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Heavy Metals: A Problem Solved?

Methods and Models to Evaluate Policy Strategies for Heavy Metals

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Abstract

Environmental problems related to heavy metals have a long history. Certain events in the past have induced governments to address these problems in their environmental policy. As a result, the emissions from point sources have been reduced significantly over the past decades in many countries. Some therefore may regard the metals' problem to be solved. However, the inflow of freshly mined metals into the world economy has remained at a high level. The question then is, if the metals no longer are emitted, what then is their fate? This question was the motive for the start of an interdisciplinary research program, the Metals program, financed by the Dutch National Science Foundation (NWO). This research program had two aspects: (1) development of methods and models to address such problems, and (2) by applying these methods and models reaching conclusions on the nature of the societal metabolism of four heavy metals in the Netherlands, the risks involved and the possibilities for a sustainable metals management: copper, zinc, lead and cadmium. The main conclusions from the Metals program can also be grouped according to those two aspects.

Methods and models
Integrated, quantitative modelling of the flows and accumulations of metals such as cadmium, zinc, copper and lead, together with their driving forces and their environmental risks, has led to substantial new insights in these metals' metabolism and in relevant management options. In dealing with the complexity at hand, we have found that an overview of the relevant information can be obtained rather by successive use of different models aiming at the answering of different questions, than by the development of one encompassing integrated model. Examples are the subsequent use of Substance Flow Analysis and Environmental Risk Assessment, and Substance Flow Analysis and Materials-Product Chain analysis. For the evaluation of the outcome of the various developed models, a set of sustainability indicators was developed. A clear and explicit definition of such indicators, both related to parameters in the economy as well as in the environment, has proven to be very useful as a basis for environmental policy as well as for scientific development.
Another conclusion was that a clear picture of the risks connected with the metals' metabolism can only be obtained if the modelling is performed at different levels of scale. Starting from a national level, at a higher scale level attention can be given to the analysis of problem shifting by pollution export, whereas at a lower level more detail can be obtained about actual risks in specific situations, such as different agricultural practices.

Metals management
The past reduction of emissions of the investigated metals to water and air appears to have gone in hand with an increase of the accumulation of these metals in stocks of materials, products and landfilled waste. As a result, a future rise in emissions to the environment will take place if no action is taken. On the long run, this will lead to a surpassing of water and soil standards for ecosystem health and of standards for human exposure through the different environmental media. Thus the present day use of the

four metals cannot be regarded as sustainable. In the surpassing of thresholds a key role is played by so-called trace flows, in contrast to the bulk flows which are generally well managed. Management measures should therefore focus on the control of these trace flows, rather than on a still further enhancement of recycling. In agriculture specific risks occur due to the occurrence of "closed loop accumulation", being accumulation in fodder-soil-fodder cycles of particularly copper and zinc. On short notice, the following measures appear to be feasible: reduction of zinc and copper concentration in fodder, terminating the use of metal based pesticides, and prevention of corrosion by coating or a partial substitution of applications in the built environment. Even with the implementation of the above measures, in non-disruptive policy scenarios political threshold values are expected to be surpassed in the long run. Other measures will be required, especially the immobilisation of metals in solid waste flows and a complete phase-out of many applications, including non-functional ones. Although there is ample time for the implementation of such measures, the question is whether such a strong sustainability approach is feasible at all in view of the many other environmental problems which must be addressed. If not, an adjustment of the present standards in the direction of weak sustainability may well become unavoidable.

Preface

This publication contains the results of an interdisciplinary research programme, the 'Metals' programme, financed by the Dutch National Science Foundation (NWO). This was one of the three research project clusters of NWO's Sustainability and Environmental Quality Programme, the aim of which was to find ways of operationalising the policy-related concepts of 'sustainability' and 'environmental quality' in a scientifically sound manner. As the title suggests, the Metals programme focused on the issue of heavy metals. The core research problem is the fact that although metals emissions have declined considerably over the last few decades, mining of these substances has remained at more or less the same level. The main research questions studied in the programme concern the fate of the mined metals, whether this fate is in any way connected with environmental risks and, if so, how to render the metals management regime more sustainable. To answer these questions it was necessary to operationalise the concepts of 'sustainability' and 'environmental quality' from the perspective of a society's management of heavy metals.

