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Mapping the potentially affected fraction (PAF) of species as a basis for comparison of ecotoxicological risks between substances and regions

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Abstract

In order to prioritize environmental policies, it is necessary to compare ecotoxicological risks of different substances, different polluted areas (which may have different mixtures of toxic substances) and to compare between effects of toxic substances and other environmental stressors (excess nutrients, acidification). The concept of ecotoxicological risk forms the basis of setting environmental quality standards for toxic substances in the Netherlands. An environmental concentration is considered to present an acceptable risk if not more than 5% of all species is exposed above their no-observed effect concentration (NOEC). This paper is concerned with the inverse problem, to calculate the potentially affected fraction of species (PAF), defined as the fraction of species exposed to a concentration above their NOEC. It is argued that the PAF is more meaningful as a basis for comparisons of ecotoxicological risks than the commonly used ratio of environmental concentration to no-effect concentration. The latter is of limited value, as the same ratio may have widely different effects for different substances. Cumulative distributions of NOECs were determined from literature data. By combining maps of environmental concentrations (from interpolated measurements or from model results) with estimates of field bioavailability, the PAF was determined for Cd, Cu, Zn and Pb and (in terms of toxic pressure) the most important pesticides. The results show the utility of the approach in ranking substances and areas. They also show the importance of uncertainties: these are mainly caused by uncertainties in toxicological data, in emission data for pesticides and in estimation of bioavailability of the heavy metals.

Keywords: Toxic substances; Ecological risk; Environmental damage; Policy indicator

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1. Introduction

The possibility to compare ecological risks is an essential requirement in a number of policy settings. This may involve different substances (e.g. in order to compare different products or processes in Life Cycle Assessment), different areas (e.g. in order to protect sensitive areas) or combinations of both (e.g. in setting priorities for remediation of polluted sites). A common method is to base comparisons on the ratio of environmental concentration to its target value. The problem with this approach is that target values are derived from a number of considerations, such as human health, ecotoxicology, a comparison with background values or simply analytical detection limits [1]. In this paper, we will consider only ecotoxicological risks. For this purpose, a uniform basis for obtaining target values may be chosen, for example the lowest no observed effect concentration (NOEC) as used by USEPA [2] or the Dutch system of using the lowest 5 percentile of all NOEC values [1]. However, even if we have uniform, ecotoxicologically based target values, the ratio of environmental concentration to target value may be difficult to interpret. Although a certain ratio of environmental concentration to target value gives a rough guide to required emission reduction, this ratio gives little information on environmental impact other than that a ratio < 1 implies no or negligible damage. If two substances have the same ratio > 1, their environmental impacts may be quite different.

In this paper, we will present an index for toxic stress between 0 and 1 based on NOECs that does allow a comparison between substances and sites or regions. It will be illustrated on soil concentrations of heavy metals and pesticides in the Netherlands. Results show the utility of the approach for risk comparison. A possible extension of the method to allow a comparison to environmental stressors other than toxic substances will be discussed.

2. Methods

The Dutch system of setting environmental quality standards is based on the cumulative distribution of NOEC data. A log–logistic curve is fitted to the data, and the 5th percentile of the distribution is used as a quality objective [3]. Basically, the PAF is simply the cumulative fraction itself [4] (Fig. 1).

Because PAF is a fraction, we can combine the effects of several substances. Assuming no correlation in sensitivities or interaction of effects, we have for the combined PAF of substances A plus B:

$$\mathrm{PAF}_{A+B} = 1 - (1 - \mathrm{PAF}_A) * (1 - \mathrm{PAF}_B). \quad (1)$$

A modification is required for heavy metals as these occur naturally in the environment. At naturally occurring metal concentrations the PAF does not need to be zero. This may not be relevant for field conditions, however, because the cumulative distribution is based on all available data, species may be included which do not occur at

