, as is the case with most minerals and energy resources. Such reasoning has to be worked out further before a better founded characterization model can be set up. The reader is referred to §6.2 for a more complete discussion of suchlike recommendations for future research.

4 — Extraction of biotic resources

4.1 — Overview of the problem

The literature with respect to the incorporation of impacts from extracting biotic resources is far less abundant than that with respect to abiotic resources. This has probably to do with the fact that biotic resources are less often associated with the material side of modern society. Although it is of course acknowledged that especially food products pose a severe claim to biotic resources, these resources are most often produced by man-managed farms or plantations, and therefore not considered as a natural resource and certainly not as a depletable resource. Indeed, the question what is extracted needs some reflection in the case of, say, sustainable harvested wood from plantations. There is a certain input of nutrients, but this will also often be a man-supplied resource. There is of course a claim on land, see the next chapter. And there will be inputs which can be traced back to abiotic resources and emissions, for instance related to logging activities or pesticide use.

The use of biotic resources is connected to the choice of system boundary with respect to the economy-environment discussion during the inventory analysis. It is most often decided that harvest from farms and plantations is not regarded as an extraction and should therefore not be assessed during characterization (see the discussion on system boundaries and impact categories, *e.g.*, Udo de Haes, 1996). Farms and plantations of course do have other types of impacts, due to land use, pesticide use, ammonia emissions, *et cetera*. But the extraction problem is only considered to be there when biotic – non-cultivated – resources are taken from nature.

4.2 — Survey of existing and proposed methods

Brief overviews of characterization methods for extraction of biotic resources are provided by Finnveden (1996) and Guinée & Heijungs (1995). Again, some recently published proposals have been added to these earlier overviews. Lindfors *et al.* (1995), which is otherwise a quite complete source of proposals for characterization methodologies, does not discuss biotic resources.

Proposal 4a

Proposals in which the size of the population is used in conjunction with the net depletion rate are provided by Heijungs *et al.* (1992), Fava *et al.* (1993), and Guinée & Heijungs (1995).

$$S_{4a} = \sum_i \frac{m_i}{R_i} \times \frac{P_i}{R_i} \quad (4.1)$$

Proposal 4b

Along a completely different line is Sas *et al.* (1996). This feasibility study distinguishes the harvest of individuals (like logging one tree) from the destruction of an ecosystem (like

cutting a forest), and describes impacts on biodiversity and the life-support function. Three types of impact scores are proposed:

$$S_{4b1} = \sum_i m_i \times \frac{T_i}{R_i} \quad (4.2)$$

to indicate the risk on the extinction of species by harvesting an individual;

$$S_{4b2} = \sum_i A_i \times T_i \times \rho_i \quad (4.3)$$

to indicate the risk on the extinction of species by destructing an ecosystem; and

$$S_{4b3} = \sum_i A_i \times T_i \times NPP_i \quad (4.4)$$

to indicate the decrease of the life-support function. In these equations, T_i denotes the restoration time of biotic resource i or ecosystem i , for instance the time from birth to maturity, ρ_i denotes the species density within ecosystem i , A_i the area of ecosystem i that is disrupted, and NPP_i the net primary production of ecosystem i .

Proposal 4c

Sometimes a qualitative scoring on the basis of red lists of endangered species or ecosystems is used. In that case, a statement like "contains tropical hardwood" is made. We are, however, not aware of methodological reports in which this approach is proposed.

Proposal 4d

Hauschild (1996) declares his proposal for abiotic resources (see 3f above) to be applicable for biotic resources as well. Thus:

$$S_{4d,i} = \frac{m_i}{T \times R_i / W} \quad (4.5)$$

is the basis of their "characterization" method, although – just like in 3f – the method does not allow for aggregation over different types of biotic resources.

Proposal 4e

Müller-Wenk (1997) puts classifies the extraction of abiotic resources under the safeguard subject ecosystem health, the same subject where ecotoxicity and acidification are located. The safeguard subject itself appears to be operationalized in terms of disrupted land surface, so with a close connection to land use (see next chapter). No formulas are given, and neither is it described how the connection between the damage to ecosystems and the extraction of one unit of species is made.