In the Metals programme these questions were addressed by an interdisciplinary team of ecologists, agricultural scientists, environmental scientists and economists. The approach adopted in the research programme was based on development and application of economy-environment models. Given the scope of the research programme, many different issues have been examined. Many issues remain unresolved, however, and many new questions have arisen in the course of work. Consequently, the outcomes of the models developed do not provide any definite answers. Nevertheless, the general direction of the results is sufficiently robust for a number of conclusions to be drawn regarding the present metals management regime as well as the basic direction in which it should be changed. Insight was gained, moreover, in the specific difficulties regarding integrated economy-environment modelling. Last but not least, we experienced what it means to cooperate in an interdisciplinary team, which was not easy in the beginning but proved to be very rewarding in the end.

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Part I Introduction

Contents:

In Part I we introduce the research problem: the actual and potential environmental consequences of the production and use of heavy metals. We argue that, contrary to general expectations, the metals problem might not one the decline. The five main research questions are stated, basic concepts are outlined and the methods of investigation employed to seek answers to these questions are presented.

I.1 General Introduction

Ester van der Voet, Helias A. Udo de Haes & Jeroen B. Guinée

I.1.1 Environmental problems related to the use of materials

Human society is facing many problems related to the environment. A significant number of these problems are the consequence of current modes of processing materials and energy. On the one hand, there are the problems related to resource depletion. These were first signalled several decades ago (Club of Rome, 1972) and have since lost some of their urgency: geological stocks are not as scarce as first believed and substitution of one stock by another may take place, moreover. Today the emerging opinion is that the main depletion problem in fact concerns biotic renewable resources. On the other hand, the processing of materials and energy leads to pollution problems. By dispersing substances in the environment natural processes are disturbed with a number of potentially adverse consequences, including direct threats to human health, ecosystem damage and economic damage, through a wide variety of mechanisms.

Large-scale impacts are caused by the human addition to biogeochemical cycles of C, N, P, S, water and other substances, transforming these into anthropo-biogeochemical cycles. Examples include global warming through the increase of the relatively small atmospheric stock of CO_2 and eutrophication of lakes and coastal waters through the increase of aquatic nutrient stocks. Frequently, it is not directly that enlarged flows cause adverse impacts but indirectly, through the resultant slow increase of relatively small but crucial stocks. Managing these cycles is difficult because these elements are very basic, not only for our economic system but even for maintaining human life: for breathing and feeding. Reducing use of these substances in anything but a marginal way is therefore often not an option; the challenge for management is to bring the human part of these cycles in line with the natural part, either by isolating the human from the natural cycle or by a major shift in the ecological grounding of our society.

On a smaller scale, emissions of micro-pollutants disturb natural processes and pose a threat to human and ecosystem health because of their toxicity, carcinogenicity, mutagenicity or hormone-mimicking properties. Examples include the more persistent organic micro-pollutants and heavy metals, which are emitted in small quantities but accumulate in the environment because of their non-degradability. These substances can likewise be analysed as economic-environmental cycles. In most cases the natural cycle is relatively small and caused only by the weathering of rocks and volcanic eruption. The anthropogenic part of the cycle thus generally predominates. Here, too, environmental stocks are often the key issue: the slow and steady increase of stocks in soils and sediments and the accumulation and bio-concentration in the food chain. Managing these cycles may be easier, on the one hand, for in many cases the human contribution can be reduced by substituting other processes or materials without any major disruption of society. On the other hand, it is more difficult since the influx of even minor amounts to the environment may pose risks and emissions may often elude us because of their low magnitude and their sometimes unexpected occurrence. The challenges involved in managing these cycles are therefore quite different but also substantial.

