

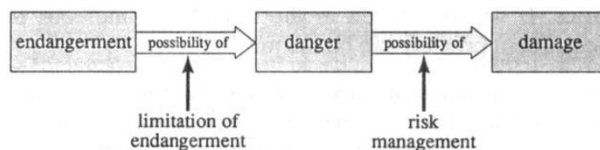
Measures of Endangerment*

by U. Müller-Herold**

1. Introduction

Whereas danger denotes the possibility of damage, endangering means “to bring into danger”. Danger, accordingly, is related to possible damage. Endangerment, in turn, denotes possible danger. This logical order implies two complementary ways of prevention: Looking at the link between danger and damage - by reducing either probabilities or magnitude of damages - is the concern of risk assessment and risk management. Controlling endangerment, on the other hand, essentially means controlling the range of a danger.

Figure 1: On the relation between danger and endangerment



The difference between danger and endangerment may be illustrated by an apparently trivial example from every day life: In the Alps every year people are killed by avalanches. Living in the mountains is inevitably related to the danger of avalanches. It is highly difficult to reliably assess the conditions under which avalanches originate in higher regions. Experienced touring skiers, instead, rely more on some long-established rules in order to avoid situations with strong tendency of avalanche formation and thus try to manage the risk. One way of excluding death by avalanches with certainty, however, is to keep away from danger, i.e. keeping off the mountains at all.

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The example indicates the probabilistic difference between the two concepts: The probability of being harmed by an avalanche, like all probabilities, is conditional. What is the probability of being harmed by an avalanche, given the fact that a ski tourist is at a certain place under certain conditions? This is a classical question of risk assessment. The analogous probability of being harmed if absent is exactly zero. This indicates that controlling endangerment means looking systematically for branches of event trees with zero conditional probability. In one respect, however, the example could be misleading: It may suggest that controlling endangerment is accomplished simply by forbidding certain activities or goals. As can be seen later on, limiting endangerment, generically, has to do much more with a choice between different ways of achieving a once given goal.

2. Limitation of endangerment and its relation to risk management

Though quantitative risk assessment has become an increasingly important tool for investigating nature and magnitude of ecological impacts, many of the methodologies employed in risk assessment are currently the subject of change and debate. The difficulties arise, at least in part, from the overcomplexity of the natural environment. This forces to concentrate on selected effects, the so-called endpoints, which have to be selected according to “societal relevance, biological relevance, unambiguous operational definition, accessibility to prediction and measurement, and susceptibility to the hazardous agent” (Suter, 1993, p 22). On the one hand, this process of selection introduces strong normative elements into the procedure, causing new types of uncertainty. On the other hand it reduces complexity – at the expense of scientific objectivity and security of the assessment procedure¹. As a result, environmental risk assessments, although conducted by scientists for a broad range of purposes, are not regarded as science in a classical sense.

Even this restricted program of environmental risk assessment, however, can require enormous amounts of time and money. For regulatory purposes it thus appears attractive to have complementary methods which, for *certain types of questions*, might give surer answers at a lower price. It will be argued in the sequel that methods for assessing and controlling of endangerment possibly can do the job.

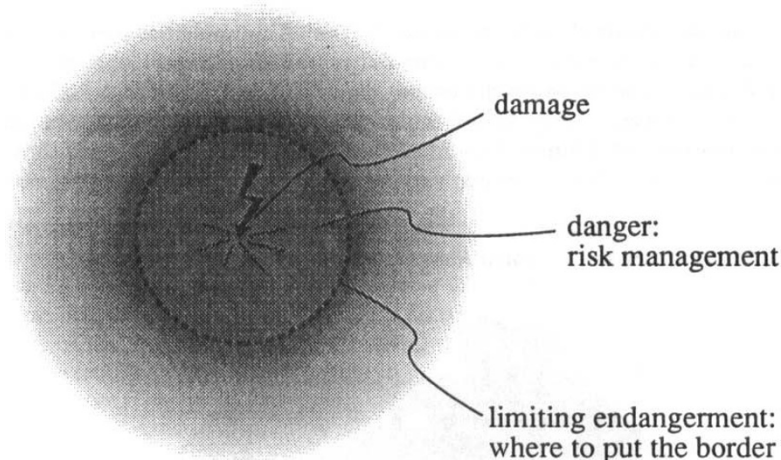
Before entering into technical details, it should be noted that the idea of limiting endangerment is closely related to the “precautionary principle” of environmental law. Recently, a variety of states and environmentalists have advocated adoption of this principle to deal with the problem of scientific uncertainty. In essence the “precautionary principle” says that rather than dealing with the product of magnitude and probability of harm, regulators should act in anticipation of environmental harm to ensure this harm not to occur at all. The principle has played an increasingly prominent role in international environmental negotiations, since first endorsed by the Second International North Sea Conference in 1987.