4.3 — Assessment results

The same procedure as in Section 3.3 will be followed.

proposal	compatible with LCA-principles	depletion problem defined in a reasonable	no double counting	unambiguous /no arbitrary elements involved	(easily) operational
4a	+	+/- [1]	+	- [2]	+/- [3]
4b	+	+	? [4]	- [5]	- [6]
4c	- [7]	+	+	- [8]	+
4d	? [9]	? [10]	+	? [11]	- [12]
4e	? [13]	+/- [14]	? [15]	+	- [16]

Explanatory arguments

- [1] The characterization is based on abundance and rate of depletion. Intrinsic differences between species are not included, and neither is the role of the species in an ecosystem or food chain.
- [2] The question of what constitutes a category is important in this approach. Are elephants one, or must we split elephants into two categories: Indian and African? Or must we even distinguish between small genetic variations in these groups? This question has, as far as we know, never been addressed in the context of LCA. The answer can, however, be decisive in a comparison between products or materials; see Heijungs (1995) for an illustration of such a difference.
- [3] For a selected number of generally accepted scarce biotic resources (like the elephant and the whale) numbers on reserve and annual production are more or less known. For the less scarce biotic resources (like the deer) such numbers are lacking.
- [4] It is unclear to what extent there is an overlap with the impact that are due to land use (Chapter 5).
- [5] One element that should be mentioned besides [2] is the dimension of ρ , the species density. Sas *et al.* (1996) argue that the affected area (A) should be expressed in the same unit of surface as the species density, *e.g.*, both involving m^2 or both involving ft^2 . However, it is reasonable to assume that ρ will not scale with this unit: we will most likely not see that $\rho (m^2) = 11 \times \rho (ft^2)$. Hence, the expression is not unit-invariant.
- [6] The method requires quite some data on restoration times, biomass production, species density, *et cetera*.
- [7] A qualitative scoring system is incompatible with the quantitative nature of LCA. A product which contains 1 mg ivory would be equally bad as a product that contains 1000 kg ivory.
- [8] The decision which species are on the red list and which are not is of course to some extent arbitrary, although one may argue that the authoritative bodies which decide on this issue must be taken for granted.
- [9] This proposal can to some extent be said to violate the prevailing LCA-structure. The method transforms an extraction of a resource into a number on the basis of the reserve, but does not use the transformed result for interpretation into a common denominator (a depletion score). It keeps separate all individual resources, and leads to a somewhat unbalanced valuation procedure: aggregated impact categories, like

acidification and global warming, must be weighted along with unaggregated interventions, like elephants and whales.

- [10] Depending on the definition of the depletion problem, it is sometimes argued that not only the reserve, but also the societal interest in the resource is important. Although the societal interest in the resource has been incorporated in the derivation of the method, it is absent in the equation.
- [11] See [2]. Because there is no aggregation over species, it is unclear to which this is a problem.
- [12] See [3]. We are not aware of a list.
- [13] It is unclear how the relation with the functional unit is made.
- [14] Depending on one's view, one might indeed argue that the problem of biotic extraction has to do with disruption of ecosystems. Other frequently heard arguments, like biodiversity, life-support function, intrinsic value and usefulness to mankind, are thus absent in this approach.
- [15] The degree to which there is a double counting depends on the way that land use itself is included.
- [16] It is probably difficult to introduce an appropriate quantitative relationship between biotic extraction and land disruption.

4.4 — Discussion

Like in §3.4, we observe that not any of the proposals is judged as completely satisfying. Nevertheless, we may identify some emerging lines. Proposal 4a is currently the most feasible one, while proposal 4b has perhaps the best prospects.

Again, like in §3.4, we see that underlying all proposals is a different perception of the environmental problem. For biotic resources, the situation is perhaps even more complex, because more aspects play a role. First, there is of course the question of availability for present and future generations, availability denoting here the possibility to use biotic resources for economic purposes. Secondly, there are the aspects of biodiversity, either direct or indirect through the function in the ecosystem or the food chain. Thirdly, we have the life-support function of biotic resources. Another complicating aspect is that, while the depletion of abiotic resources may be argued to have a global aspect, the local depletion of biotic resources may have local impacts to biodiversity, life-support and ecosystem health, but not to global biodiversity. These more local aspects could impose additional requirements to the inventory analysis. In §6.2 a proposal is made to more clearly discern the different types of impact: reduced availability, loss of biodiversity and damage to life-support.

