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Threshold-based life cycle impact assessment and marginal change: incompatible?

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Summary

A recent contribution in this journal on the application of the RAINS model for acidification in life cycle impact assessment is examined as to mathematical consistency and conceptual content. A general recipe for deriving equivalency factors for life cycle impact assessment is derived. This leads to a rejection of threshold-based impact indicators as a basis for tabulating equivalency factors for use in life cycle assessment of marginal changes. This conclusion extends beyond the impact category of acidification on the basis of RAINS, but is equally valid for any impact indicator that is based on a “track 2” philosophy.

1 Introduction

Potting *et al.* (1998) showed in a recent contribution to this journal that by using the RAINS model (Alcamo *et al.*, 1990) major improvements in the life cycle impact assessment (LCIA) of acidifying substances can be made. The RAINS model of acidification (Alcamo *et al.*, 1990) is a widely recognised model for connecting emission sources to acidifying impacts. This model has not been used so far for the purpose of LCIA for reasons of impracticality. Using environmental models for each impact category in every life cycle assessment (LCA) is very time consuming. LCIA therefore normally uses equivalency factors that have been derived from such models. Equivalency factors have the advantage over models that they can be tabulated in LCA guides and that they can easily be incorporated in LCA software. The derivation of equivalency factors from RAINS had not been carried out prior to the attempt by Potting *et al.* (1998).

However, as we will argue, there is a problem with using the step-wise, threshold-oriented, environmental impact indicator for LCA purposes proposed by Potting *et al.* (1998). In this paper we discuss the nature of this problem and propose a new impact indicator for acidification, which still makes use of valuable information from RAINS, but better suits LCA.

The conclusions of this paper have a broader validity than the case of acidification alone. They also apply to other threshold-based impact indicators, which could, for instance, be developed for toxicity and eutrophication. We will, however, illustrate most of our ideas on the implementation of RAINS by Potting *et al.* (1998). For the purpose of exposition, we concentrate on the main relevant aspects of that paper and extend where necessary to more general notions.

2 Mathematical problems

2.1 The theoretical basis of equivalency factors

The paper of Potting *et al.* (1998) follows, with most other papers on LCIA, the approach of marginal change. This means that there is a constant background of emissions and concentrations, and that only a very small functional unit is introduced, with small perturbations of emissions and concentrations on top of that background. In symbols: E_0 (emission) becomes $E_0+\Delta E$. This leads to a new impact magnitude $I_0+\Delta I$, where I stands for acidifying impact.

Deriving equivalency factors following the approach of marginal change rests on the assumption that it is possible to approximate the change in impact (ΔI) by a proportionality factor (Q) times the change in emission (ΔE). In formula:

$$\Delta I \approx Q \times \Delta E \qquad (1)$$

The quest for equivalency factors thus reduces to finding the Q-values, for different substances, for different sites, and for different impact categories.

One thus needs an expression, a recipe, on how to find Q. We will formulate such a recipe by starting with an exact approach (*cf*. Heijungs *et al.*, 1992, p.60-61). This exact approach is in general a non-linear relationship between E and I, expressed as a mathematical function $I(E)$. Standard mathematics offers a powerful approach to investigate the behaviour of a non-linear function around a certain point by a power series: the Taylor's expansion. For I as a function of E around E_0, it is given as

$$I(E_0+\Delta E) = I(E_0) + \left[\frac{\mathrm{d}I}{\mathrm{d}E}\right]_{E=E_0} \times \Delta E + \left[\frac{1}{2}\frac{\mathrm{d}^2 I}{\mathrm{d}E^2}\right]_{E=E_0} \times (\Delta E)^2 + \left[\frac{1}{6}\frac{\mathrm{d}^3 I}{\mathrm{d}E^3}\right]_{E=E_0} \times (\Delta E)^3 + \cdots \qquad (2)$$

where the subscripts $E = E_0$ indicates that the derivatives have to be evaluated at that value of the argument E. Under the assumptions of a relatively small value of ΔE and of well-behaved derivatives, the infinite series can be reduced to the following approximation

$$I(E_0+\Delta E) \approx I(E_0) + \left[\frac{\mathrm{d}I}{\mathrm{d}E}\right]_{E=E_0} \times \Delta E \qquad (3)$$