This book studies the cycles of a number of micro-pollutants and addresses the problems related to heavy metals as they occur in the Netherlands. As in many industrial countries, emissions of these metals to the atmosphere and to surface waters have been reduced considerably over the past few decades. As a result, the emerging opinion in environmental policy circles is that the metals problem has been more or less solved, at least in the Netherlands. Among environmental scientists, however, the nagging feeling remains that this might be too optimistic: although metals emissions have been reduced, mining operations have remained at a high level. This feeling resulted in the combined research programme of which this book is one of the outcomes (Udo de Haes et al., 1992). States very concisely, the purpose of this research programme was to establish whether the environmental problems related to metals have indeed been solved in the Netherlands, and if not, in which direction a sustainable management regime for these metals should be sought.

Below we address the problem of heavy metals in the Netherlands and the reason for doubting the status 'solved' and the research questions with which we set out. We then discuss some of the basic starting points of the research programme.

I.1.2 Environmental problems related to metals

Environmental problems related to heavy metals have a long history. Heavy metals have toxic properties, leading to adverse effects on human and ecosystem health even in small doses. Another problem-causing property is their non-degradability: once they enter the environment they will remain there for a long time. Metals tend to accumulate in soils and sediments, with immobilisation due only to geological, and therefore extremely slow, processes. Accumulation in the food chain may lead to an increased stock in biota, thereby magnifying the human dose.

Well-known examples of metals poisoning in past centuries include the lead poisoning from water pipes in ancient Rome and the mercury poisoning of the 'mad hatters' in Europe (Markham, 1994; O'Carroll et al., 1995). In this century we have seen, among other cases, the tragedy of mercury poisoning in the Minamata Bay in Japan, through consumption of coastal fish, and that of cadmium poisoning through consumption of polluted rice (Japanese Ministry of Health and Welfare, 1968). Lead in petrol has caused health problems in many cities, especially for children (see, for example, Rhode Island Kids Count Factbook, 1997). These and similar incidents have spurred governments to implement environmental policies and industries to reduce their emissions substantially. Comparing current emissions from industrial and other point sources to those of several decades ago, at least in the industrialised countries, there has evidently been a very major reduction (e.g. Ayres & Rod, 1986; Stigliani & Anderberg, 1992). Present policies regarding heavy metals include not only end-of-the-pipe emission reduction but also recycling and even more source-oriented measures limiting or banning certain applications altogether (e.g. Bulletin of Acts, Orders and Decrees of the Kingdom of the Netherlands, 1990). In the Netherlands a comprehensive heavy metals policy is currently being formulated. The general feeling is that the main problems have been solved and that it is now a question of tying up a few loose ends and then continuing to enforce legislation. One of these loose ends is the existence of polluted sites, a relic of the past, described by Stigliani & Salomons (1993) as 'chemical time bombs'. Such sites may become unsuitable for agriculture or housing construction. If they remain unattended metals may become available and leach to the groundwater through increasing soil acidity. Other loose ends refer to applications considered risky, such as metal-based pesticides and paints, but which have not been regulated.

Although emissions in the Netherlands have undoubtedly declined - today the single major source of surface water pollution is the Rhine water entering the country - there are still several matters that are cause for concern. One is the fact that environmental metals concentrations are not decreasing in the Netherlands. This may be due to a time lag - once emissions have been reduced the metals already in the environment disappear only at a geological rate - but it may also have more serious causes. We observe that the inflow of metals into the economic system - equivalent, at a global level, to the amount of metals being mined - has not decreased but has remained at a high level, as shown in Table I.1.1. This global trend also shows up quite clearly in the Netherlands (FOE, 1998).

