

Letter to the Editor

MEASURING ABSORPTION EFFICIENCIES: SOME ADDITIONAL CONSIDERATIONS

To the Editor:

The paper of Penry [1] was extremely important in pointing out the need for consistency in the nomenclature for describing the efficiency of accumulation of contaminants from an ingested source. Beyond the nomenclature discussion, the author also concluded that the selectivity index (SI) method [2], which uses the feeding selectivity of the organism to account for the relative ingestion of contaminant compared to bulk sediment in determining absorption efficiency, should not be used in favor of a dual-labeled approach. Using the SI method with caution is reasonable, but the logic used for rejecting the approach is flawed. Using the equation presented by Penry [1] for the toxicant absorption efficiency (TAE),

$$\text{TAE} = 1 - \left[\frac{\text{Tox}_{\text{feces}}}{\text{Tox}_{\text{sed}}} \cdot \frac{\text{TOC}_{\text{sed}}}{\text{TOC}_{\text{feces}}} (1 - R) \right]$$

Penry [1] states: “The SI method is thus valid only when the product of the ratios ($\text{Tox}_{\text{feces}}/\text{Tox}_{\text{sed}}$) and ($\text{TOC}_{\text{sed}}/\text{TOC}_{\text{feces}}$) is less than or equal to 1.” This need only be the case when R (the fractional loss of carbon through the gut) is equal to zero, equivalent to a nonassimilated tracer in the dual-labeled approach. In all other cases, the value of the product can exceed one. This model condition could have been seen clearly if the lines in Penry’s Figure 3 [1] had been extended to the abscissa. The only model constraint that applies is that the argument in brackets must be less than one for the TAE to be measured by this method. For example, assuming an SI of 2, an R of 0.25, and a TAE of zero, the product of the ratios would be 1.3333, which is definitely greater than 1. A TAE of zero would be expected for a compound such as polydimethylsiloxane and is definitely less than R. The adsorption is constrained by the characteristics of the compound and not by R. Further, this meets the conditions of the model where the absorption efficiency is between zero and one. This is achieved in the following manner. If the TOC in the sediment is set at 1.0, then with an SI of 2 and an R of 0.25, the TOC in the feces would be 1.5. If the amount of contaminant is also 1.0 in the sediment with an SI of 2, then the amount in the feces would be 2. Plugging in the various values leads to the product of the ratios of 1.333 as given above and a value of the argument in the brackets of 1; therefore, the TAE would be 0. Thus, there is no reason to constrain the product of the ratios in the manner suggested. As a result, the argument that the TAE would always have to be greater than or equal to R is invalid.

Penry goes on to state that toxicant absorption efficiency is overwhelmingly dependent on TOC absorption efficiency. This constraint is definitely not the case for polydimethylsiloxane [3], although toxicant absorption is expected to be driven in part by accumulation of carbon. The carbon accumulation reduces the fugacity capacity of the gut contents and increases the concentration driving up the fugacity of the toxicant, there-

by increasing the gradient for accumulation [4,5]. Thus, in compounds that can be accumulated, greater toxicant accumulation efficiency is expected with greater carbon efficiency, but the overall toxicant accumulation efficiency would still not be required to be greater than the carbon efficiency. The toxicant accumulation efficiency depends on the fugacity gradient, the residence time in the gut, and the characteristics of the compound interactions with the remaining food and its ability to pass through the intestinal membrane.

Other arguments make use of the SI method questionable. Does the organism excrete carbon as a part of a peritrophic membrane? It is clear that, over the long term, the amount of carbon excreted in this manner cannot be more than is taken in or the organism would not survive and grow. It is possible, however, that in the course of a relatively brief experiment, such a shortage could occur and may invalidate the method. The mere fact that carbon is excreted, however, is not an a priori invalidation of the method. As long as the proportion of carbon excreted is in proportion to the amount taken in, the result appears as a smaller carbon accumulation (R) and the method can still function. Nevertheless, caution is advised.

One additional assumption was not mentioned by Penry [1]. The contaminant must be uniformly distributed with the TOC so that selection of the TOC allows for equal selection of the contaminant. This may not be a reasonable assumption. Several investigators report that contaminants do not partition uniformly to sediment organic carbon in both natural sediments [6,7] and laboratory-dosed sediments [8–10]. If the distribution is not uniform with respect to the organic carbon, then the SI approach will not work without a way to account for the relative ratio on ingestion as suggested by Forbes and Forbes for dual-labeled experiments [11]. This is probably the reason for the failure of the method to measure the TAE for hexachlorobiphenyl in *Diporeia* [8].

