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A SAFETY FACTOR FOR  $LC_{50}$  VALUES ALLOWING FOR  
DIFFERENCES IN SENSITIVITY AMONG SPECIES

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## A SAFETY FACTOR FOR $LC_{50}$ VALUES ALLOWING FOR DIFFERENCES IN SENSITIVITY AMONG SPECIES

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**Abstract**—A safety factor has been derived that can be applied to the mean  $LC_{50}$  value of several test species for a particular toxic compound, for the purpose of arriving at what has been called a hazardous concentration for sensitive species. The application of this factor should provide limited protection to a certain number of species in a relevant community. The derivation is based on the assumption that the  $LC_{50}$  values for both the test species and for the community species can be conceived of as independent random trials from a log-logistic distribution.

The proposed hazardous concentration for sensitive species has been chosen such that the  $LC_{50}$  value of the most sensitive species in a community of a certain number of species exceeds that concentration by a specified probability. It allows for the uncertainty in the mean and variance of the  $LC_{50}$  values for the test species that is due to the number of test species being limited. It is possible to calculate the optimum number of species to be tested on basis of a cost-benefit analysis. Examples of the application are given.

**Key words**—safety factor,  $LC_{50}$ , most sensitive species, log-logistic distribution, number of best species, number of community species

### NOMENCLATURE

Symbol	Dimension	Interpretation
$t$	time	exposure time to toxic compound
$\tau$	time	time constant for the elimination process
$LC_{50}$	concn	lethal concentration for 50% of the organisms
HCS	concn	hazardous concentration for sensitive species
$X_i$	$\ln \text{concn}$	logarithm of the $LC_{50}$ for species $i$
$\bar{X}_m$	$\ln \text{concn}$	sample mean of $\ln LC_{50}$ s for $m$ test species
$S_m$	—	sample standard deviation of $\ln LC_{50}$ s for $m$ test species
$\alpha$	$\ln \text{concn}$	location parameter of the log-logistic distribution
$\beta$	—	scatter parameter of the log-logistic distribution
$m$	—	number of test species
$n$	—	number of community species
$\delta_1$	—	prob{minimum $LC_{50} \leq \text{HCS}$ given $\alpha$ and $\beta$ }
$\delta_2$	—	prob{minimum $LC_{50} \leq \text{HCS}$ }
$C_m$	—	coefficient with value $\ln\{(1 - \delta_1)^{1/n} / [1 - (1 - \delta_1)^{1/n}]\}$
$d_m$	—	value such that $\text{Prob}(S_m > d_m) = \delta_2$
$T$	—	application factor between HCS and $\exp(\bar{X}_m)$ .

### INTRODUCTION

The purpose of this paper is to define the concept of a hazardous concentration for sensitive species (HCS), and to provide an algorithm for its computation from  $LC_{50}$  values obtained for a sample of test species. The HCS can be regarded as a lower bound for concentrations that can be expected to be

harmful for a given community. It is related to the concept of critical effect concentrations, which is sometimes used.

All honest scientific research workers will feel rather uncomfortable with such a task, and the author is no exception. This feeling finds its roots in the extrapolation of experimental findings far beyond the limits of our knowledge. If legislation aims to protect sensitive species in the community under consideration, ideally one has to test all the species in order to locate the most sensitive ones, as long as no clear-cut patterns in sensitivity have been found. Regrettably, this appears to be the case for almost all xenobiotic chemicals. But to test all species is impossible for financial, technical as well as ethical reasons. This lack of sufficient data is the reason why legislators persist in asking for algorithms, for safe concentrations. The author believes it is possible to improve a little on this situation by providing an algorithm based on explicit assumptions that can be updated in the light of new findings.

In this paper the  $LC_{50}$  defined as the concentration of compound at which the survival probability is half that of the blank, will be conceived of as a fixed number, any experimental error being neglected, i.e. this error is assumed to be small with respect to the variation in  $LC_{50}$ s among species. Statistical considerations in determining  $LC_{50}$  values as a function of the exposure time to the chemical have been treated in Kooijman (1981, 1983). The next section gives some ideas that may be of use in relating an acute  $LC_{50}$  to a chronic one, which is considered to be the most relevant. Subsequent sections deal with the

assumptions leading to the proposed HCS and with discussions on the numbers of test and community species to be chosen. They are an elaboration of the ideas given in Kooijman (1985) and are followed by examples of application and a discussion on the use of the ideas presented.