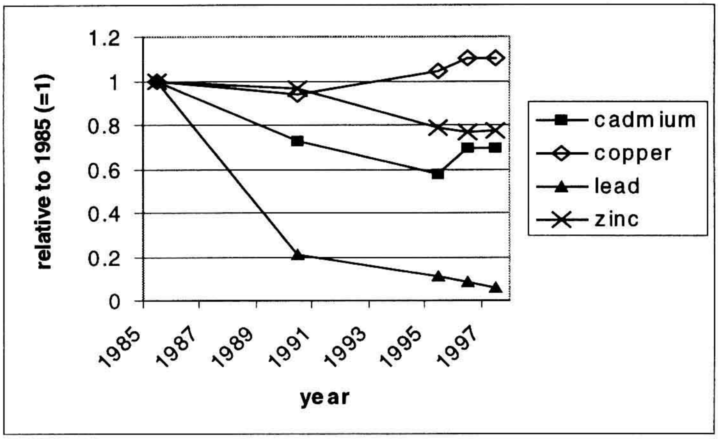
Table I.1.1: Global production rates of some metals for the period 1980-1992 (ktonnes/yr.); data cover intentional metal ore production unless noted otherwise.

	1980[1]	1983[1]	1986[2]	1989[2]	1992[3]
arsenic	25	28	40	40	34
cadmium[4]	18	17	19	21	20
copper	7760	8500	7993	8887	8900
chromium	2717	2500	3625	3737	4025
lead	3186	3240	3335	3395	3200
zinc	6338	6300	6936	7062	7365

[1] USBM, 1985 (Mineral Facts and Problems).
[2] USBM, 1989 (Minerals In The World Economy).
[3] USBM, 1993 (Mineral Commodity Summaries).
[4] Cadmium extracted from zinc ore.

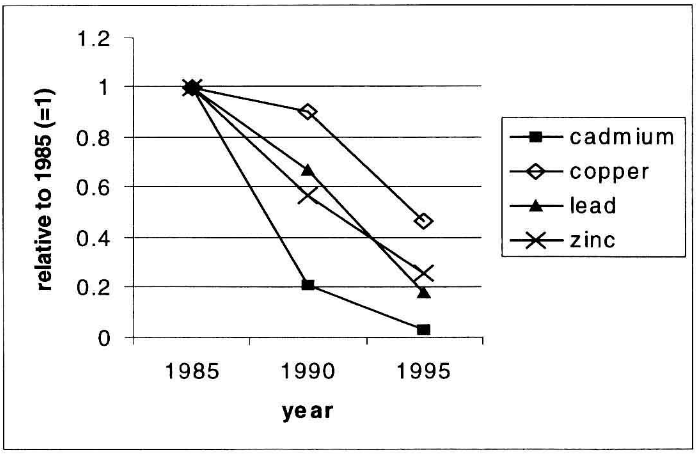
Figures I.1.1 and I.1.2 show the trends of heavy metals emissions to the atmosphere and to surface waters.

Figure I.1.1 *Trends in heavy metals emissions to the atmosphere in the Netherlands, 1985 - 1996.*



Source: RIVM, 1998.

Figure I.1.2 *Trends in heavy metals emissions to surface waters in the Netherlands, 1985 - 1995.*



Source: CBS.

Here we quite clearly see the reduction of the emissions over the past 15 years, especially the emissions to water. This raises the question: if emissions have indeed been reduced, then where does the inflow into the economy end up? There are several possibilities in theory:

- Although point-source emissions have decreased we have no insight into the more diffuse emissions. Examples of such emissions include phosphate fertiliser, which is polluted with small amounts of metals and which is emitted directly into agricultural soils. Of such emissions there are no records and they may even have increased.

- Emissions may have been replaced by landfill, i.e. there may have been a shift from emissions to the atmosphere and surface waters to dumping in landfill sites.
- The metals entering the economy may be accumulating in materials and products, thus increasing the societal stock and in due course, i.e. in the waste phase, causing emissions to rise once again.
- The Netherlands may have 'exported' the more polluting stages of the metals' life cycle to other countries, thus enjoying the benefits of consumption while transferring the burden of mining, production and waste management elsewhere.
- Safe storage may have been established for waste metals, reducing emissions from waste materials to zero.