We are also faced with a number ideological problems. The extraction of biotic resources may be compensated by "feeding" the environment. For instance, the phosphate emissions to the North Sea have an important positive influence on the fish population. And what if species are extinct in the environment, but survive in zoos or herbaria?

5 — Land use

5.1 — Overview of the problem

The problem that is associated with land use is not often addressed in LCA. This remark applies especially to case studies, where on the one hand data availability is limited and on the other hand the ideas on how to inventory and characterize land use are incomplete and quite diverse. In fact, the perception of what is to be understood by land use is far from clear. Some authors interpret land use in terms of a claim on surface, regardless the quality of the land and the disturbing aspects of the activity that is undertaken. The other extreme is that a careful analysis is made what type of land is disturbed for how long, including aspects like regeneration time and biodiversity.

5.2 — Survey of existing and proposed methods

One of the most comprehensive discussions on land use in relation to LCA is the *Ph.D.*-thesis by Knoepfel (1995). More restricted overviews are in Lindfors *et al.* (1995) and Blonk & Lindeijer (1995).

Proposal 5a

One of the simplest forms to characterize land use starts from the presumption that "land = land". Thus, the amount of land that is used in relation to a product life cycle is calculated, without wishing to distinguish between different forms of land use and without wishing to incorporate the original state. Baumann *et al.* (1992) and Jolliet & Crettaz (1996) follow this type of reasoning:

$$S_{5a} = \sum_i a_i \quad (5.1)$$

where a_i is the area that is occupied for a functional unit of product. The basic reasoning here is apparently that land use will compete out nature in the end.

Proposal 5b

Slightly more sophisticated is to distinguish a number of qualities of land use. Examples of categorizations are the following:

- natural systems, modified systems, cultivated systems, built systems and degraded systems (Heijungs *et al.* (1992), Wegener Sleeswijk *et al.* (1995));
- arable land, grass land, forest land and other types of land (Steen & Ryding, 1993).

Apart from differences in the characterization, also the inventory analysis may be different. Heijungs *et al.* (1992) suggest to measure changes due to the activity under consideration. For instance, if a farm is closed to allow for a factory, we might consider this as a transition from category III to category IV. Wegener Sleeswijk *et al.* (1995) propose to neglect history and concentrate on the actual land use instead of the transition. For them, the above mentioned situation would be typified as a category IV land use. Both sources propose the

measure of $m^2 \cdot yr$ for land use, instead of m^2 , like Baumann *et al.* (1992) do. Steen & Ryding also use the unit of $m^2 \cdot yr$.

Different impact scores may be formed. Heijungs *et al.* (1992) make the assumption that a transition from category III to IV is the only one that counts:

$$S_{sb} = \sum_i a_{III \rightarrow IV, i} \quad (5.2)$$

The characterization may therefore be said to be 1 (dimensionless) for the transition III \rightarrow IV, -1 for the reverse transition, and 0 for all other possibilities.

Knoepfel (1995) essentially reasons from similar principles. His conclusion is that a characterization of land use requires an intrinsically normative weighting between different types of land use (the categories I to V).

Proposal 5c

Fava *et al.* (1993) consider land as just one form of abiotic resources (in their language: a stock resource). This means that they effectively apply the same equation as for ordinary abiotic resources:

$$S_{sc} = \sum_i \frac{a_i}{R_i} \times \frac{P_i}{R_i} \quad (5.3)$$

The "reserve" R is the amount of land that is available, the "production" P is the amount that is yearly used. No differentiation between qualities of land or land use is suggested.

Proposal 5d

In a recent Dutch study (Blonk & Lindeijer, 1995), the discussion concentrates on the degradation of ecosystems and landscape as a consequence of land use. For this aim, the concept of nature value is introduced. The general characterization formula for degradation of ecosystems is

$$S_{sd} = \sum_i (N_{r,i} - N_{a,i}) \times a_i \quad (5.4)$$

Here, $N_{a,i}$ denotes the nature value during the activity (*e.g.*, the exploration of the mine), while $N_{r,i}$ denotes a reference value. Although several choices of this reference value may be considered, Blonk & Lindeijer propose the nature value of the situation that would be there without human intervention. The nature value N itself may also be measured in different ways. Blonk & Lindeijer propose to use the net biomass production (the *NPP*, see also proposal 4b), as it somehow indicates the functioning of the ecosystem.