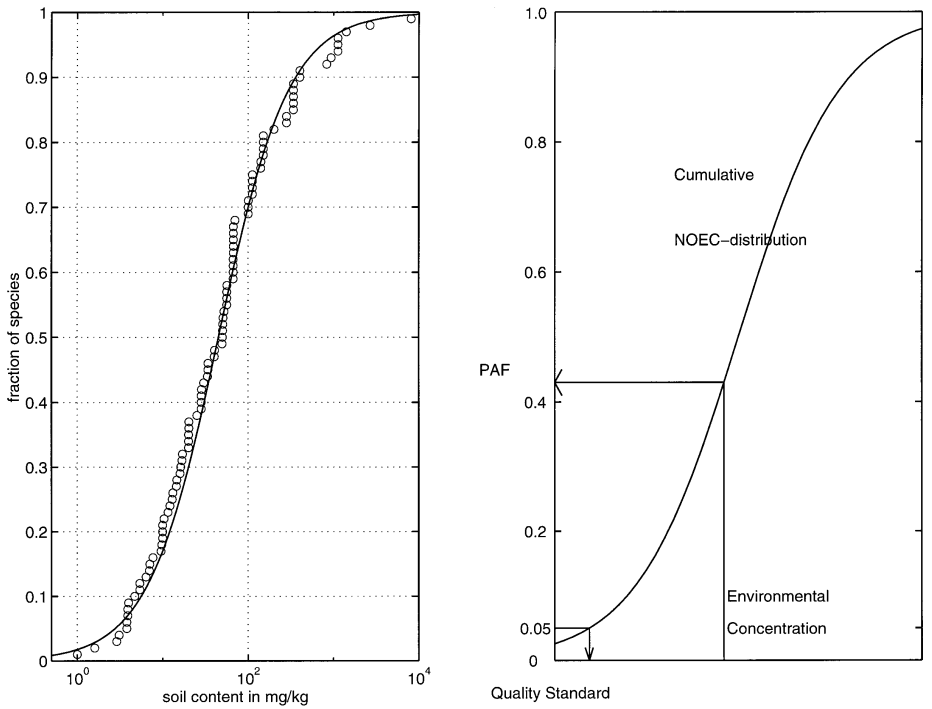

Fig. 1. Cumulative distribution of NOECs for cadmium in soil (left-hand panel). The fitted log–logistic curve can be used to derive quality objectives and the Potentially Affected Fraction of species (right-hand panel).

the location in question. Even if realistic (species may in fact be present that are stressed by naturally occurring metal concentrations) this would not be relevant from a viewpoint of environmental policy: natural stress (which commonly occurs for factors such as nutrients, moisture or temperature) may contribute to biodiversity and should not be expressed in a policy indicator for toxic pressure. For this reason, an anthropogenic PAF was defined by subtracting the PAF from natural background levels ($PAF_{background}$) from the PAF at total metal content (PAF_{total}), and scaling to the species *not* affected at natural levels:

$$PAF_{ant} = \left(PAF_{total} - PAF_{background}\right)/\left(1 - PAF_{background}\right). \quad (2)$$

This equation truncates the NOEC-distribution at natural background levels. It has the effect of a decreasing sensitivity for a certain amount of metal added with increasing natural levels (Fig. 2). Natural background levels were estimated from soil properties [5].

Although metal contents in both field and laboratory are expressed as totals in mg/kg, the major exposure route is by porewater. For this purpose, the toxicity data for heavy metals and pesticides [5] were not directly used but recalculated to porewater concentrations. For heavy metals these calculations require soil pH, organic matter and clay content; for pesticides, organic matter content only.