#### ACUTE VS CHRONIC TOXICITY

Since exposures to toxic chemicals in the environment will often be of a chronic nature, chronic toxicity data seem to be more suited to predict effects than acute data. Mortality, as related to exposure time, is usually (but not always) well described by the death an organism suffers as soon as it has accumulated the chemical above some threshold value in the whole organism or a target organ. (The term accumulation as it is used here refers to the transport process and, it does not necessarily imply that the concentration inside the organism is supposed to rise above the concentration in the environment.) Kooijman (1981) demonstrates that the concentration  $Q(t)$  inside the organism or target organ is related to  $LC_{50}$  values in accordance with

$$Q(t) = Kc LC_{50x} / LC_{50}, \quad (1)$$

where  $t$  denotes exposure time,  $c$  the concentration in the environment and  $K$  the bioaccumulation factor (which may be  $< 1$ ). A natural first approximation to this accumulation process of xenobiotic chemicals is the so-called one-compartment model:

$$Q(t) = Kc [1 - \exp(-t/\tau)] \quad (2)$$

where  $\tau$  can be interpreted as the time constant of the elimination process. This means that the value of this time constant can be obtained from a comparison of acute and chronic  $LC_{50}$  values:

$$\tau = -t / \ln(1 - LC_{50x} / LC_{50}). \quad (3)$$

If, in contrast with  $LC_{50}$  values for exposure times  $t_1$  and  $t_2$ , the ultimate lethal concentration  $LC_{50x}$  is not available,  $\tau$  can be obtained by solving the equation

$$LC_{50,2} [1 - \exp(-t_2/\tau)] = LC_{50,1} [1 - \exp(-t_1/\tau)]. \quad (4)$$

In general, the value of  $\tau$  will depend on the nature of the chemical (detergents have small  $\tau$  values, whereas heavy metals have large ones) as well as on the species of organism. For instance, the time constant is likely to increase with the size of the organism. For this reason, chronic  $LC_{50}$  values are expected to vary less among species than acute ones. This reduction in scatter is expected to greatly overcompensate for chronic  $LC_{50}$ s being less than acute ones in the calculation of HCS values, which is discussed in the next section. (The HCS decreases for increasing scatter and decreasing mean  $LC_{50}$ .) It would be worthwhile to make a more systematic search for patterns in the values of the time constant. If its value is known in a particular case, it might be

used to estimate the ultimate  $LC_{50}$  from an acute one, using

$$LC_{50x} = LC_{50} [1 - \exp(-t/\tau)]. \quad (5)$$

Of course, such an estimation would only make sense so long the assumptions remain valid. Note that if the time constant does not vary too much among species, the ratio between acute and ultimate  $LC_{50}$  values is fixed for equal exposure times. It relates to the application factor proposed by Mount and Stephan (1967) given in Southworth *et al.* (1982).

#### HAZARDOUS CONCENTRATIONS FOR SENSITIVE SPECIES

It is an empirical finding that toxic effects of xenobiotic chemicals, like mortality, should be related to the logarithm of the concentration, rather than to the concentration itself. The survival probability of individuals of the same species often show a more or less logistic relation with the logarithm of the concentration of toxic compound after a given exposure time. This corresponds to the threshold concentrations having a log-logistic distribution.

In analogy with this "rule", we shall assume that the  $LC_{50}$  values of the test species, as well as of the community species can be conceived of as random trials from a log-logistic distribution, i.e. the probability that the  $LC_{50}$  of a species is  $\leq x$  is given by

$$\text{Prob}(\ln LC_{50} \leq x) = \{1 + \exp[(\alpha - x)/\beta]\}^{-1} \quad (6)$$

where  $\alpha$  and  $\beta$  are parameters. In order to test the validity of this assumption, the set of data given by Slooff *et al.* (1983) has been examined for this property, ignoring the (few) inequality signs in the data. The results are given in Fig. 1. The data include a rather wide variety of aquatic organisms but, like most literature data, they are of an acute nature. (The exposure time was two days.) If the scatter in time constants among species is small, the result of the previous section indicate that chronic data differ only in the location parameter  $\alpha$  (namely by an amount of  $\ln[1 - \exp(-t/\tau)]$ ), because we are considering logarithmically transformed concentrations. In conclusion we might state that most data do not indicate large deviations from the log-logistic distribution. Where deviations do occur, some of them can be traced back to chemical properties of the chemicals involved.

In the derivation of HCS, I shall assume in this section that the parameter values  $\alpha$  and  $\beta$  are known. In practice, this will not be the case. The next section therefore deals with complications that arise when these values are estimated from data on a (small) number of test species.

The survivor function,  $F(x)$ , for the  $\ln LC_{50}$  of the most sensitive of  $n$  species for the chemical in ques-