They also discuss how to measure degradation of landscape as a result of land use. They conclude that this might be difficult to connect to LCA.

Proposal 5e

Müller-Wenk (1997) discusses the safeguard subjects human health, ecosystems and resources. Land use is then considered to be contributing to endanger ecosystem health. This safeguard subject is, nevertheless, proposed to be expressed in terms of disrupted land surface. This makes the connection between the intervention land use and the proposed safeguard subject straightforward.

5.3 — Assessment results

The assessment will again be made in a similar way.

proposal	compatible with LCA-principles	depletion problem defined in a reasonable	no double counting	unambiguous /no arbitrary elements involved	(easily) operational
5a	- [1]	- [2]	+	+	- [3]
5b	+/- [4]	- [5]	+	- [6]	- [7]
5c	+	? [8]	+	- [9]	- [10]
5d	+	+	- [11]	- [12]	- [13]
5e	+	? [14]	? [15]	+	+

Explanatory arguments

- [1] Baumann *et al.* state their proposals as if the intervention has the unit m^2 . Assuming this to be changed into $m^2\text{-yr}$, the approach is compatible with the inventory results.
- [2] If the problem is indeed defined as the use of land, a weighting between qualities of land is not necessary. This view will perhaps not be shared by many people.
- [3] Currently, most databases do not contain the relevant information with respect to occupation of land.
- [4] It can be argued that changes in land use are difficult to reconcile with the principles of LCA. If a forest is cut to make space for a bottle factory, we have a singular event, that cannot be allocated in a consistent way to an infinite large fleet of bottles. Proposals that look at the actual land use do not suffer from this inconsistency.
- [5] The coarseness of the categories is often felt to be a problem: it is impossible to distinguish *e.g.* intensive from extensive agriculture. Furthermore, the discussion between assessing the state or the change is not settled, nor is the question of how to define equivalency factors to aggregate the different categories of land use.
- [6] The choice of the categories contains a quite arbitrary element. Also, the attribution of a certain type of land use to one of these five types is to some extent ambiguous.
- [7] See [3]. Moreover, the type of land use is also most often unknown. An estimate is, however, often possible on the basis of the nature of the activity: farming will most probably take place in category III, while steel production will most probably take place in category IV.
- [8] Land is considered as a normal resource. This may lead to strange situations. As the total area that is available for airports is much smaller than that for tropical forests, the construction of a cafe on an airport will be judged as more problematic than the construction of the same cafe in the forest.
- [9] The definition of which types of land are distinguished is important in this approach and to a large extent arbitrary.
- [10] See [7].
- [11] Assuming that the impacts of, say, toxic releases are accounted for elsewhere, it is difficult to envisage how the productivity of the actual state can be decoupled from those toxic impacts.

- [12] The definition of a reference state is highly ambiguous.
- [13] See [7]. Net productivities will most likely be difficult to estimate.
- [14] It is questionable to what extent land use is connected in a linear way to ecosystem health.
- [15] The degree of double counting may be influenced by the way extraction of biotic resources are operationalized.

5.4 — Discussion

Again, we see that not any of these proposals is satisfying. In fact, they all have severe shortcomings, from a theoretical point of view, as well as from the practical side, the data availability. It is our feeling that we should not recommend any of these approaches for the moment. For future reference, proposal 5d is perhaps the most promising, although some theoretical questions have to be addressed in advance.

Another time we experience that it is the exact perception and hence definition of the environmental problem that is the crucial factor in constructing a satisfactory approach to characterize land use. Is it the pure use of land in its aspect of competing out nature? Or is it a problem of biomass production, and hence more related to the life-support function of ecosystems? And what about physical interventions in the ecosystem or landscape, leading to fragmentation of landscape, distortion of the soil and other aspects.

6 — Conclusion

6.1 — Recommended methods for characterization

It appears that none of the characterization methods for abiotic and biotic extractions and land use is unambiguously favoured. Nevertheless, some recommendations evolve.