Finally, a point mentioned but not emphasized strongly enough in the Penry paper is the potential influence of contaminant elimination on the ability to measure absorption efficiency. To obtain good measures of absorption efficiency, whether using the SI approach or the dual-labeled approach, the measurement must be made well before the organisms begin to excrete substantial amounts of contaminant. As the organism approaches steady-state, the amount of compound eliminated, often via the feces, can obscure absorption efficiencies, which decline with the approach to steady state [12].

Thus, although consideration of the SI approach for determining the TAE should be viewed with caution, it may still be a reasonable means of estimating TAE in many situations. The real difficulty is that the value of R is unknown in most cases, but reasonable ranges can be bracketed from the literature. To make the method truly valid, R for the particular species needs to be determined. Finally, one advantage of the SI approach is that it can be used with natural sediments; the use of radiolabeled spikes is not required.

Peter F. Landrum
Great Lakes Environmental Research Laboratory
Ann Arbor, Michigan, USA
Jussi Kukkonen
University of Joensuu Joensuu, Finland
Michael J. Lydy
Wichita State University Wichita, Kansas, USA
Henry Lee II
U.S. Environmental Protection Agency
Newport, Oregon, USA

REFERENCES

1. Penry D. 1998. Applications of efficiency measurements in bioaccumulation studies: Definitions, clarifications and a critique of methods. *Environ Toxicol Chem* 17:1633-1639.
2. Lee H, Boese BL, Randall RC, Pelletier J. 1990. A method for determining gut uptake efficiencies of hydrophobic pollutants in a deposit-feeding clam. *Environ Toxicol Chem* 9:215-219.
3. Kukkonen J, Landrum PF. 1995. Effects of sediment-bound polydimethylsiloxane on the bioavailability and distribution of benzo[a]pyrene in lake sediment to *Lumbriculus variegatus*. *Environ Toxicol Chem* 14:523-531.
4. Gobas FAPC, Zhang X, Wells R. 1993. Gastrointestinal magnification: The mechanism of biomagnification and food chain accumulation of organic chemicals. *Environ Sci Technol* 27:2855-2864.
5. Gobas FAPC, McCorquodale JR, Haffner GD. 1993. Intestinal absorption and biomagnification of organochlorines. *Environ Toxicol Chem* 12:567-577.
6. Evans KM, Gill RA, Robotham PWJ. 1990. The PAH and organic content of sediment particle size fractions. *Water Air Soil Pollut* 51:13-31.
7. Umlauf G, Bierl R. 1987. Distribution of organic micropollutants in different size fractions of sediment and suspended solid particles of the River Rotmain. *Z Wasser Abwasser Forsch* 20:203-209.
8. Harkey GA, Lydy MJ, Kukkonen J, Landrum PF. 1994. Feeding selectivity and assimilation of PAH and PCB in *Diporeia* spp. *Environ Toxicol Chem* 13:1445-1455.
9. Kukkonen J, Landrum PF. 1996. Distribution of organic carbon and organic xenobiotics among different particle-size fractions in sediments. *Chemosphere* 32:1063-1076.
10. Landrum PF, Gossiaux DC, Kukkonen J. 1997. Sediment characteristics influencing the bioavailability of nonpolar organic contaminants to *Diporeia* spp. *Chem Speciat Bioavail* 9:43-55.
11. Forbes VE, Forbes TL. 1997. Dietary absorption of sediment-bound fluoranthene by a deposit-feeding gastropod using the ^{14}C : ^{51}Cr dual-labeling method. *Environ Toxicol Chem* 16:1002-1009.
12. Kukkonen J, Landrum PF. 1995. Measuring assimilation efficiencies for sediment-bound PAH and PCB congeners by benthic organisms. *Aquat Toxicol* 32:75-92.

The author's reply:

Landrum, Kukkonen, and Lydy [1] lend support to my critique of problems with the application of efficiency measurements in studies of bioaccumulation [2] and add emphasis to many of the points that I made. Some of their comments indicate, however, that my analysis of the selectivity index (SI) method for estimating toxicant absorption efficiencies [3] needs further clarification. The flaws are in the SI method, not in my logic.

