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COMMENTARY AND DISCUSSION ARTICLE

The average versus marginal debate in LCIA: paradigm regained

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Ten years ago, three authors put a neglected theme on the discussion agenda (Huijbregts et al. 2011). It concerns the difference between using a marginal and an average approach for assessing the effects of ecotoxic pollutants in the context of life cycle impact assessment (LCIA). The authors advocated a "paradigm shift" from marginal to average. Since then, their approach has received quite some attention (Scopus mentions mid 2020 40 citations), including a comment (Weidema 2012) and a debate paper on marginal versus average (Forin et al. 2020), commenting on an attempt to develop non-marginal factors (Boulay et al. in press). Furthermore, the debate does not seem to have been ended conclusively. The present contribution adds new fuel to the debate.

Because LCA is a quantitative model, we will add a mathematical treatment to the primarily visual approach by Huijbregts et al. (2011), which has been reproduced for convenience in Fig. 1.

The effect curve is described by a function f, which takes the concentration (C) of phosphorous (P) as argument, and which yields an effect (PDF, potentially disappeared fraction of freshwater macroinvertebrate species). We will assume a background concentration ($\widetilde{C}$) of phosphorous, so $\widetilde{C}_P$. Altogether, this gives the following:

$$\mathrm{PDF} = f(C_P) = \frac{1}{1 + 4.07 C_P^{-1.11}}$$

yielding a background effect

$$\widetilde{\mathrm{PDF}} = f\left(\widetilde{C}_P\right) \approx 0.76$$

According to the marginal approach (a), the effect factor, EF, is given by

$$\mathrm{EF}_{\text{marginal}} = \left.\frac{df}{dC_P}\right|_{C_P=\widetilde{C}_P}$$

which can be worked out as

$$\mathrm{EF}_{\text{marginal}} = \left.\frac{1.11 \cdot 4.07 C_P^{-2.11}}{\left(1 + 4.07 C_P^{-1.11}\right)^2}\right|_{C_P=10} \approx 0.02$$

The average approach (b) yields an effect factor

$$\mathrm{EF}_{\text{average}} = \frac{f\left(\widetilde{C}_P\right)}{\widetilde{C}_P}$$

which further gives

$$\mathrm{EF}_{\text{average}} = \frac{\frac{1}{1 + 4.07 \widetilde{C}_P^{-1.11}}}{\widetilde{C}_P} \approx 0.08$$

This makes sense, in the following two ways. First, the marginal factor tells us what the change in effect will be when a small amount of P is added on top of the background. Indeed, when we increase C_P from $\widetilde{C}_P = 10$ to 10.1, the new result according to f changes by approximately 0.002, which neatly corresponds to 0.02×0.1. Second, the impact of 0.76 is entirely caused by a concentration of 10, which means a per-unit of concentration effect of approximately 0.08.

Moving from the marginal approach to the average approach, as argued by Huijbregts et al. (2011), seems to better agree with long-term policy goals. In particular at the high end of the impact curve, the marginal effect approaches zero, but the environment gets very polluted. An average approach is thus worth investigating.

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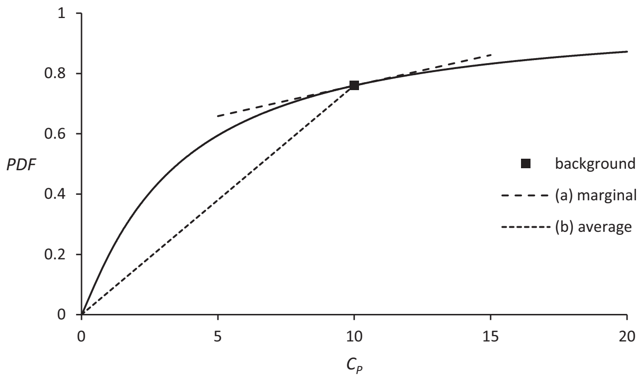

Fig. 1 A stressor, P, present with a concentration C_P, causes an effect on biodiversity. The curve is a univariate function, PDF = $f(C_P)$. The background value is indicated by the square. Adapted from Huijbregts et al. (2011)

The distinction between the two approaches was probably introduced in LCA by Steen (1999), using the following metaphor: "if 11 persons have one litre of waste water to get rid of and pore it into a waste water system having a container with a capacity of 10 litre, there will be a spill of 1 litre on the floor ... What environmental impact should be allocated to each person? If we think in a guilt perspective, it would probably be 1/11 of a litre ... Maybe you can argue that the last person bears most of the guilt, as it was actually he or she that caused the overflow." Steen refers to these two paradigms as those of Guilt and Consequence.