For the moment, for abiotic resources it seems best to opt for the aggregation of energy carriers in energetic terms (3b), for the weighting of resources with their reserve (3c), or with a combination of reserve and annual production (3d). For biotic resources, a characterization on the basis of reserve and net production (extraction minus regeneration) is perhaps the best there is at the moment. For land use, no reasonable approach seems to be there. All recommended methods, however, are only recommended within the context of present operationalization.

On the longer term, none of them is satisfactory. The next section describes a number of arguments to be considered in future research. Especially the last topic can be regarded as a preliminary proposal to develop "depletion themes", in analogy to the broadly accepted pollution themes like acidification and global warming.

6.2 — Recommended future developments

This section ends up with a number of questions that is to be addressed when developing new or improved characterization approaches for input-related interventions.

Is land a deposit or a flow?

We have seen that most books on LCA-methodology express land use in terms of surface \times time, e.g., $m^2\cdot yr$. This has some consequences for the place of land in the conceptual scheme of deposits, funds and flows.

Land as a provider of surface may be regarded in the same way as the sun is a provider of power. Observe that the term energy has been replaced here by power. In fact, the amount of energy that is provided by the sun depends on the "use" time, while the amount of power is "use" time-independent. Power is expressed in W, energy in W \cdot s (which is equivalent to J and can be converted into MJ, kWh, etc.). The parallel with land is that the earth provides a "use" time-independent surface (in m^2), and that the amount of land use depends on the "use" time. It is therefore expressed in $m^2\cdot s$ (or equivalents thereof, like ha \cdot yr). Since we have labelled solar energy as a flow, it seems natural to label the associated land use quantity as a flow as well. But then we need a quite sharp terminology, like in the case of the sun.

- Solar energy that is used can not be used fully again; it has been converted into lower-exergy heat. In that sense we must label solar energy a deposit. But solar power is then a flow. So we may still say that we consume and deplete high-exergy solar energy.
- Land surface-time that is used can not be used again; it has been dissipated, because the past can never be experienced another time. In that sense we must label land

surface-time a deposit. But land surface is then a flow. So we may still say that we consume and deplete land surface-time.

The consequence is that we may assess the competing aspects of solar power along with that of land surface. The depleting aspect of solar energy and of land surface-time will most probably be excluded from the impact assessment.

Recycling of resources and land

Related to the previous issue is that of "recycling" of land. There appears to be an inconsistency in the current ideas with respect to the two main input categories (abiotic) "resources" and "land". A brief review follows.

- One may say that the product system that is responsible for the first use of a material is responsible for the extraction of the resource from the environment, and therefore deserves to be "fined" with the full depletion score. Should the material after useful product life be recycled, the life cycle of the product will be "rewarded" by needing less waste treatment. A user of recycled material will never be "charged" with the impacts of extraction of the virgin material. Also, degradation of material quality along cascades does not explicitly enter the procedure.
- At the same time, one may say that land use is to be "charged" to the product system that actually occupies this land. The amount of land of a certain quality that is occupied for a certain time is proposed to represent the land use score.

What is the inconsistency? Land degradation or land use is "charged" for every product that contributes to it, while material degradation or material use is never "charged" because only the product that uses virgin material is "charged".

- Would one be consistent and extend the resource idea to land, the first peasant in the bronze age that changed the land from natural into cultural would be "fined" and all subsequent peasants, builders and industrial managers would have no land use impact.
- Would one be consistent the other way around and extend the land idea to resources, everyone that either uses or degrades a certain material would be "charged".

Which of the two consistent approaches could be preferred? That's not for sure. But it inspires thoughts for alternatives. These alternatives are also inspired by the discussions in the SETAC-Europe Working Group on Impact Assessment (Udo de Haes, 1996).

One often defines the problem of depletion in terms of a reduced availability for others. Here one must distinguish the reduced availability now from the reduced availability in future. Suppose that the ultimate reserve of quality-A copper is 100 ton. A product that consists of 1 ton quality-A copper makes that the availability of quality-A copper is reduced by 1%. After the product's useful life, there are two options. Either all the copper is again available at the original A-quality for everyone who needs it. In that case the availability of quality-A copper has only been reduced for a limited time. But it may also be that the copper has become mixed with other materials or that it has been dispersed through the atmosphere. In that case the availability of quality-A copper is reduced permanently. (Unless someone takes effort to collect and purify; if this is considered to be part of the product system we retrieve the first situation, if it is not we retrieve the second situation; hence there is no third situation.) The consequences for an impact assessment are as follows:

- There is one impact category "resource competition", which measures how much of a certain resource of a certain quality is occupied by the product system for how long. This score thus reflects the reduced availability for people that would like to use the resource at the same time.
- There is one impact category "resource consumption", which measures how much of a certain resource of a certain quality is lost. This score thus reflects the reduced

availability for people that would like to use the resource in future. This latter score is compensated by the production of lower quality material that goes to other product systems.