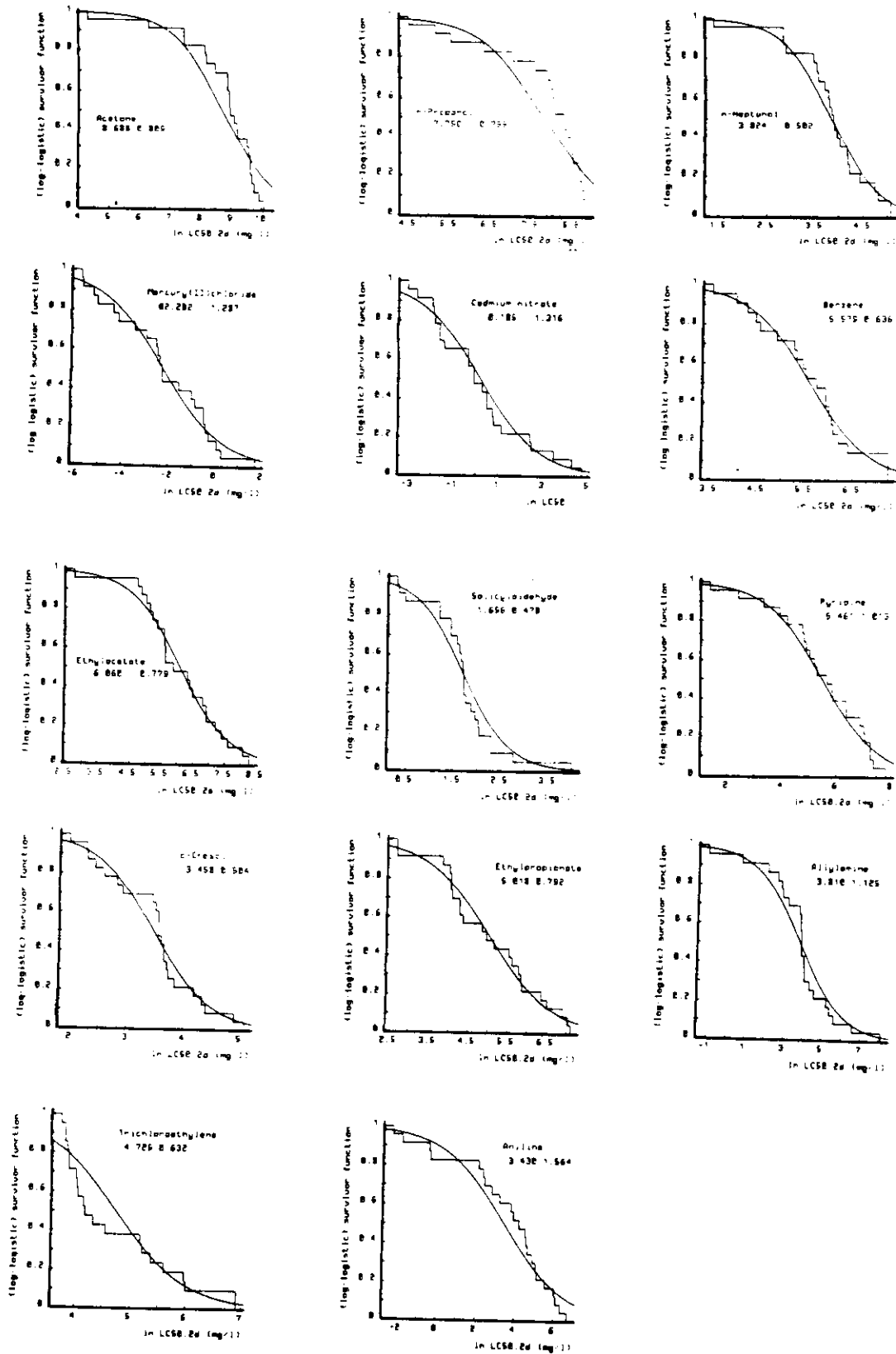


Fig. 1. Empirical survivor functions for the natural logarithm of the acute  $LC_{50}$ s for different toxic compounds, compared to the logistic one with the indicated parameter values for  $\alpha$  and  $\beta$  being moment estimations. Data from Slooff *et al.* (1983).

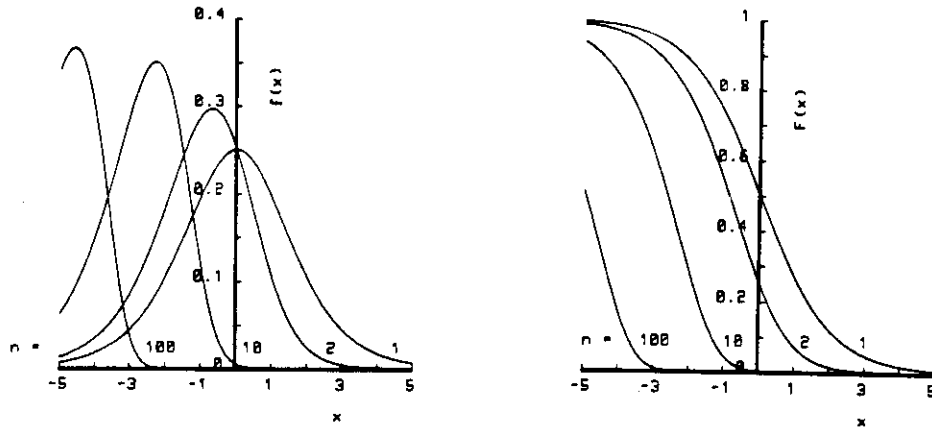


Fig. 2. Probability density function  $f(x)$  left, and survivor function  $F(x)$  right of the minimum of  $n = 1, 2, 10$  and  $100$  independent random variables, having a standard logistic distribution.

tion, defined as the probability that this  $\ln LC_{50}$  will exceed a value  $x$ , is given by

$$F(x) = \text{Prob}(\ln LC_{50} \text{ of the most sensitive of } n \text{ species} > x)$$

$$\Rightarrow F(x) = [\text{Prob}(\ln LC_{50} \text{ of a species selected at random} > x)]^n$$

$$\Rightarrow F(x) = [1 - \text{Prob}(\ln LC_{50} \text{ of a species selected at random} \leq x)]^n$$

$$\Rightarrow F(x) = \exp[n(\alpha - x)/\beta] \{1 + \exp[(\alpha - x)/\beta]\}^{-n} \quad (7)$$

Figure 2 illustrates this survivor function for several selections of  $n$  and for  $\alpha = 0$  and  $\beta = 1$ , in which case the logistic distribution is called the standard logistic distribution. The figure also illustrates the corresponding probability density functions (obtained from the survivor functions by taking minus the derivative with respect to  $x$ ). As might be expected, the location of the densities move to the left for an increasing number of species and they become skew to the left.