So far, the precautionary principle has been advocated most frequently with respect to marine pollution. Proponents of the principle argue that there is insufficient scientific

¹ For a discussion on the role of overcomplexity and normative indeterminacy in environmental risk assessment see Berg and Scheringer (1994).

knowledge in order to take the traditional regulatory approach, which is to calculate permissible waste discharges based on the assimilative capacity of the receiving waters. Often, discharges that are initially thought safe cause unanticipated long-term damage. Regulators should therefore be eager to cutting down discharges into the marine environment as much as possible, if not eliminating them altogether.

Figure 2: Limiting endangerment



The main weakness of the precautionary principle in its present form, however, is its quantitative vagueness: How much caution should be taken? What types of precautionary actions are warranted, and at what price? It is proposed to use quantitative measures of endangerment as elements of a quantitative basis for applications of the precautionary principle: Making the endangered domain as small as reasonably possible is a direct realization of the precautionary principle outside the endangered domain.

3. Spatial and temporal range as measures of endangerment

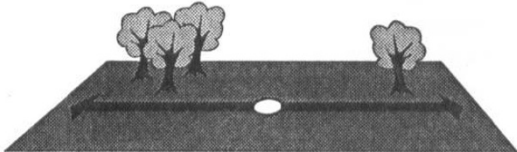
Endangerment, as stated in the introduction, is first of all a *logical* concept and there is no general natural basis for its quantitative assessment. Quantitative measures of endangerment, accordingly, arise in connection with particular types of actions. Eventually such special measures can be applied to other types of actions and acquire broader validity. In the domain of chemical pollution, temporal and spatial range of a unit quantity released from a point source appear as natural measures of endangerment. If defined properly, they allow identification of zones of (absolute) safety, i.e. of no endangerment, and of endangered zones in space and time, where risk assessment must apply.

This may be illustrated, again, by a straightforward example. Imagine two explosive charges of identical explosive power which are evaluated, say, for a mining operation. One of the charges consists of a conventional chemical explosive, the other is a nuclear blasting

composition. What can be said with respect to endangerment? If the conventional device explodes, its components react to oxidized products rapidly vanishing in the metabolic pool of the earth's chemosphere. The temporal range of the explosion may be in order of weeks, the effective spatial domain of influence may be in the order of some dozen kilometers. Endangerment, accordingly, is restricted to a narrow spatio-temporal window. The nuclear device, on the other side, through its long-living fission products, has a temporal range of hundreds to thousands of years. This time is long enough for fission products to distribute equally around the earth, so that in fact the spatial range is global.

Choosing the chemical explosive means first of all choosing between two domains of endangerment. In a second step the comparative risk of the two explosives within the endangered domain can be assessed. For one single blasting operation the differences between the two explosives may be of minor importance as the effects of the fission products vanish through dilution. The difference, however, is enhanced and thus becomes important, if there is a choice between two corresponding *technologies*. This would mean

Figure 3: Spatial Range of two different explosives



**conventional chemical explosive:
narrow spatio-temporal window**



**nuclear blasting composition:
global range**

that the blasting operations under consideration are carried out many times and at different places. It seems conceivable, under these circumstances, that a decision between the two explosives is made on the basis of endangerment alone.