An example is perhaps clarifying. A product system that has an input of 5 kg A-quality copper and that has after 1 year an output of 2 kg A-quality copper, 1 kg B-quality copper, and 2 kg waste-quality copper gets "charged" with:

- "resource competition" = 5 kg \times 1 year A-quality copper = 5 kg \times year A-quality copper.
- "resource consumption" = 5 kg A-quality copper - 2 kg A-quality copper - 1 kg B-quality copper = 3 kg A-quality copper - 1 kg B-quality copper. An equivalency factor between different materials of different qualities might be developed. Assuming that the equivalency factor A-quality copper is 5/kg and that of B-quality copper is 4/kg, the aggregated score becomes 11.
- "waste" = 2 kg, of which impacts may be further quantified in terms of toxicity, land use, etc.

Clearly, both impact categories need equivalency factors to achieve an aggregation within each category. Their nature is outside the present memorandum. It might be that these impact categories need further subdivision, for instance into biotic and abiotic, or energetic and non-energetic, or renewable and non-renewable.

Exactly the same scheme applies to land: there are two impact scores: "land competition" and "land consumption", the former measuring how much of a certain land quality is occupied for how long, the latter measuring how much of a certain land quality is lost.

Does complete recycling exist?

It is often stated that many abiotic resources (like metals) do not disappear. This is then further elaborated in different ways: some propose to focus on the disappearance of ores, others on the reduced availability of the metal, *et cetera*. Still others use this as an argument that the extraction of metals can do without a depletion score.

Without wishing to re-enter this discussion, it should be observed that there is, independent for the LCA-world, an ongoing discussion on the truth of the assumption of the existence of complete recycling. The interested reader is referred to Georgescu-Roegen (1971), Biancardi *et al.* (1993, 1996), Converse (1996a, 1996b). It may be wise to anyhow construct a depletion score for these resources, and to leave the argument of unimportance to the valuation element.

Non-linear characterization models and the derivative

It is reasonable to assume that the seriousness of the extraction of a resource is a non-linear function of the reserve. This could be understood as an argument for non-linear characterization formulas, and hence as a plea for the abolishment of equivalency factors. This interpretation is, however, not correct. The present section discusses the derivation of equivalency factors from non-linear response functions.

If one assumes for a certain impact category, say human toxicity, a linear dose-response function, one obtains the situation of Figure 6.1. E is the emission flux in kg/yr and S is the impact score, for example in victims/yr.

In an LCA, one is concerned with emissions in kg, not emission fluxes in kg/yr. We proceed as follows: by assuming that the emission flux increases marginally as a result of the functional unit. This emission is denoted by m (so: small letter for kg). The marginal increase of the impact (s in victims, so not per year) may be found by following the tangent

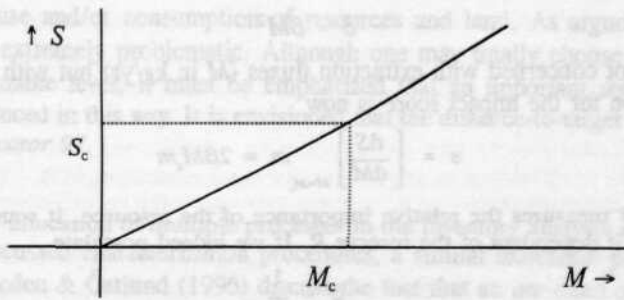


FIGURE 6.1. Assumed linear relationship between emission flux (E) and problem measure (P) for a certain impact category.

of the graph at the point of present emission (M_c) and present impact (S_c). By incidence, the tangent and the graph coincide in this linear case.