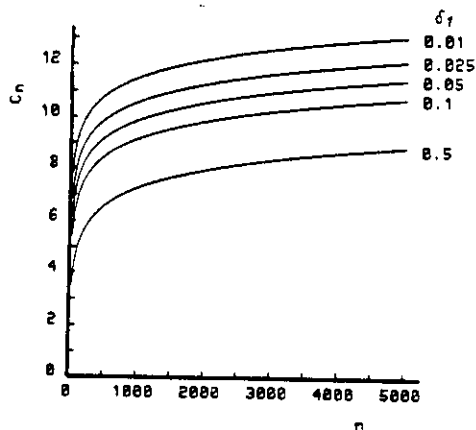


Fig. 3. Coefficient  $C_n$ , given in equation (10), as a function of the number of species  $n$ . Different choices for  $\delta_1$  have been made.

A reasonable proposal for an HCS is a value such that the probability that the  $LC_{50}$  of the most sensitive of  $n$  species will be below this value equals a chosen small value,  $\delta_1$  for instance  $0.05$ . Equating the survivor function given by equation (7) to one minus this value yields the equation

$$F(\ln HCS) = 1 - \delta_1 \quad (8)$$

the  $\ln HCS$  is found to be given by

$$\ln HCS = \alpha - \beta C_n \quad (9)$$

where

$$C_n = \ln \{ (1 - \delta_1)^{1/n} / [1 - (1 - \delta_1)^{1/n}] \} \quad (10)$$

Plots of  $C_n$  vs  $n$ , for various choices of  $\delta_1$  are shown in Fig. 3.

#### NUMBER OF TEST SPECIES

In the previous section we assumed that the values for the location parameter  $\alpha$  and the dispersion parameter  $\beta$  were known. Usually they are not, and so have to be estimated from  $LC_{50}$ s of a number, say  $m$ , of test species. This can be done by means of the moment estimators, obtained by equating the theoretical first and second moments to the sample values. This leads to the parameter estimates

$$\hat{\alpha} = \bar{X}_m \quad (11)$$

$$\hat{\beta} = S_m \sqrt{3/\pi} \quad (12)$$

where the sample mean,  $\bar{X}_m$ , and sample SD,  $S_m$ , are given by

$$\bar{X}_m = \sum_i X_i / m \quad (13)$$

$$S_m = \left[ \frac{m}{m-1} (\sum_i X_i^2 / m - \bar{X}_m^2) \right]^{1/2} \quad (14)$$

and  $X_i$  is the  $\ln LC_{50}$  of the  $i$ th species.

The accuracy of the estimates obviously depends on the number  $m$  of test species, as illustrated in Fig. 4. Computer simulation studies indicate that maximum likelihood estimators for  $\alpha$  and  $\beta$ , which