The temporal range of a pollutant is identified with its half life in the environment, and closely related to the concept of persistence, which has been proposed as a measure of ecological threat. In first line this concerns persistent organic chemicals with low acute toxicity: Unlike degradable chemicals, they accumulate in the environment. If eventually serious noxious effects have become evident, there is no way of removing these substances from the environment. Although this view has been advocated since the seventies, the practical efforts of determining effective global decay rates have been hindered by serious difficulties. The difficulties come from the confusing multitude of natural degradation mechanisms, from the complicated multi-phase structure of the natural environment, and from the interplay of degradation and partitioning via multiple phase-transfer and mixing dynamics.

The spatial range of a pollutant was proposed as a measure of endangerment was proposed by Scheringer, Berg, and Müller-Herold (1993) and by Scheringer and Berg (1994). Spatial range is a measure describing how far a chemical can travel from the place where it was released before being degraded according to one of the numerous chemical mechanisms of the environment. It is the result of an interplay of dynamic properties of transport with reaction kinetics in the environment. In connection with chemical pollution, spatial and temporal range reflect the structure of exposure patterns, and thus appear as natural measures of endangerment.

4. The design of alternative HCFCs as example of a “limitation of endangerment”- strategy

Atmospheric concentrations of chlorinated and fluorinated halocarbons, especially the fully halogenated chlorofluorocarbons (CFCs), have considerable negative environmental impact. CFC emissions into the atmosphere are the most important cause of deterioration of the ozone layer (Hayman, 1989). Furthermore, CFCs are suspected of contributing substantially to the greenhouse effect (Krause et al. 1989). After the discovery of the ozone hole over the Antarctic (Farman et al., 1985), a number of CFC-producing countries agreed on a 50% reduction in CFC production and use by 2000 relative to 1986. This agreement, known as the Montreal Protocol (UNEP, 1987), has been renegotiated in London (UNEP, 1990). Production and use by industrial countries will probably have phased out by the end of this century.

For the cut-down in CFC production and use, chemicals are needed to replace them. In order to understand the strategies of solution, the physical basis of the problem is briefly recapitulated: Starting at the earth's surface, the atmosphere can be divided into several distinct regions based on a temperature-altitude profile. While the temperature initially decreases with increasing altitude in the troposphere (which is the lowest layer) this is reversed approximately 15 km above the earth's surface at the tropopause. Accordingly, there is a strong vertical mixing in the troposphere so that particles and gaseous air pollutants can move from the earth's surface to the top of the troposphere in a few days or less, depending on the meteorological conditions. Above the tropopause vertical transport

becomes very slow as, in the stratosphere, the temperature again increases to an altitude of about 50 km.

In the stratosphere, the processes responsible for ozone depletion and greenhouse warming occur. As the crossover from the troposphere to the stratosphere is relatively slow, a pollutant's potential for ozone depletion and greenhouse warming crucially depends on the pollutants' lifetime in the troposphere. The classical CFCs, in fact, reside in the troposphere for very long times, from decades to centuries, slowly diffusing up across the tropopause into the stratosphere.

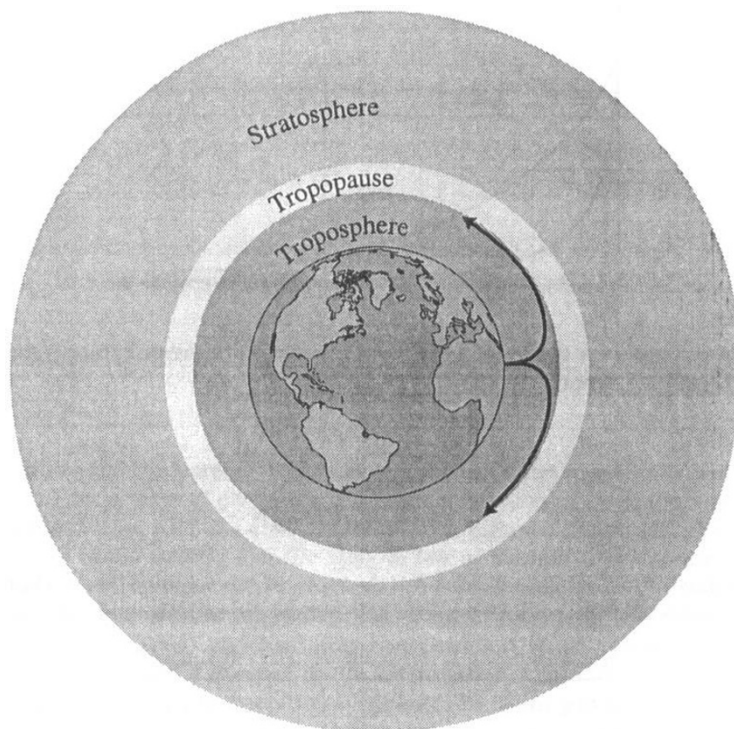
The basic idea for the design of substitutes of the CFCs is to restrict the tropospheric lifetimes and thus keeping them away from the stratosphere. This is accomplished in the following way: The primary atmospheric sink for many organic compounds is the reaction with hydroxyl radicals in the troposphere. Chlorofluorocarbons containing hydrogen (so-called HCFCs) often have shorter tropospheric lifetimes than fully halogenated compounds, because reactions with hydroxyl radicals result in rapid destruction. The simplest idea, accordingly, would be to substitute some fluor or chlorine atoms in the classical fully halogenated CFCs for hydrogen: On the one hand, this essentially conserves the physico-chemical properties which are necessary for practical use; on the other hand it reduces the potentials for ozone depletion and greenhouse warming. It has to be said, however, that the tropospheric half-lives are long enough for a global distribution in the tropospheric layer, occurring on a time scale of about one year.