The critical investigation starts by reflecting on what we actually mean by an average. We can say that a 75-kg adult and a 25-kg child have an average weight of 50 kg, because 2 × 50 gives the total of 100 kg. An average, per-item value, multiplied by the number of items, should give the total value. Let's keep that in mind.

Below, we will see that the argument of Huijbregts et al. (2011) evaporates when we acknowledge the fact that multiple environmental stressors contribute together to the same impact. The mathematical framework for treating this more realistic situation is available (Van Zelm et al. 2009), but there is no simple visual interpretation, and, as we will show, the idea of an average impact becomes problematic.

Before we discuss the "real" case, we take a simpler one to get a more intuitive feeling of the idea. Suppose you have a door of 100-cm width (w) and 200-cm height (h). We will discuss two illustrative questions on the "impact" of this door (see Fig. 2).

Question 1 is about the presence of gaps, through which a heat loss may occur. The total length of the gap (G) around the door is

$$G = g(w, h) = 2w + 2h$$

which gives 2 × 100 + 2 × 200 = 600 cm. We may easily calculate the marginal change of gap length as an effect of a change of either w or h:

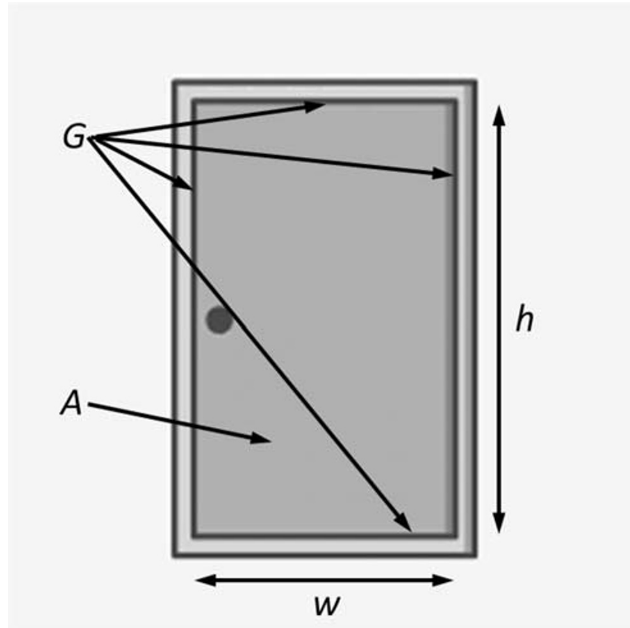

Fig. 2 A door with width w and height h, causing two "impacts": an additive impact G (gap length) and a multiplicative impact A (area)

$$\frac{\partial G}{\partial w} = 2 \text{ and } \frac{\partial G}{\partial h} = 2$$

Next, let us find the average gap impact. Following the one-dimensional logic of Huijbregts et al. (2011), we could construct

$$\frac{G}{w} = 6 \text{ and } \frac{G}{h} = 3$$

but that is certainly wrong, because 6 × 100 + 3 × 200 ≠ 600. In fact, we proceed as follows. G is made up of two parts: 200 by w and 400 by h. So, per unit of w, we have $\frac{200}{100} = 2$ cm of gap. And likewise, we have $\frac{400}{200} = 2$ cm of gap per unit of h. Let us check that the averages make sense. The average gap per unit of w is 2, so with an actual value of w = 100, we find a gap of 200. Likewise, we find another 400 for the part by h. In total 600, which is just right.