This means that we may approximate the change in impact as

$$\Delta I \approx \left[\frac{\mathrm{d}I}{\mathrm{d}E}\right]_{E=E_0} \times \Delta E \qquad (4)$$

so that the expression for the equivalency factor Q becomes

$$Q = \left[\frac{\mathrm{d}I}{\mathrm{d}E}\right]_{E=E_0} \qquad (5)$$

This is the general recipe for making equivalency factors. But it is important to keep in mind that two assumptions need to be satisfied in order to use the concept of equivalency factors according to this recipe: (i) small values for the change ΔE, and (ii) well-behaved derivatives.

Now a problem arises with the approach of Potting *et al.* (1998). In RAINS, a certain area fully contributes when the critical load is exceeded, if only slightly, and the same area is completely disregarded if the critical load is not exceeded, if only slightly. The approach is thus based on step functions, and step functions do not possess a well-behaved derivative. Step functions are very likely to be introduced in a threshold-oriented approach. This class of approaches is also known as "track 2", where actual impacts and above-threshold situations form the main object of impact assessment (Udo de Haes, 1996; White *et al.*, 1995). Due to the above mentioned mathematical problem c*haracterisation with equivalency factors on the basis of marginal changes in environmental impact is not compatible with a modelling of environmental impact on the basis of an above-threshold philosophy ("track 2").* This means that threshold-based impact indicators can not be used in deriving equivalency factors for marginal changes which may be an important theoretical ingredient in the debate on above-threshold approaches. We will show this in detail for the calculation of equivalency factors for acidification.

2.2 Equivalency factors for acidification on the basis of RAINS

RAINS has a peculiar form for $I(E)$. It is defined as the area of the part of Europe in which the critical load for acidification is surpassed. This is done by covering Europe by cells; we will denote the area of cell j by A_j.

Let the deposition at cell j denoted by D_j, and the critical load of that cell by CL_j. The contribution of cell j to the acidification score is then either 0 or the cell's surface. Symbolically: it is equal to I_j, with

$$I_j = \begin{cases} A_j \text{ if } D_j \geq CL_j \\ 0 \text{ otherwise} \end{cases} \tag{6}$$

This partial score I_j is a step function: 0 as long as the load does not exceed the critical load, and A_j as soon as it is does. A step function is often abbreviated with the symbol Θ. The total acidification score is obtained by adding the partial scores for each grid cell:

$$I = \sum_{j \in \text{Europe}} A_j \times \Theta(D_j - CL_j) \tag{7}$$

where the summation runs over the total model world, in this case Europe.

Following RAINS, the relation between emission within cell i (E_i) and deposition at cell j (D_j) is one of proportionality:

$$D_j = \sum_{i \in \text{Europe}} t_{ji} \times E_i \tag{8}$$

where t_{ji} represents transport and other fate characteristics.

The complete relation between total acidification (I) and emission in cell i (E_i) is now

$$I = \sum_{j \in \text{Europe}} A_j \times \Theta\left(\left(\sum_{i \in \text{Europe}} t_{ji} \times E_i\right) - CL_j\right) \tag{9}$$

For use in LCA, the equivalency factors are derived according to the recipe of the previous section:

$$Q_i = \frac{\mathrm{d}I}{\mathrm{d}E_i} = \frac{\mathrm{d}\sum_{j\in\mathrm{Europe}} A_j \times \Theta\left(\left(\sum_{i\in\mathrm{Europe}} t_{ji} \times E_i\right) - CL_j\right)}{\mathrm{d}E_i} \tag{10}$$

where Qi indicates the equivalency factor for the change in total acidifying impact in Europe as a function of the change of the emission in cell *i*.