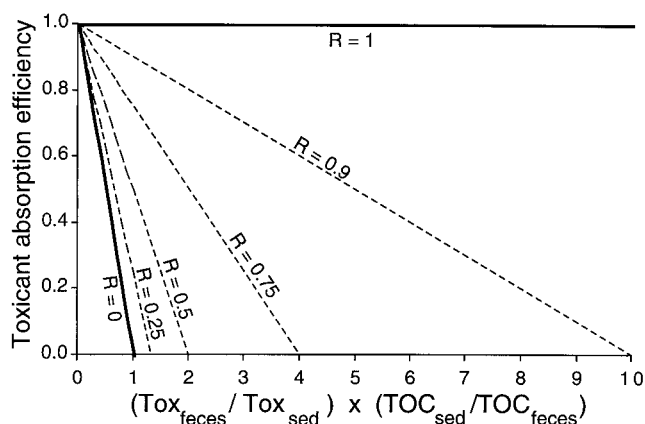


Fig. 1. The effect of R, TOC absorption efficiency, on calculated toxicant absorption efficiencies. This figure is an extension of Figure 3 in Penry [2].

Toxicant absorption efficiency estimated using the SI method is a function of three nondimensional parameters, the ratio of toxicant concentration in feces to toxicant concentration in sediment ($\text{Tox}_{\text{feces}}/\text{Tox}_{\text{sed}}$), the ratio of total organic carbon (TOC) concentration in sediment to total organic carbon concentration in feces ($\text{TOC}_{\text{sed}}/\text{TOC}_{\text{feces}}$), and absorption efficiency or fractional absorption of organic carbon (R). Toxicant absorption efficiency = $1 - [(\text{Tox}_{\text{feces}}/\text{Tox}_{\text{sed}}) \times (\text{TOC}_{\text{sed}}/\text{TOC}_{\text{feces}}) \times (1 - R)]$ [2]. The most important shortcoming of the SI method is that a value must be assumed for R, and calculated toxicant absorption efficiency is often very sensitive to the value that is assumed.

Landrum et al. are correct when they state that the product $[(\text{Tox}_{\text{feces}}/\text{Tox}_{\text{sed}}) \times (\text{TOC}_{\text{sed}}/\text{TOC}_{\text{feces}})]$ can be greater than one (Fig. 1). However, when this product exceeds one, the minimal value of TOC absorption efficiency (R) increases (see Fig. 2, [2]) and the range of values that can be assumed for R decreases. For this reason, I limited my original analysis of the SI equation to cases in which $[(\text{Tox}_{\text{feces}}/\text{Tox}_{\text{sed}}) \times (\text{TOC}_{\text{sed}}/\text{TOC}_{\text{feces}})]$ is less than or equal to one.

Reported values of R for deposit feeders range from 0 to 0.76 [4]. Values for R assumed in applications of the SI method generally range from 0 to 0.22 [3,5,6]. There is no a priori justification for restricting the minimal value that can be assumed for R, but, in order to obtain nonnegative toxicant absorption efficiencies using the SI equation, the minimal value that can be assumed for R must increase (to a limit of one) when the product $[(\text{Tox}_{\text{feces}}/\text{Tox}_{\text{sed}}) \times (\text{TOC}_{\text{sed}}/\text{TOC}_{\text{feces}})]$ is greater than one. Landrum et al. discuss an example in which the product is 1.33. When the product is 1.33, the minimal value that can be assumed for R is 0.25 (Fig. 1), and values of R that fall within the range most commonly used in published applications of the SI method (0 to 0.22) [3,5,6] would not be valid.

I originally restricted my analysis of the SI equation [2] to values of the product $[(\text{Tox}_{\text{feces}}/\text{Tox}_{\text{sed}}) \times (\text{TOC}_{\text{sed}}/\text{TOC}_{\text{feces}})]$ less than or equal to one for the reason discussed above. All of the conclusions reached are valid for that set of values, including the conclusion that Landrum et al. dispute, that is, that calculated toxicant absorption efficiency will always be greater than or equal to TOC absorption efficiency. Since Landrum et al. raise the issue of values of the product greater than one, it is useful to consider the behavior of the SI equation over a wider range of product values.

When the product $[(\text{Tox}_{\text{feces}}/\text{Tox}_{\text{sed}}) \times (\text{TOC}_{\text{sed}}/\text{TOC}_{\text{feces}})]$ equals one, toxicant absorption efficiency = $1 - [1 \times (1 - R)]$ and is determined completely by the value assumed for R. In other words, the value calculated for toxicant absorption efficiency is exactly equal to the value assumed for R. As the product approaches zero, calculated toxicant absorption efficiency approaches one and becomes more and more insensitive to variation in R. For example, when the product equals 0.5, an incremental change in R of 0.25 from $R = 0.5$ to $R = 0.75$ results in a relatively small change in calculated toxicant absorption efficiency from 0.75 to 0.875.