*Table 1: Tropospheric lifetimes of CFCs and HCFCs. (From Ballschmiter, 1992).
For a more comprehensive list see Nimitz and Skjaggs (1992)*

CFCs	HCFCs	Tropospheric half-lives /years
CCl ₃ F		60
CCl ₂ F ₂		120
CCl ₃ -CClF ₂		90
CClF ₂ -CClF ₂		200
CClF ₂ -CF ₃		400
	CHCl ₂ -CF ₃	1.6
	CH ₃ -CCl ₂ F	7.8

Summing up, it can be said that the temporal range has been considerably reduced. As for the spatial range, this applies only for vertical direction. Here, in fact, endangerment has been excluded from the upper layers of the atmosphere. The horizontal range of the substitutes, however, remains global. Their degradation products come down with rain – with largely unknown effects to ecosystems. As for controlling endangerment, the development of substitutes for the CFCs is only a partial success.

Figure 4: Vertical versus horizontal range of HCFCs

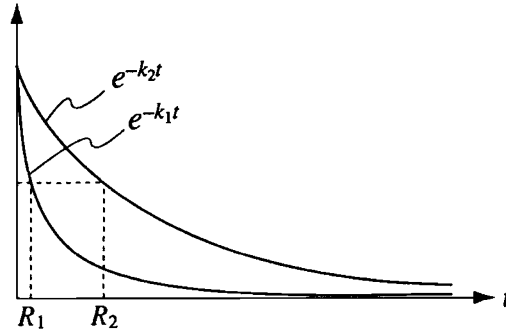


5. Measures of endangerment: For the practitioner's use

In order to establish endangerment as a quantitative concept for preventive ecology, simple standard procedures are needed to assess its range. In connection with chemical pollution, this requires methods for the assessment of temporal and spatial range of a chemical. For the assessment of the global temporal range of a pollutant, a simple general law has been derived by the author (Müller-Herold, 1995). It gives a general formula for the overall environmental lifetime in terms of local degradation rates and partitioning coefficients in the limit of rapid transport and phase exchange (this limiting case is close to the real situation with persistent chemicals).

In order to state the main result, imagine a decomposition of a relevant part of the environment into n compartments. Degradation constants k_i , $i = 1, 2, \dots, n$, – leading to exponential decay of the pollutant in the respective compartments in case of no transport between them – are assumed to be known, as well as the compartments' Volumina V_i , and partition constants K_{ij} for the thermodynamical equilibrium distribution between compartment i and j – in case of no degradation. These data may be taken from standard compilations of environmental data (Howard, 1989; Howard, 1991; Samiullah, 1990).