At the outset some of these possibilities already seem more credible than others. We do know, for example, that no storage at present qualifies as safe in the sense of reducing emissions to zero. Pollution export may indeed take place at the level of a small country but this does not explain a decrease in global emissions. The other three possible explanations all appear reasonable. All of them, to varying degrees and in various ways, cause us to query the characterisation of the metals problem as a problem of the past.

I.1.3 Research questions of the Metals programme

The purpose of the research programme has been to establish whether the environmental problems related to metals have indeed been solved in the Netherlands, and if not, in which direction sustainable management of these metals should be sought. The above considerations have led to a number of research questions being addressed in the research programme. These questions are not only scientific but also policy-oriented: in answering them we may arrive at additional recommendations for an environmental policy aimed at metals. The research questions stated in the original application form are the following:

1. *What are the flows and stocks of the selected metals through the economy and the environment?*
   This question can be regarded in the tradition of the concept of 'industrial metabolism', the description of the economy in terms of the processing of materials. This concept is introduced in Section I.2. Having an overview of flows and stocks in society enables one to establish links with environmental flows on the one hand and with economic processes on the other.
2. *How can these flows and stocks be modelled?*
   In order to establish the linkages between economy and environment in a quantitative manner, the aforementioned overview is not sufficient. The relations between flows and stocks and between flows and economic or environmental variables are important from the perspective of metals management. In Section II.1 this will be further elaborated. A number of models have been developed in the course of the research programme; these are described in Part II. The application

of these models to describe and analyse (parts of) the heavy metals problem is treated in Part III.

3. *What is the fate of the mined metals and what are the related environmental risks?*
   This refers to the inconsistency between the constant level of mining and the sharp reduction of recorded emissions and is in fact the main question. This question is addressed with the aid of an account and a model of metal flows (see Section 1.2).
4. *Is the present metals management regime sustainable?*
   This question refers to the present situation in the Netherlands but also to future developments, or rather the future consequences of the present management regime, and to the situation in other countries due to pollution export, as mentioned above. For evaluating management in terms of sustainability a number of indicators have been developed. These are treated in Section II.6. In Section I.2 a more general treatment of the concepts of sustainability, environmental quality and sustainable development is presented.
5. *In as far as the present metals management regime is not sustainable, how can we design a management strategy that is?*
   In the research programme no attempt has been made to draw up a formal method to design a sustainable scenario. In Part IV a comprehensive attempt is made to formulate scenarios 'offhand', based mainly on the results of the analyses of the previous research questions. Three scenarios of increasing stringency, and therefore also of increasing societal disruptiveness, are described and evaluated using the developed models and sustainability indicators.
6. *Can a statement be made with regard to the 'net sustainability' of the Netherlands?*
   This refers to the possibility of the economies of industrialised countries such as the Netherlands having being 'cleaned up' at the expense of other parts in the world, by locating the more polluting stages of the metals' life cycles such as mining, refinery and waste treatment elsewhere. To signal this a 'pollution footprint' indicator has been developed and applied. This indicator is described in Section II.6.

Some demarcations and methodological choices have been made to focus the research:

- The heavy metals considered are copper (Cu), zinc (Zn), lead (Pb), and cadmium (Cd). The reasons for this choice are both practical (well-investigated metals, therefore good data availability) and theoretical (all four are metals with decreasing emissions and a more or less constant economic inflow). Moreover, all four are addressed by the Dutch heavy metals policy-to-be.
- The geographical boundaries are those of the Netherlands; the territorial waters of the North Sea are not regarded as part of the system.
- Within the Netherlands we have endeavoured to be comprehensive in the investigation of flows and stocks, regarding both the economy and the environment.
- Two economic sectors have been investigated in more detail: the housing sector, because of the large flows and stocks associated with it, and agriculture, where flows are much smaller but involve greater risks to human health.
- The reference year is 1990, for reasons of data availability. For evaluation of the scenarios, the years 2050 and 2100 have been taken. This may seem a rather long time-frame from the perspective of policy formulation, but since the life-span and residence time of metals in both economic and environmental stocks is very long,