When the product increases above one, R approaches one and calculated toxicant absorption efficiency is increasingly sensitive to R. For example, when the product equals 2, the same incremental change in R from 0.5 to 0.75 results in a change in toxicant absorption efficiency from 0 to 0.5. This change is fourfold greater than that observed when the product equals 0.5. At the same time, the range of values of R that yield nonnegative values for toxicant absorption efficiency decreases from 0 to 1 (when the product equals 0.5) to 0.5 to 1 (when the product equals 2).

I had originally concluded [2] that the SI method is valid only when the product $[(\text{Tox}_{\text{feces}}/\text{Tox}_{\text{sed}}) \times (\text{TOC}_{\text{sed}}/\text{TOC}_{\text{feces}})]$ is less than 1, but now I would go even further and suggest that, unless TOC absorption efficiency is measured directly, the method is in fact valid only when the product is less than about 0.2. In this region, an assumed value for R has little effect on calculated toxicant absorption efficiency; unfortunately, this region is of little relevance in studies of toxicant uptake by deposit feeders, at least where hydrophobic organic toxicants are concerned. When the product is 0.2 or less, calculated toxicant absorption efficiencies range from 0.8 to 1, but observed toxicant absorption efficiencies for deposit feeders are generally less than 0.6 for hydrophobic organic compounds [3,5–8].

Finally, in my original analysis, I stated that toxicant absorption efficiency is overwhelmingly dependent on TOC absorption efficiency when the ratios of $\text{Tox}_{\text{feces}}$ to Tox_{sed} and $\text{TOC}_{\text{feces}}$ to TOC_{sed} are approximately equal [i.e., when $(\text{Tox}_{\text{feces}}/\text{Tox}_{\text{sed}}) \times (\text{TOC}_{\text{sed}}/\text{TOC}_{\text{feces}})$ is close to one]. The dependence of toxicant absorption efficiency on TOC absorption efficiency that I discussed is solely a mathematical artifact of the SI equation.

Neither the equation nor my discussion of it should be interpreted as implying anything about potential biological or chemical relationships between toxicant and TOC absorption efficiencies. Thus, the discussion of fugacity and other chemical and biological factors affecting toxicant absorption efficiency in Landrum et al. is extremely important but not relevant to my original conclusion.

I hope that this exchange will serve to reinforce the central points on which Landrum et al. and I strongly agree. The SI method for estimating toxicant absorption efficiencies must be viewed with caution, and values for important parameters such as organic carbon absorption efficiency must be measured, not assumed.

Deborah L. Penry
Department of Integrative Biology
University of California
Berkeley, California, USA

REFERENCES

1. Landrum PF, Kukkonen J, Lydy MJ, Lee H. 1999. Measuring absorption efficiencies: Some additional considerations. *Environ Toxicol Chem* 18:2403–2404.
2. Penry DL. 1998. Applications of efficiency measurements in bioaccumulation studies: Definitions, clarifications and a critique of methods. *Environ Toxicol Chem* 17:1633–1639.
3. Lee H, Boese BL, Randall RC, Pelletier J. 1990. A method for determining gut uptake efficiencies of hydrophobic pollutants in a deposit-feeding clam. *Environ Toxicol Chem* 9:15–219.
4. Lopez GR, Levinton JS. 1987. Ecology of deposit-feeding animals in marine sediments. *Quart Rev Biol* 62:235–260.
5. Lydy MJ, Landrum PF. 1993. Assimilation efficiency for sediment-sorbed benzo[a]pyrene by *Diporeia* sp. *Aquat Toxicol* 26:209–223.
6. Kukkonen J, Landrum PF. 1995. Measuring assimilation efficiencies for sediment-bound PAH and PCB congeners by benthic organisms. *Aquat Toxicol* 32:75–92.
7. Klump JV, Krezoski JR, Smith ME, Kaster JL. 1987. Dual tracer studies of the assimilation of an organic contaminant from sediments by deposit feeding oligochaetes. *Can J Fish Aquat Sci* 44:1574–1583.
8. Penry DL, Weston DP. 1998. Digestive determinants of benzo[a]pyrene and phenanthrene bioaccumulation by a deposit-feeding polychaete. *Environ Toxicol Chem* 17:2254–2265.