Question 2 is about the area of the door, which represents a painting-relevant impact. The one-sided area (A) is

$$A = g(w, h) = w \times h$$

which in the present case is 100 × 200 = 20,000 cm^2. The marginal area impacts are

$$\frac{\partial A}{\partial w} = 200 \text{ and } \frac{\partial A}{\partial h} = 100$$

What about the average area impact? The total impact of 20,000 is due to a non-additive combination of 100 and 200 so it is impossible to say which part of the 20,000 is due to these two contributing factors.

The fundamental difference between questions 1 and 2 is that question 1 involves an additive combination rule, while question 2 involves a non-additive combination rule. An additive rule implies that we can work out the combined effect of w and h as an addition of separate contributions:

$$G = g(w,h) = f_1(w) + f_2(h)$$

The average effect of w and h can then easily be set as

$$\frac{f_1(w)}{w} \textit{ and } \frac{f_2(h)}{h}$$

For the non-additive case, that does not work:

$$A = g(w,h) \neq f_1(w) + f_2(h)$$

Most traditional impact assessment methods in LCIA work under the assumption of additivity. The climate impact score of 10 kg of CO_2 and 2 kg of CH_4 is the same as the climate impact score of 10 kg CO_2 plus the climate impact score of 2 kg CH_4.

But in more sophisticated and innovative impact models, such as the multi-substance PAF by Van Zelm et al. (2009), the combination rule is not additive. And that is exactly the one Huijbregts et al. (2011) use in their proposal to develop average characterization factors. Below, we will study their case in more detail.

Let us assume there are two stressors, in addition to the original stressor P one extra, indicated by the letter Q. For concreteness, let us take a numerical example. In accordance with Huijbregts et al. (2011) and Van Zelm et al. (2009), we use the form

$$\mathrm{PDF} = g(C_P, C_Q)$$
$$= 1 - \left(1 - \frac{1}{1 + 4.07 C_P^{-1.11}}\right)\left(1 - \frac{1}{1 + 3.12 C_Q^{-1.05}}\right)$$

where we have arbitrarily used for stressor Q the coefficients 3.12 and −1.05. For the background concentrations, we will assume $\left(\widetilde{C}_P, \widetilde{C}_Q\right) = (10, 5)$, yielding a background PDF of 0.91. A visualization of this impact function is in Fig. 3.

The marginal effects are given by

$$\mathrm{EF}_{\mathrm{marginal},P} = \left.\frac{\partial g}{\partial C_P}\right|_{(C_P,C_Q)=\left(\widetilde{C}_P,\widetilde{C}_Q\right)} \text{ and } \mathrm{EF}_{\mathrm{marginal},Q}$$
$$= \left.\frac{\partial g}{\partial C_Q}\right|_{(C_P,C_Q)=\left(\widetilde{C}_P,\widetilde{C}_Q\right)}$$

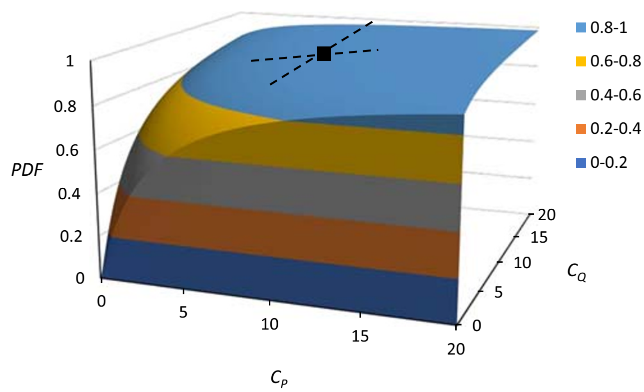

Fig. 3 Two stressors, P and Q, together contribute to an effect on biodiversity. The curve is a bivariate function, PDF = $g(C_P, C_Q)$. The background value is indicated by the square. The dashed lines illustrate the two partial derivatives (see text)

This can be easily worked out as follows:

$$\mathrm{EF}_{\mathrm{marginal},P} = \left(1 - \frac{1}{1 + 3.12 C_Q^{-1.05}}\right) \left.\frac{1.11 \cdot 4.07 C_P^{-2.11}}{\left(1 + 4.07 C_P^{-1.11}\right)^2}\right|_{(C_P,C_Q)=(10,5)} \approx 0.007$$

and

$$\mathrm{EF}_{\mathrm{marginal},Q} = \left(1 - \frac{1}{1 + 4.07 C_P^{-1.12}}\right) \left.\frac{1.05 \cdot 3.12 C_Q^{-2.05}}{\left(1 + 3.12 C_Q^{-1.05}\right)^2}\right|_{(C_P,C_Q)=(10,5)} \approx 0.01$$