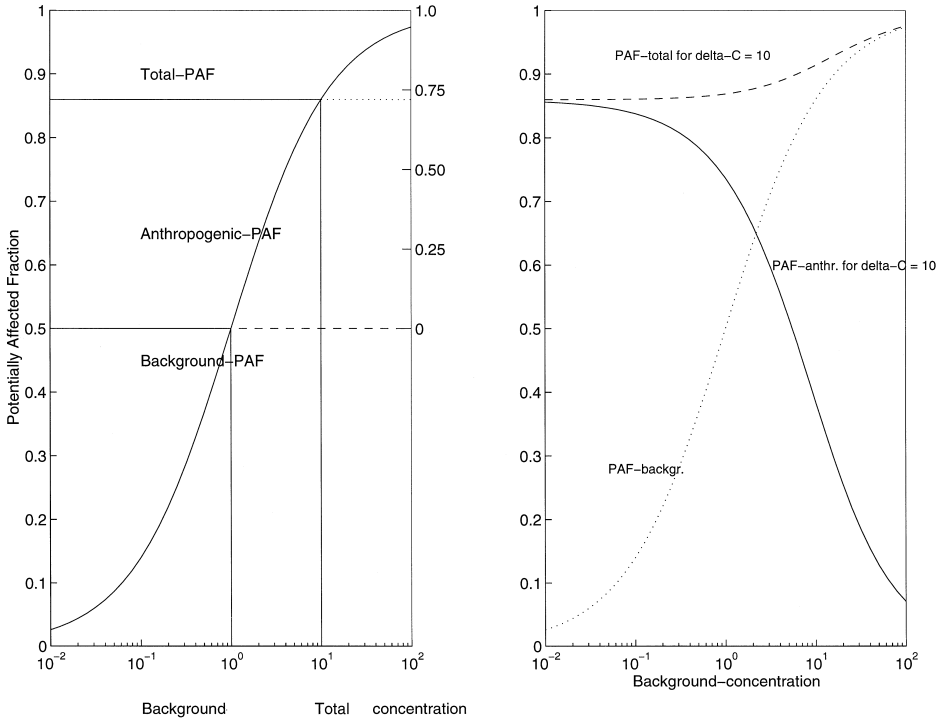

Fig. 2. The calculation of an anthropogenic PAF for heavy metals. By subtracting background concentration and scaling to not-affected fraction (left-hand panel) the NOEC distribution is truncated and rescaled (right-hand scale). This correction has the effect that sensitivity for a given anthropogenic addition *decreases* for increasing background concentrations (drawn line in right-hand panel).

Maps of heavy metal content of soils in the Netherlands were based on interpolated measurements [6]. For pesticides own calculations were required. These were restricted to non-agricultural soil, as the toxic stress from pesticides in agricultural areas was not considered an *ecological* risk. Pesticides may be present in non-agricultural soils because of volatilization and subsequent wet or dry deposition. The 180 registered pesticides in the Netherlands were screened on application volumes and toxicity, selecting the 24 substances with the highest ratios of use to toxic concentration. More detailed calculations were performed for these, estimating volatilization, atmospheric behaviour and soil fate from chemical properties [7,8]. Emissions were estimated in detail for the Netherlands (on a municipality level) and on a decreasing resolution for the rest of Europe (grid ranging from 50–200 km^2). Atmospheric transport and deposition were calculated using long-term averaged atmospheric conditions [9].

At all levels in the calculations there are substantial uncertainties. For heavy metals, this mainly concerns the calculation of porewater concentrations and the estimated natural background levels, for pesticides major uncertainties are atmospheric emissions and fate, and toxicity. In order to quantify uncertainties, parameters in the calculations

were sampled from their uncertainty range and results presented as percentiles of the resulting distribution.

3. Results

The results (Figs. 3–5) show that the highest PAF values are generally found in the most sensitive areas: the acid, sandy soils, poor in organic matter of the central and