A symbolic representation of the dose-response curve is as follows:

$$S = \alpha M \quad (6.1)$$

The marginal increase is then found by evaluating the derivative at the point of present emission and present impact:

$$s = \left[\frac{dS}{dM} \right]_{M=M_c} = \alpha \quad (6.2)$$

The coefficient α measures the relative hazard of the substance. It will be large for a highly toxic chemical and for a highly persistent chemical, so, simplified

$$\alpha = \frac{DT_{50}}{NOEC} \quad (6.3)$$

We may extrapolate from this to the situation of a non-linear dose-response curve. We will demonstrate this for depletion of abiotic resources. Figure 6.2 shows the assumed dose-response curve.

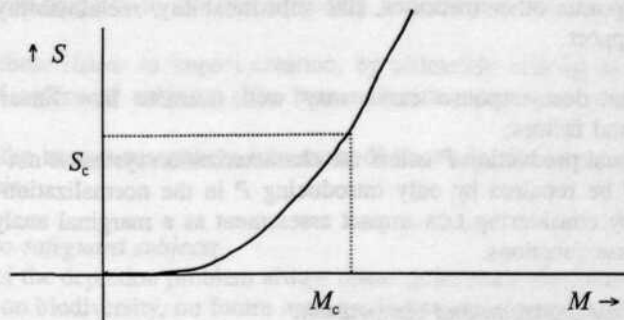


FIGURE 6.2. Assumed non-linear relationship between emission flux (E) and problem measure (P) for another impact category.

This curve may be described as a parabola:

$$S = \beta M^2 \quad (6.4)$$

Again, we are not concerned with extraction fluxes (M in kg/yr) but with extractions (m in kg). The equation for the impact score is now

$$s = \left[\frac{dS}{dM} \right]_{M=M_c} m = 2\beta M_c m \quad (6.5)$$

The coefficient β measures the relative importance of the resource. It sounds reasonable to assume to make it dependent of the reserve R . If we indeed postulate

$$\beta = \frac{1}{R} \quad (6.6)$$

we obtain a characterization formula like

$$s = 2 \frac{M_c}{R} \times m \quad (6.7)$$

As argued by Guinée & Heijungs (1995), such a characterization formula leads to dimensional inconsistencies. The term M_c is the numerator should appear with a power that is one lower than the term R appears in the denominator. An alternative suggestion for β which meets this requirement is

$$\beta = \frac{1}{R^2} \quad (6.8)$$

This gives for the characterization formula

$$s = 2 \frac{M_c}{R^2} m \quad (6.9)$$

This coincides, except for an irrelevant factor 2 and except for the aggregation, with proposal 3d:

$$s = \frac{P}{R^2} m \quad (6.10)$$

The only thing that is left to proof is that aggregation is permitted, *i.e.* that the importance of a resource is fully measured by the reserve and the annual production, and that there is no need to incorporate other measures, like substitutability, reclaimability, or function for society or life-support.

In conclusion:

- a non-linear dose-response curve may well translate into linear characterization principles and factors;
- that the annual production P enters the characterization system is not a conceptual flaw that should be repaired by only introducing P in the normalization step, but can be explained by considering LCA impact assessment as a marginal analysis of non-linear dose-response functions.

Are there targets for depletion and competition?

The *Eco-indicator 95* is able to formulate a single indicator by assuming that the distance-to-target approach provides the weighting between different safe-guard subjects (human health, ecosystem degradation, summer smog). By extending the system with resource extraction and land use, the question of weighting should be addressed anew. When we stick to the distance-to-target concept, this means that targets should be developed for the impact categories that

are related to use and/or consumption of resources and land. As argued by Blonk *et al.* (1996), this is extremely problematic. Although one may finally choose a certain political target or sustainable level, it must be emphasized that an important source of errors and debate is introduced in this way. It is envisioned that the distance-to-target will be abandoned in the *Eco-indicator 97*.

Allocation

The problem of allocation of multiple processes in the inventory analysis is well-known. For some of the discussed characterization procedures, a similar allocation procedure might be required. Finnveden & Östlund (1996) discuss the fact that an ore often contains more than one metal. Extraction of the ore then automatically means that more than one metal is produced. Some characterization methods should account for this. Another example is natural gas, that contains helium in a concentration that is much higher than the atmospheric concentration. For biotic resources, similar arguments might hold. It is well known that fishery of tuna has serious implications for the dolphin. Some types of land use might also be very difficult to decouple with the disappearance of species on that and neighbouring spots. All these issues have not extensively been discussed in the context of LCA.