Figure 5: Decay rates k and their relation to temporal Range $\tau_{1/2} = \ln 2 / k$



The lower bound for the overall temporal range $\tau(\infty)$ of the pollutant is then given by $\tau(\infty) = \ln 2 / \lambda_{\min}(\infty)$, where

$$\lambda_{\min}(\infty) = \frac{k_1 + \sum_{j=2}^N k_j K_{1j} V_j / V_1}{1 + \sum_{i=2}^N K_{1i} V_i / V_1}$$

As an illustration, let us consider the example of hexachloroethane. (For details of the example see Müller-Herold, 1996). The half-lives $\tau_{1/2}$ in soil, air, and water are given by

$\tau_{1/2 \text{ soil}} / \text{h}$	$\tau_{1/2 \text{ air}} / \text{h}$	$\tau_{1/2 \text{ water}} / \text{h}$
$4,32 \times 10^3$	6×10^5	$4,32 \times 10^3$
(6 months)	(73 years)	(6 months)

As the degradation constants k_i are related to the half-lives through $k / \ln 2 = 1 / \tau_{1/2}$ one has to take the inverse half-lives in order to obtain the respective degradation constants. The partition constants K_{ij} for phase equilibrium, K_{SW} (soil/water) and K'_H (air/water), read

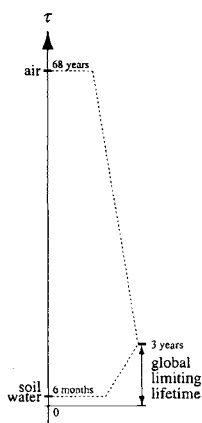
$$\frac{K_{SW} = c_s / c_w}{2.04 \times 10^3} \quad \frac{K'_H = c_a / c_w}{5.3 \times 10^2}$$

where c_s , c_w , and c_a denote the pollutants concentration in soil, water and air. The volumes of water (V_w), soil (V_s), and air (V_a) are assumed to behave as $V_w : V_s : V_a = 250 : 1 : 2 \cdot 10^5$. Choosing water as phase 1 and inserting K_{SW} , K'_H , $1/\tau_{1/2 \text{ soil}}$, $1/\tau_{1/2 \text{ air}}$, and $1/\tau_{1/2 \text{ water}}$ into the expression for $\tau(\infty)$ yields the final result:

$$\tau(\infty) = \ln 2 / \lambda_{\min}(\infty) = 27\,000 \text{ h} = 3 \text{ years}$$

A closer look on the dominant contributions to this result shows that for hexachlorethane the overall result for $\tau(\infty)$ in equation (1) is essentially determined by high solubility and rapid degradation in soil (numerator), and by the large volume of the atmosphere (denominator).

Figure 6: Phase-related and global lifetimes of hexachlorethane



What can be further learned from this example? As to be seen from equation (1), the limiting overall decay time of chemicals is a rational function of three types of quantities: phase related half-lives, partition constants and phase volumes. No simple, physically intuitive dependence of the limiting half-life $\tau(\infty)$ on few of them is to be expected in general. Such a picture, however, may arise for special classes of pollutants. The global decay of apolar, persistent, non-volatile substances, e.g., is governed by the interplay of soil (high concentration, low volume) and air (low concentration, large volume). Which of the phases “wins” in this case is decided by the degradation constants in the following way: The dominant phases (in the numerator) contributes its degradation constant and the sub-dominant second phase (in the denominator) modifies it to the final value of $\lambda_{\min}(\infty)$.

6. Summing up

The concept of endangerment was defined and proposed as a new starting point for ecological prevention. There are several reasons for this: It seems that assessing endangerment, eventually, can be easier, more reliable, and less expensive than assessing risks. Controlling endangerment, in addition, is on environmentalists’ agenda and related to the «precautionary principle» of environmental law. The main weakness of endangerment, however, is its lack of well-defined quantitative meaning.

It was pointed out that endangerment is first of all a logical category, complementary to danger and risk. In order to establish endangerment as a concept for regulatory purposes, quantitative measures are needed. In the domain of chemical pollution spatial and temporal range are suggested as measures of endangerment and a simple asymptotic formula for the assessment of global temporal range of a chemical has been presented. It then was demonstrated that the design of alternative HCFCs is an example of a “limitation of endangerment”-strategy, leading to a partial success by restricting the vertical range of the substitute. The HCFCs accordingly avoid entering into the stratosphere and damaging the stratospheric ozone layer.

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