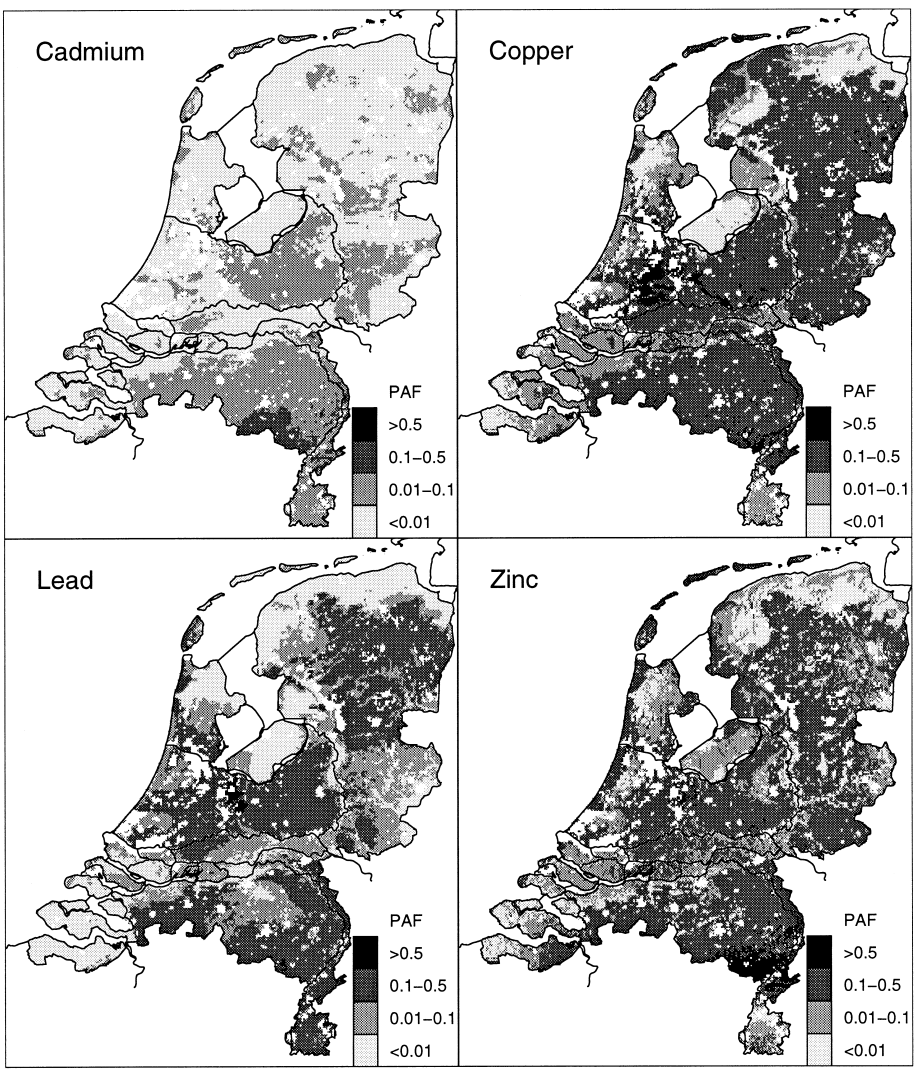

Fig. 3. The potentially affected fraction of soil organisms by four heavy metals in the Netherlands (median results).

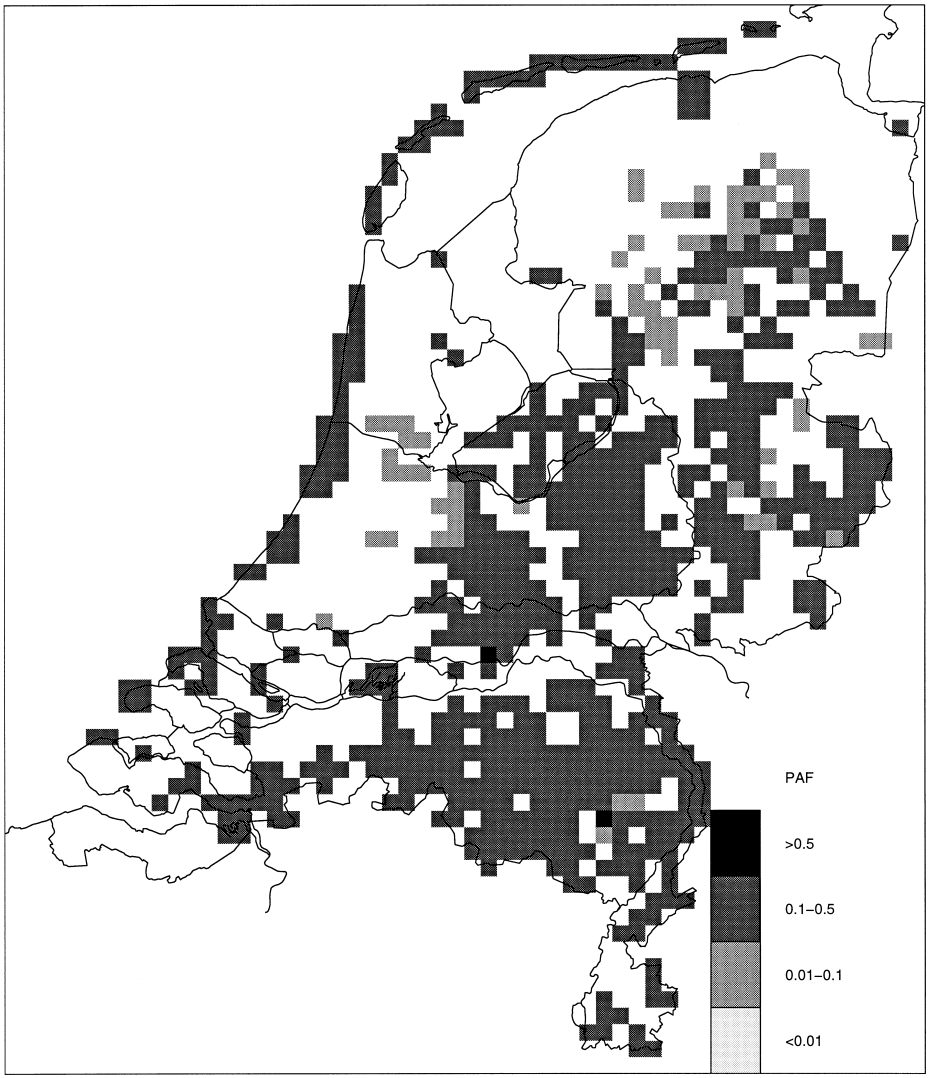

Fig. 4. The potentially affected fraction of soil organisms by pesticides resulting from atmospheric deposition on non-agricultural soil (median results).

south-eastern parts of the country and on the Wadden islands in the north. It is interesting to note that the highest PAF does not correspond to the highest soil contents of metals and pesticides [5,6]. In terms of ranking of substances, it appears that the metals as a group exert a larger toxic pressure than the pesticides. Within the metal group, the toxic stress can be ranked as cadmium < lead < copper ≅ zinc. Within the group of pesticides, the major stressors are lindane, mevinfos and bentazone.