Typology of inputs

In the assessment of the different proposals, it was sometimes said that the typology of inputs was decisive yet unclear. This applies in particular for biotic resources: is the elephant one type, or is it two (African and Indian), or is it more, taking different varieties into account? For land use, a similar problem was raised: do we consider agriculture to be one type of land use, or do we distinguish different types within? And is tropical forest one type of original ecosystem, or is there a fine separation? We could even do this for abiotic resources, see the reasoning on diamond in Guinée & Heijungs (1995).

The separation of characterization and valuation and the role of normalization

To arrive at an evaluation of product alternatives, the impact assessment may be seen as consisting of three different types of steps:

- stating physical impacts of the functional unit, in terms that are relevant for problem analysis;
- relating these impacts to the corresponding impacts that are caused by society as a whole;
- assessing these shares in impact creation, by ultimately relating to basic values on a number of safeguard subjects (like human health, ecosystems quality and material welfare).

By splitting up the impact assessment into more distinct separate steps, more clarity might be attained in this.

A separation into safeguard subjects

The discussion of the depletion problem always opens quite some discussions: on availability, on substitution, on biodiversity, on future impacts. Below, we propose to define three impact categories in which many different aspects that were discussed during this report may be positioned:

- reduced availability;
- loss of biodiversity;
- damage to life-support.

By making such a distinction, we in fact propose a radical break with the now prevalent concept of a one-to-one correspondence between type of input and impact category. After all, abiotic resources are now most often mapped onto the impact category for abiotic resources, *et cetera*. With the new proposal, we effectively introduce depletion themes, in a way which resembles the pollution themes like global warming, acidification and toxicity. It must be emphasized that the discussion concentrates on the input-related impacts. The output-related impacts could be reconsidered as well, perhaps leading to the incorporation of ecotoxicity into damage to life-support, or perhaps not: that question is beyond the scope of this report.

In the new proposal, extraction of an abiotic resource, of a biotic resource, and use of land are all mapped onto the three aforementioned impact categories by means of equivalency factors. Obviously some equivalency factors are zero, just like the zero acidification potential of CFCs. The general structure is thus:

$$S_{6a} = \sum_i Q_{a,i} \times m_i + \sum_j Q_{a,j} \times a_j \quad (6.11)$$

for the impact category reduced availability,

$$S_{6b} = \sum_i Q_{b,i} \times m_i + \sum_j Q_{b,j} \times a_j \quad (6.12)$$

for the impact category loss of biodiversity, and

$$S_{6c} = \sum_i Q_{c,i} \times m_i + \sum_j Q_{c,j} \times a_j \quad (6.13)$$

for the impact category damage to life-support. In these equations, m_i indicates the extraction of any resource (abiotic or biotic, non-renewable or renewable, fund, flow or resource) while a_j indicates the use of land of type j .

The problem is, of course, how to obtain the three sets of equivalency factors (the Q s). We do not go into that subject now, but would nevertheless like to make a few suggestions.

- The equivalency factors for reduced availability (category a) is in principle non-zero for abiotic and biotic resources and for land. It could even be argued that no special case is made here for biotic resources, as the intrinsic nature value is accounted for elsewhere, namely in category b. Reduced availability can then be interpreted in a completely anthropocentric way: the reduced availability for creating human welfare and wellbeing.
- The equivalency factors for loss of biodiversity (category b) could be zero for the abiotic resources. Thus, extraction of biotic resources and use of land in principle contribute to these impact categories. By also putting land use in this category, we are able to introduce the disruption of ecosystems without the extraction of the species or the individuals themselves.
- The equivalency factors for damage to life-support (category c) could also be zero for most abiotic resources. The main difference with loss of biodiversity that ought to be expressed by the equivalency factors is that category b focuses on intrinsic value, while category c deals with the function in the food chain, in the ecosystem equilibrium, *et cetera*.

Obviously, this proposal is far from operational. The authors nevertheless feel that a distinction of these (or slightly different) depletion themes is an important step towards a satisfactory characterization method for input-related interventions.

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