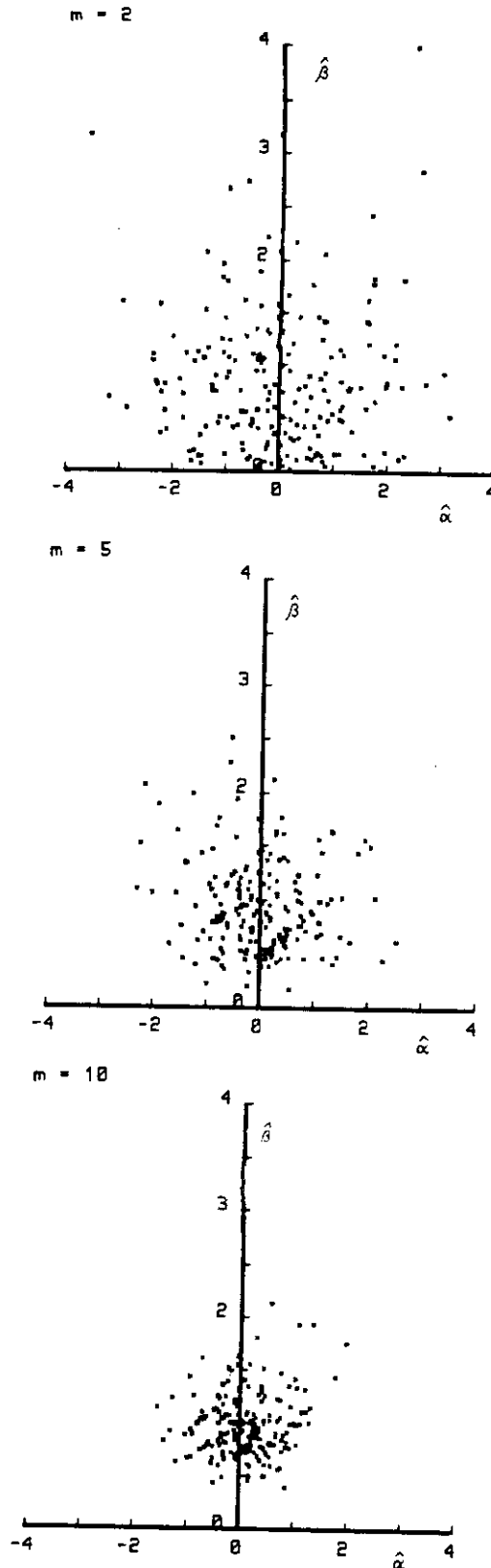


Fig. 4. Moment estimations of the parameters of the standard logistic distribution, based on  $m = 2, 5$  and  $10$  random trials. On the abscissa are the estimated values for location parameter  $\alpha$  and on the ordinate those for the scatter parameter  $\beta$ .

are an alternative to the moment estimators, seriously underestimate  $\beta$  for small values of  $m$ . For larger  $m$ , ( $5 < m < 30$ ), the two estimators are about equivalent.

If the estimated values,  $\hat{\alpha}$  and  $\hat{\beta}$ , are substituted for  $\alpha$  and  $\beta$  on the righthand side of equation (9), then the quantity obtained,

$$Z = \hat{\alpha} - \hat{\beta} C_n \quad (15)$$

is a random variable whose properties depend on the distribution of the  $\ln LC_{50}$ s. The  $\ln HCS$  is now defined by means of the equation:

$$\text{Prob}(Z \leq \ln HCS) = \delta_2 \quad (16)$$

where  $\delta_2$  is a chosen small value, for example,  $0.05$ . From equations (15) and (16) it follows that

$$\text{Prob}(\hat{\alpha} - \hat{\beta} C_n \leq \ln HCS) = \delta_2$$

$$\Rightarrow \text{Prob}(\hat{\alpha}/C_n - \hat{\beta} \leq \ln HCS/C_n) = \delta_2 \quad (17)$$

$$\Rightarrow \text{Prob}[(\hat{\alpha} - \alpha)/(\beta C_n) - \hat{\beta}/\beta \leq (\ln HCS - \alpha)/(\beta C_n)] = \delta_2. \quad (18)$$

Now we consider the left-hand side of the inequality sign of equation (18). Writing  $X_i^*$  for  $(X_i - \alpha)/\beta$  and  $\bar{X}_m^*$  for their sample mean, it follows from equations (11) and (13) that

$$\begin{aligned} (\hat{\alpha} - \alpha)/(\beta C_n) &= (\sum X_i/m - \alpha)/(\beta C_n) \\ &= \sum (X_i - \alpha)/\beta / (m C_n) \end{aligned}$$

$$\Rightarrow (\hat{\alpha} - \alpha)/(\beta C_n) = \sum X_i^*/(m C_n) = \bar{X}_m^*/C_n. \quad (19)$$

Writing  $S_m^*$  for the sample SD of the  $X_i^*$ 's, it follows from equations (12) and (14) that

$$\hat{\beta}/\beta = \left[ \frac{m}{m-1} (\sum X_i^{*2}/m - \sum_i^2 X_i^*/m) \right]^{1/2} \sqrt{3/\pi} \beta$$

$$\hat{\beta}/\beta = \left\{ \frac{m}{m-1} [\sum (X_i/\beta)^2/m - \sum_i^2 (X_i/\beta)/m] \right\}^{1/2} \sqrt{3/\pi}$$

$$\begin{aligned} \hat{\beta}/\beta &= \left( \frac{m}{m-1} \left\{ \sum [(X_i - \alpha)/\beta]^2/m \right. \right. \\ &\quad \left. \left. - \sum_i^2 [(X_i - \alpha)/\beta]/m \right\} \right)^{1/2} \sqrt{3/\pi} \end{aligned}$$

$$\begin{aligned} \Rightarrow \hat{\beta}/\beta &= \left[ \frac{m}{m-1} (\sum X_i^{*2}/m - \sum_i^2 X_i^*/m) \right]^{1/2} \sqrt{3/\pi} \\ &= S_m^* \sqrt{3/\pi}. \quad (20) \end{aligned}$$

From equation (6), it is obvious that the assumption that  $X_i$  is logistically distributed with parameters  $\alpha$  and  $\beta$  corresponds with the assumption that  $X_i^*$  is standard logistically distributed. On basis of equations (19) and (20), the problem of finding a value  $\ln HCS$  such that equation (17) holds given that the  $X_i$ 's follow a logistic distribution with parameters  $\alpha$  and  $\beta$  therefore reduces the problem of finding a value  $\ln HCS$  such that the equation

$$\text{Prob}[\hat{\alpha}/C_n - \hat{\beta} \leq (\ln HCS - \alpha)/(\beta C_n)] = \delta_2 \quad (21)$$

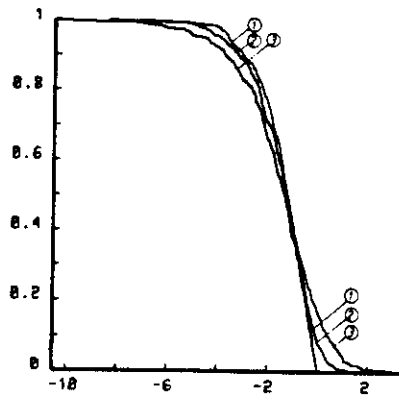


Fig. 5. Survivor function for (1):  $\bar{X}_m - S_m$ , for (2):  $\bar{X}_m/2 - S_m$  and for (3):  $-S_m$ , where  $\bar{X}_m$  and  $S_m$  are the sample mean and standard deviation based on  $m = 2$  trials from the standard logistic distribution.

holds, given that the  $X_i$ 's follow a standard logistic distribution.