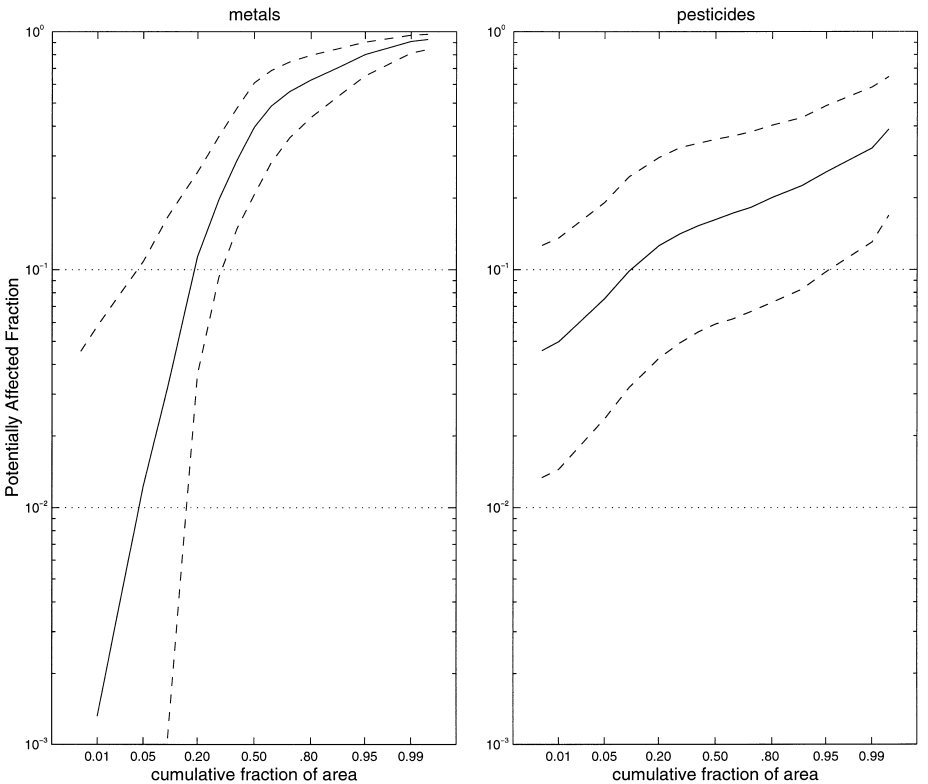

Fig. 5. The combined PAFs for metals and pesticides as cumulative distributions of area. Graphs are given for median (drawn), 5th and 95th percentiles (dotted) of Monte Carlo results.

The uncertainty analysis (Fig. 5) shows that considerable caution should be applied in this ranking, however, the uncertainty regarding pesticide-PAF is high, and overlaps with metal-PAF in a large part of the country. Clearly, these results point to the need for a better understanding of pesticide behaviour (emissions, atmospheric fate) and toxicity.

4. Discussion and conclusion

It should be stressed that the present status of the PAF is not more than an indicator for toxic stress. Its value cannot be directly observed, as the ecological implications of a certain PAF value are not clear. If the NOEC is exceeded in the field, we may expect some toxic effects (increased respiration, decreased growth or fertility, possibly increased mortality), but this need not have any impacts on a population level. Even increased mortality could have little impact on a population that experiences a high predation pressure. Under different conditions, however, even sub-lethal effects may have a dramatic impact on population level. This uncertainty makes it difficult to compare PAF with the effects of other stressors such as excess nutrients, acidification or

dessication. The effects of these pressures in the Netherlands are expressed as a decrease in probability of occurrence of species, which is directly estimated from field observations [10].

Nevertheless, uncertainty about effects does not hamper the utility of PAF for risk comparison in an ecotoxicological context where the NOEC is a well-established measure. For example, we may not know the implications of a lower reproduction in the field; but we *are* able to compare the strength of the response of two substances for this particular endpoint, and rank them accordingly. This is a considerable advantage in comparison with target-exceedence ratios, where we could only rank concentrations of a single substance, but no comparison could be made between substances.

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