Following the approach of Potting et al. (1998) Q_i is ill-defined, because the derivative of a step-function is ill-defined. In the case of RAINS, the derivative of the partial score I_j with respect to a marginal increase of the load is either zero or infinity. It is zero for almost all values of D_j, and infinity for the isolated singularity where D_j equals CL_j. An important consequence of the step-wise way of calculation is that it leads to a step-wise relationship between the marginal emission change and the change in unprotected ecosystem area. Potting *et al.* (1998) solve this problem by replacing the infinitesimal dE by a ΔE, for which they take 10% of the present emission, so $\Delta E = 0.1 \times E_0$. When instead of 10% emission change a different emission change is used in the computation, all equivalency factors will change, and if, say, 0.1% is used, they will all become 0, because the emission change will be too small to change any unprotected ecosystem area in protected ecosystem area or the other way around. Thus, the impact factors are highly dependent on the choice of which marginal emission change is taken.

3 A proposal for improvement

The conclusions above do not imply a rejection of the use of RAINS for life cycle impact assessment. We can, apart from the solution chosen by Potting *et al.* (1998), conceive at least two options for solving the mathematical problems. First, we may replace the step function by a smooth path that somehow fits the original curve. It is possible, but it requires a careful and explicit redefinition, consistent with Taylor's expansion. A problem is, that data smoothing again introduces arbitrary aspects, like the choice of the smoothing method. This line of thinking tries to remain as close as possible to the original RAINS impact indicator: surface of land that is exposed above the critical load. A more drastic solution is to be found in redefining the impact indicator. A natural candidate for this is one in which we do not measure square metres of threatened surface, but one in which we try to use the idea of environmental utilisation space. We may do so in a way that is also used in many approaches towards toxicity: the hazard index, or PEC/PNEC. The new impact indicator is not concerned with the degree to which an environmental standard or critical load is actually exceeded, but with the degree to which it is potentially filled up (*cf.* Heijungs & Guinée, 1993). So we replace

$$I = \sum_{j\in\mathrm{Europe}} A_j \times \Theta(D_j - CL_j) \tag{7}$$

by

$$I = \sum_{j\in\mathrm{Europe}} A_j \times \frac{D_j}{CL_j} \tag{11}$$

The new measure is smooth and continuous, and is differentiable everywhere. Therefore, we may submit it to the recipe of equivalency factors, and obtain

$$Q_i = \frac{\mathrm{d}I}{\mathrm{d}E_i} = \frac{\mathrm{d} \sum_{j \in \text{Europe}} A_j \times \frac{\left(\sum_{j \in \text{Europe}} t_{ji} \times E_i \right)}{CL_j}}{\mathrm{d}E_i} = \sum_{j \in \text{Europe}} A_j \times \frac{t_{ji}}{CL_j} \tag{13}$$

We do not wish to suppress that this proposal has its own problems. For instance, the proposed impact indicator is one that lacks a sound empirical motivation, and it effectively rests on ambiguous concepts like environmental utilisation space. On the other hand, it is in line with an important conceptual foundation of LCIA (at least in Europe): it is based on potential impacts according to what has become known as “track 1” (Udo de Haes, 1996; White *et al.*, 1995).

4 Discussion

The criticism and the proposal for improvement were largely discussed in the context of acidification and the RAINS model. The connection between threshold-based impact indicators and the “track 2” philosophy is, however, much more general. There are numerous impact categories for which threshold-based impact indicators may be developed. Important examples are human toxicity, ecotoxicity and nutrification. The discussion above on acidification demonstrates that the principles for choosing an appropriate impact indicator should not only be guided by considerations of scientific validity and environmental relevance, but that consistency with the basic principles of life cycle assessment is an important addition. As has been discussed, this rules out the use of pure threshold thinking along “track 2”. This lesson applies to all impact categories, as we may everywhere in the text replace the terms “acidification” and “critical load” by appropriate equivalents like “ecotoxicity” and “no-effect concentration”.

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