Figure 2 indicates that  $C_n$  is typically  $> 2$  and computer simulations demonstrate that, for  $C_n > 2$ , the distribution of the random variable  $\hat{\alpha}/C_n - \beta$  is very similar to that of the random variable  $-\beta$ . This is not surprising because the sample mean of standard logistically distributed variables is expected to be close to zero. Figure 5 gives empirical survivor functions for  $\hat{\alpha} - \beta$ ,  $\hat{\alpha}/2 - \beta$  and  $-\beta$  which are based on 500 estimations for  $m = 2$  trials from the standard logistic distribution. The convergence of the survivor function for  $\hat{\alpha}/C_n - \beta$  to that for  $-\beta$  is very fast in the left tail (which is the relevant one), and for  $C_n = 10$ , the left tail of the survivor function for  $\hat{\alpha}/C_n - \beta$  can hardly be distinguished from that for  $-\beta$ . This equation (21) may be approximated by the equation

$$\begin{aligned} \text{Prob}[-\beta \leq (\ln \text{HCS} - \alpha)/(\beta C_n)] &= \delta_2 \\ \Rightarrow \text{Prob}[S_m > (\pi/\sqrt{3})(\alpha - \ln \text{HCS})/(\beta C_n)] &= \delta_2. \end{aligned} \quad (22)$$

Figure 6 gives empirical survivor functions for  $S_m$ ,

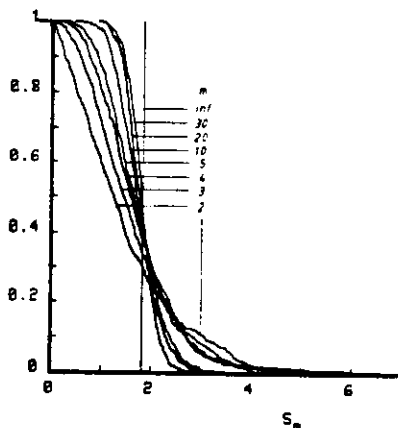


Fig. 6. Survivor function for the sample standard deviation based on  $m$  trials from a standard logistic distribution.

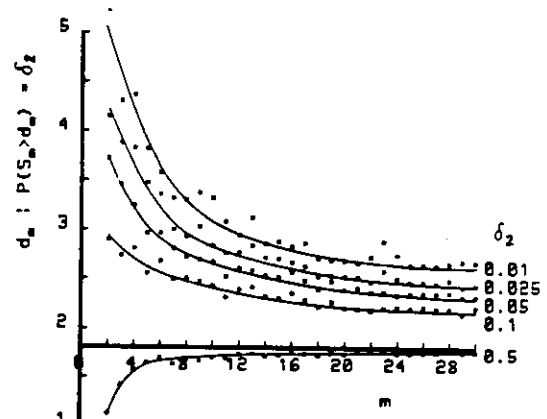


Fig. 7. Values such that the probability that the sample standard deviation based on  $m$  trials from the standard logistic distribution exceeds this value equals  $\delta_2$  as a function of the number of trials.

based on 500 estimations from  $m$  trials from the standard logistic distribution. Such a computer simulation study can be used to obtain values  $d_m$  such that  $\text{Prob}(S_m > d_m) = \delta_2$ . The results are given in Fig. 7 and Table 1. Having selected a value for  $\delta_2$ , the value of  $d_m$  may be determined by rearranging the equation

$$d_m = (\pi/\sqrt{3})(\alpha - \ln \text{HCS})/(\beta C_n)$$

to obtain

$$\ln \text{HCS} = \alpha - \beta C_n d_m \sqrt{3}/\pi. \quad (23)$$

Note that this equation differs from the corresponding one in case of  $\alpha$  and  $\beta$  being known, equation (9), only by the term  $d_m \sqrt{3}/\pi$ . This term allows for the fact that the unknown  $\alpha$  and  $\beta$  may differ from the known values  $\hat{\alpha}$  and  $\hat{\beta}$  with certain probabilities. Since for increasing  $m$ , we have that  $\hat{\alpha} \rightarrow \alpha$  and  $\hat{\beta} \rightarrow \beta$ , this corresponds with  $d_m \sqrt{3}/\pi \rightarrow 1$  for increasing  $m$ , so equation (23) gradually reduces to (9).

