The environment has become exposed to a range of chemical contaminants from a wide variety of sources, including the application of pesticides. Regulation of chemical accumulation in the environment has frequently been hampered by difficulties in cooperation between disparate disciplines in the natural, social and political sciences.

This volume forms the conclusion of five years' collaboration between toxicologists, economists and lawyers in the understanding and analysis of the problem of accumulative chemicals. As well as a case study of the accumulation of pesticides in groundwater in one particular region (the European Union), the book forms a general study of the value of interdisciplinary approaches in environmental policy-making.

This volume will be a valuable resource for a broad group of academics and researchers in the area of environmental science and environmental policy. It will also form a useful supplementary reference text for courses in environmental policy, science, economics and toxicology.

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Regulating chemical accumulation in the environment

The integration of toxicology and economics in environmental policy-making

Edited by Timothy Swanson
and Marco Vighi

CAMBRIDGE
UNIVERSITY PRESS

PUBLISHED BY THE PRESS SYNDICATE OF THE UNIVERSITY OF CAMBRIDGE
The Pitt Building, Trumpington Street, Cambridge CB2 1RP, United Kingdom

CAMBRIDGE UNIVERSITY PRESS
The Edinburgh Building, Cambridge CB2 2RU, UK http://www.cup.cam.ac.uk
40 West 20th Street, New York, NY 10011-4211, USA http://www.cup.org
10 Stamford Road, Oakleigh, Melbourne 3166, Australia

First published 1998

Printed in the United Kingdom at the University Press, Cambridge

Typeset in Monotype Utopia 9.25/13.5 pt, in QuarkXpress™ [SE]

A catalogue record for this book is available from the British Library

Library of Congress Cataloguing in Publication Data

Regulating chemical accumulation in the environment : the integration
of toxicology and economics in environmental policy making / edited
by Timothy Swanson and Marco Vighi.
p. cm.
ISBN 0 521 59310 7 (hardbound)
1. Environmental policy. 2. Environmental chemistry – Economic
aspects. 3. Environmental toxicology. I. Swanson, Timothy M.
II. Vighi, M.
GE170.R445 1998
363.738–dc21 98-13354 CIP

ISBN 0 521 59310 7 hardback

For Richard Lloyd, a valued colleague
and calming influence.

It was a pleasure to work with you.

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Preface: The regulation of pesticides in Europe – past, present and future

Marco Vighi, Carolina Sbriscia Fioretti and Timothy Swanson

Moving towards a preventive approach

Toxicology and ecotoxicology are disciplines that have developed in response to a need for information about the possible damages that might result from chemical usage. During the seventies a shift occurred from *a posteriori* control of chemical impacts to the prevention of this type of damage. The change in emphasis occurred first in the scientific community and then in the administrative and political spheres. As a result, many important regulations were approved for application across Europe. The essence of these regulations was to require preliminary information on the toxicology and ecotoxicology of chemicals in order to make available data needed for a preventive risk assessment of the characteristics of the marketed chemicals.

In particular, the Toxic Substances Control Act (US EPA, 1978) in the USA and the Sixth Amendment to the Directive on Dangerous Substances (EEC Council Directive, 1979) in Europe require the development of a basic set of information before a new chemical substance may be marketed. The required data set dealt with several characteristics of the substance (chemical structure, use patterns, physico-chemical properties, analytical methods, etc.) and includes toxicological and ecotoxicological tests at different levels of complexity in relation to the amount of the substance produced and the results at the preliminary levels (see Table 1).

The challenge to the scientific community was therefore: to what extent can the impacts of the chemicals be predicted by reference to this relatively limited set of data? The complexity of the question depends mainly on the fact that any kind of evaluation for a potentially harmful substance must take into account two types of factors – the first intrinsic to the substance, the second related to the extrinsic conditions (environmental factors,

Table 1. *Toxicological and ecotoxicological tests at three different complexity levels required by Directive 79/831/EEC (sixth amendment of Directive 67/548/EEC on the approximation of the laws, regulations and administrative provisions relating to the classification, packaging and labelling of dangerous substances)*

	Base set	Level 1	Level 2
Toxicological tests	Acute toxicity Oral Inhalation Cutaneous Skin irritation Eye irritation Skin sensitisation Subacute toxicity NOEL at 28 days Other effects Mutagenicity	Fertility study Teratology study Subchronic and/or chronic toxicity study Additional mutagenisis studies	Chronic toxicity study Carcinogenicity study Fertility study Teratology study Acute and subacute toxicity study on a second species Additional toxicokinetic studies
Ecotoxicological tests	Effects on organisms Acute toxicity for fish Acute toxicity for *Daphnia magna* Degradation Biotic Abiotic	Algal growth inhibition test Prolonged toxicity study with *Daphnia magna* Test on a higher plant Test on an earthworm Prolonged toxicity study with fish Test for species accumulation	Additional tests for accumulation, degradation and mobility Prolonged toxicity study with fish (including reproduction) Additional toxicity study (acute and subacute) with birds Additional toxicity study with other organisms Absorption/desorption study

Note:
NOEL, no observed effect level.

population exposure, etc.) and their interactions. Obviously, a preliminary report based upon laboratory data can take into account, at most, only the intrinsic properties of the substance.

This toxicological and ecotoxicological risk assessment of new chemicals is a key feature of Directive 91/414/EEC concerning the placing of plant protection products on the market (EEC Council Directive, 1991). In brief, it requires that the applicant for the authorisation of a plant protection product produce information on the uses, efficacy, and chemical and toxicological properties of the compound. The dossier must be submitted to a commission of experts of the Member States of the European Union (EU) and a final monograph must be drawn up containing a complete evaluation of the information provided. In particular, for the ecotoxicological evaluation, in addition to the results of a wide set of toxicological tests (see Table 2), information must be provided on the distribution and ultimate fate of the chemical in the major environmental compartments (soil, water, air).