Now, does this make sense? Let us change $\widetilde{C}_P$ marginally, from 10 to 10.1, and simultaneously $\widetilde{C}_Q$ from 5 to 5.2. Using g, so without the use of derivatives, the new impact has increased to

$$g\left(\widetilde{C}_P + 0.1, \widetilde{C}_Q + 0.2\right) \approx 0.9153$$

Using the linearized approach with marginal characterization factors, we find

$$g\left(\widetilde{C}_P, \widetilde{C}_Q\right) + \mathrm{EF}_{\mathrm{marginal},P} \times 0.1 + \mathrm{EF}_{\mathrm{marginal},Q}$$
$$\times\, 0.2 \approx 0.9154$$

So indeed, the marginal factors predict very well what a small addition to a background will do, even for the multi-substance case.

Let us next explore the average effect factors. To find these, we first need to separate the contributions by P and Q, so we need to express

$$\mathrm{PDF} = g(C_P, C_Q) = f_1(C_P) + f_2(C_P)$$

after which we would use

$$\mathrm{EF}_{\mathrm{average},P} = \frac{f_1\left(\widetilde{C}_P\right)}{\widetilde{C}_P} \text{ and } \mathrm{EF}_{\mathrm{average},Q} = \frac{f_2\left(\widetilde{C}_Q\right)}{\widetilde{C}_Q}$$

But, because the combination rule of the multi-substance PAF is non-additive, we cannot separate the contributions by the two stressors P and Q in an unambiguous way. Only by making ad hoc "allocations" (e.g., half of the combined impact goes to P and half to Q) would we be able to separate the contributions, as a first step in an averaging procedure. Clearly, these ad hoc arguments include subjective decisions, arguing what a "fair" distribution of the total impact is. Perhaps that is acceptable for a policy discourse, but its place in a science-based analysis is questionable.

Steen (1999) already recognized the problematic status of the average approach, when he wrote that "it is obvious that there is no 'scientific' answer to the question of how to allocate 'guilt' or 'benefits' unless they are related to consequences". He therefore chose to make it "a principle to estimate environmental consequences of various human activities".

The take-home message of this short note is a triple one:

- arguments on the basis of only one variable may oversimplify the analysis, and lead to debatable or unclear conclusions;
- arguments on the basis of simple visual diagrams or simplified mathematics are of limited value too;
- when we stick to science-based arguments, there is no place for the paradigm shift from marginal to average (or as Steen (1999) would say, from consequence to guilt).

So, the future for an average paradigm looks bleak. We may desire it, and we can even develop it for the case of impacts that are due to one stressor only or for the case of additive stressors. But for the more general case of a non-additive combination rule, it appears that it is not possible to define characterization factors that satisfy the interpretation of representing the average impact per unit of stressor.

I do not rule out the possibility that someone will come up with a clear and unambiguous formula to calculate average characterization factors in the case of non-additive stressors. But then, it must be based on precise arguments. As a challenge, let me propose the concrete case of $\mathrm{EF}_{\mathrm{average},\ P}$ and $\mathrm{EF}_{\mathrm{average},\ Q}$ above. How would you calculate these, given the toxicologically inspired non-linear and non-additive $g(C_P, C_Q)$ and the background values $\widetilde{C}_P = 10$, $\widetilde{C}_Q = 5$, and $\widetilde{\mathrm{PDF}} = 0.91$?

In the end, what matters most, of course, is how we use the characterization factors. If we use them for small changes, a marginal approach will be perfect, but for non-marginal changes, an incremental approach is needed (Forin et al. 2020). As such we are facing a value choice, with clear connections to the goal and scope of the study. The average approach, as propagated by Huijbregts et al. (2011) and to some extent by Boulay et al. (in press), runs into unsurmountable problems in the case of non-additive combination rules, at least for now.

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