Replacement of  $\alpha$  and  $\beta$  by their sample estimates yield the equation

$$\ln \text{HCS} = \bar{X}_m - 3S_m d_m C_n / \pi^2 \quad (24)$$

$$\Rightarrow \text{HCS} = \exp(\bar{X}_m - 3S_m d_m C_n / \pi^2)$$

$$\Rightarrow \text{HCS} = \exp(\bar{X}_m)/T$$

$$\Rightarrow \text{HCS} = (\text{geometric mean of the sample of } \text{LC}_{50}\text{s})/T. \quad (25)$$

The value  $T$  can be regarded as an application factor, which should be applied to the geometric mean of the sample of  $\text{LC}_{50}\text{s}$  and is given by

$$T = \exp(3S_m d_m C_n / \pi^2).$$

Note that HCS increases (up to a limit) for an increasing number of test species, because more information is available; it decreases (down to zero) for an increasing number of community species  $n$  because large communities are more likely to include very sensitive species. This latter theme will be discussed in the next section.



Table 1. Values  $d_m$  such that  $\text{Prob}(S_m > d_m) = \delta_1$ , based on estimations from materials from a standard logistic distribution

$\delta_1$ $m$	0.01	0.025	0.05	0.1	0.5
2	5.09	4.15	3.72	2.91	1.12
3	4.58	3.87	3.40	2.77	1.41
4	4.25	3.60	3.22	2.70	1.56
5	3.99	3.42	3.06	2.64	1.65
6	3.74	3.25	2.93	2.59	1.68
7	3.52	3.11	2.82	2.53	1.68
8	3.34	2.99	2.72	2.49	1.69
9	3.20	2.90	2.65	2.45	1.69
10	3.09	2.83	2.59	2.42	1.70
11	3.01	2.77	2.56	2.39	1.70
12	2.95	2.73	2.53	2.36	1.71
13	2.91	2.70	2.51	2.34	1.71
14	2.88	2.67	2.50	2.32	1.72
15	2.86	2.65	2.49	2.30	1.72
20	2.76	2.56	2.44	2.24	1.76
30	2.62	2.42	2.30	2.19	1.77
$\infty$	1.814	1.814	1.814	1.814	1.814

The financial cost of obtaining LC<sub>50</sub>s is likely to increase linearly with  $m$ , say with a factor  $S_1$ , whereas the cost associated with the application factor  $T$  increases with  $T$ , possibly also linearly, say with factor  $S_2$ . If this is true, it is possible to calculate the number of test species expected to be most cost-effective, by minimizing the total cost  $S_1 m + S_2 T$  as a function of  $m$ . The optimum  $m$  is found from  $-\partial T / \partial m = S_1 / S_2$ . Figure 8 gives  $-\partial T / \partial m$  as a function of  $m$ . The figure makes it clear that the optimum choice for  $m$  rapidly increases with increasing scatter among the LC<sub>50</sub>s.

#### NUMBER OF COMMUNITY SPECIES

The number of species in the community to be polluted depends on its type and the size of the polluted area. Figure 3 gives the coefficient  $C_n$  as a function of  $n$ . It rises sharply with increasing  $n$  up to  $n = 500$ , but for larger values of  $n$ , the increase is less

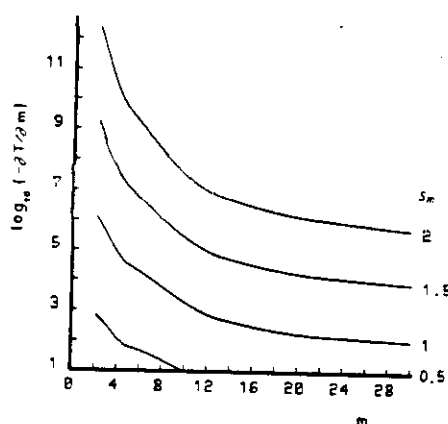


Fig. 8. The logarithm to base 10 of minus the deviate of the application factor with respect to the number of test species  $m$ , as a function of  $m$ . The most cost-effective choice for  $m$  corresponds to the ordinate value equal to the logarithm of the ratio between the costs for testing one species and for one unit of application factor. Different choices for the SD of the  $\ln$  LC<sub>50</sub>s,  $S_m$ , has been made, while  $\delta_1 = \delta_2 = 0.025$  and  $n = 1000$ .

dramatic. The problem of a suitable choice of  $n$  is complicated by the wide variety of organisms involved: bacteria, fungi, plants and animals. In bacteriology, for example, definition of species is not clear cut, so one has to revert to definitions of groups based on physiological characteristics. To the authors knowledge, no systematic study has yet been done on the extent to which taxonomically related species are likely to have equal LC<sub>50</sub>s. In such a study, acute toxicity data are of a limited value, because related species differing in size are likely to have different acute LC<sub>50</sub>s, whereas the chronic LC<sub>50</sub>s may not differ very much. If this is true,  $n$  may be taken to be the number of genera or families, instead of the number of species. At the moment, however, there is little ground for such a substitution.

In the ecological literature, the number of species as a function of surface area of habitat is known as the species-area curve. The usual form of the function is

$$n(a) = ba^\gamma \quad (26)$$

where  $a$  is the surface area,  $b$  a constant related to the number of species in a unit of surface area (of dimension length<sup>-2 $\gamma$</sup> ), and  $\gamma$  another (dimensionless) constant. The primary motivation for this particular choice is that  $\ln n_a$  is linear in  $\ln a$ , and that a linear model is so attractively simple, although the scatter in the data usually allows of a wide variety of models. A rather fundamental problem connected with this particular choice is that the selection of the taxonomic group highly depends on the interests of the student, and that the sum of the number of species in two taxonomic groups only has a species-area curve of this type if the values for  $\gamma$  are identical. Pianka (1978) gives values from about 0.12 to 0.17 for mainland situations and from 0.23 to 0.49 for islands.

#### EXAMPLES

Table 2 lists the mean and standard deviations of the chronic  $\ln$  EC<sub>50</sub> values given in Adema *et al.* (1981), together with the calculated HCS for  $\delta = \delta_1 = \delta_2 = 0.1$  and  $n = 1000$  (it is hard to see any argument for choosing  $\delta_1$  different from  $\delta_2$ ). The value  $0.4 \mu\text{g l}^{-1}$  for 2,4-dichloroaniline, for instance, is obtained from  $\exp(\bar{X}_m - S_m d_m C_n 3/\pi^2)$ , with  $\bar{X}_m = 1.13$  and  $S_m = 1.33$  from Table 2,  $d_m = 2.42$  from Table 1 for  $m = 10$  and  $\delta_1 = 0.1$ , and  $C_n = \ln[0.9^{1/n}/(1 - 0.9^{1/n})]$ , which gives  $C_n = 9.16$  for  $n = 1000$ . The extremely low value for potassium dichromate is mainly due to a diatom species found to be extremely sensitive to this chemical (this might be related to the trace element composition of the medium, which calls for further research; Hanstveit, personal communication). An argument against the present application may be that the data include bacterial and algal species, for which the EC<sub>50</sub> values (defined as concentrations affecting a certain quantified property of the organism up to 50%), refer

Table 2. Mean  $\bar{X}_m$  and SD  $S_m$  of  $m$  chronic  $\ln EC_{50}$  values given in Adema *et al.* (1981). Based on these values, hazardous concentrations for sensitive species have been calculated for  $\delta = 0.1$  and  $n = 1000$

Compound	$\bar{X}_m$ ( $\ln mg l^{-1}$ )	$S_m$	$m$	HCS ( $\mu g l^{-1}$ )	Application factor $T$
2,4-Dichloroaniline	1.13	1.33	10	0.4	7800
Tetrapropylenebenzene sulphonate	3.45	0.87	10	90.0	350
Tricresyl phosphate	-0.49	1.59	10	0.014	45000
2,6-Dimethylquinoline	2.59	0.60	10	222	60
2,4-Dinitrotoluene	1.12	1.41	10	0.23	13300
Diisopropylamine	4.60	1.40	10	7.96	12500
Potassium dichromate	0.88	2.68	10	$3.10 \cdot 10^{-5}$	$7.10^7$

to effects on the population growth rate, whereas the values for fish and crustaceans refer to effects on survival.

The application factor  $T = \exp(\bar{X}_m)/HCS$  in Table 2 should be compared to safety factors usually taken in practice: 1000 for non-degradable compounds with a high octanol/water partition coefficient and 100 for readily degradable compounds. On the basis of the present reasoning, the application of such "safety" factors threatens our environment for most chemicals.

#### DISCUSSION

The requirements for a safety factor for  $LC_{50}$  values of the type discussed in this paper are to a high degree conflicting. The first requirement is that it should not make use of an extensive compound-specific knowledge of toxic effects. This is because the acquisition of such knowledge would call for time and cost-intensive research, defeating the purpose of the entire exercise. The second requirement is that its application "guarantees" the quality of our environment, implying that we have to take account of the differing properties of chemicals.

In this context, the definition of HCS presented is an attractive one because its calculation requires data which is relatively easily obtained. The weakest point, in my opinion, is the choice of the log-logistic distribution for the  $LC_{50}$ s. It is doubtful, however, that a better candidate can be found for such a general purpose as describing sensitivities of unspecified species to unspecified xenobiotic compounds. Any improvement on the present ideas will probably make use of patterns in sensitivities among species. Except for biocides, this subject is hardly touched upon in the open literature, and would certainly require a huge research effort.

The choice of test species is severely restricted by the condition that it should be possible to keep them stress-free in the laboratory during the chronic exposure to the chemical. Some biologists are of opinion that this is only possible for species insensitive to chemicals. On the other hand, some toxicologists state that they selected the species they use in standard tests on the basis of their supposed sensitivity. The data the author has seen give little support to the idea that a species found to be relatively sensitive to one xenobiotic compound will also be relatively sensitive

to another one. I consider this an open problem that should be studied more systematically. It seems to the point, however, to remember that the scatter in the  $LC_{50}$ s greatly dominates the mean in their contribution to the proposed HCS. This should be borne in mind in selecting test species.

In terms of protection, the present HCS is not likely to be overprotective. On the contrary, with a proper choice of the number of community species, many individuals of the more sensitive species are expected to die at the HCS, and up to 50% of individuals of the most sensitive species. The probability that the situation is even worse is  $\delta$ . In addition, many sublethal effects, such as effects on reproduction, can affect the community as such. For this reason terms like acceptable concentrations or equivalent ones have been avoided. The term safety factor in the title is only meant to identify the field of interest.

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