The risk assessment of the chemical must be based on the evaluation of toxicology–exposure ratios (TERs) calculated as the ratios of the predicted environmental concentrations (PECs) and various toxicological end points (e.g. the dose needed to kill 50% of a sample population of experimental animals (LD_{50}) and the highest dose that does not produce any evidence of an effect (NOEL, no observed effect level) on a number of terrestrial and aquatic living organisms. At the current time, there is an active debate occurring at European level regarding the standardisation of the criteria for evaluation of this dossier and for the drawing up of the monographs. Special care must be taken in the selection of methods applicable to the range of various agronomic and environmental conditions typical of the European territory and capable of producing comparable results in the complex situation of the different Member States of the EU. The heterogeneity of the European land mass makes prediction of overall outcomes a very complex undertaking.

The predictive approaches of toxicology and ecotoxicology have been developed (see Vighi *et al.*, Chapter 4, this volume) in an attempt to provide suitable answers to these difficult questions, but the role of prediction is necessarily a limited one. All chemical substances have the capacity for some environmental impacts. In addition, many of the most useful chemical substances will necessarily have some capacity to accumulate within the enviroment. This is because toxicity (at least for the target organisms) is

Table 2. *Toxicological and ecotoxicological tests required by Directive 91/414/EEC, for placing plant protection products on the market*

Toxicological tests	Ecotoxicological tests
Acute toxicity	Effect on birds
Oral	Oral acute toxicity
Inhalation	Short-term dietary toxicity
Cutaneous	Effects on reproduction
Intraperitoneal	Effects on aquatic organism
Skin irritation	Acute toxicity to fish
Eye irritation	Chronic toxicity to fish
Skin sensitisation	Effects on reproduction and growth of fish
Subacute toxicity	Bioaccumulation in fish
Subacute oral toxicity (28 days)	Acute toxicity for *Daphnia magna*
90 days' feed trials	Fertility test for *Daphnia magna*
Additional exposure routes	Effects on algal growth
Chronic toxicity	Effects on other non target organisms
Long term oral toxicity and carcinogenicity	Acute toxicity for honeybees and other beneficial arthropods
Mutagenicity	Toxicity for earthworms and other non-target soil macroinvertebrates
Effects on reproduction	Effects on non-target soil microorganisms
Teratology studies	Effects on other non-target organisms at risk
Multigenerational studies on mammals	Effects on biological methods for treatment of waste water
Studies on mammals metabolism	
Adsorption, distribution and excretion patterns	
Metabolic patterns	
Studies on neurotoxicity	
Additional studies	
Effects of metabolites	
Studies on mode of action	
Effects on cattle and domestic animals	
Medical and epidemiological data	

an important characteristic of agricultural chemicals, and accumulation in the environment results from chemical stability (i.e. non-degradation) in the general environment, also a desirable trait of commercial chemicals. Clearly, the capacity to predict chemical toxicity and accumulation is not sufficient in itself for adequate chemical regulations; prediction must be combined with a measure that determines when toxicity and accumulativeness reach ‘undesirable’ levels. This will depend upon the meaning given to ‘undesirable levels of accumulation’, and it must also depend upon the various conditions under which a chemical is used.

The setting of quality objectives and standards for pesticides

In Chapter 4 of this book, Vighi *et al.* describe the procedures adopted by various international organisations for the setting of quality objectives, in particular for the protection of the aquatic environment. All of the approaches are extremely laborious and require an amount of toxicological information which is available for only a relatively small number of potentially dangerous compounds. As a consequence, the number of scientifically sound quality objectives produced and accepted by internationally acknowledged organisations is very low (no more than a few hundred) in comparison with the huge number of potential contaminants.

In particular, the Scientific Advisory Committee on Ecotoxicity and Environment (CSTEE) of the EU has produced Water Quality Objectives for about 100 substances, selected and published in a list of priority chemicals (CSTEE/EEC, 1994*a*). Among them, 32 are pesticides and the figures proposed are reported in Table 3. Pesticides figure prominently in these objectives because they are specifically designed to be biocides, toxic substances particularly effective against some target groups of living organisms (plants, insects, etc.). The Quality Objectives are aimed at protecting the whole ecosystem, including the most sensitive species of the natural biological communities. It may be observed, however, in many cases these Water Quality Objectives are extremely low, sometimes orders of magnitude below the guidelines for drinking water. It should be stressed that a Water Quality Objective is not a legal standard but only a scientific suggestion. It may be used as an indicator of the need for suitable interventions for the protection of the natural environment, at local or national level, but it is a function of ecological as well as political and economic factors.

Table 3. *Water Quality Objectives (WQO) for pesticides proposed by the EU/CSTE*

Compounds	WQO (mg/m^3)	Compounds	WQO (mg/m^3)
Atrazine	1.00	Linuron	1.00
Azinphos-ethyl	0.01	Malathion	0.01
Azinphos-methyl	0.01	Methylparathion	0.01
Biphenyl	1	Mevinphos	0.01
Carbon tetrachloride	10.00	Omethoate	0.01
Chlorophenylid	0.10	Parathion	0.01
DDT	0.002	Pentachlorophenol	1.00
Demeton-methyl	0.10	Pyrazon	0.10
1,3-Dichloropropene	10.00	Simazine	1.00
Dichlorovos	0.001	Sulcofenuron	10.00
Endosulfan	0.001	2, 4, 5-T	1.00
Fenitrothion	0.01	Tributyltin oxide	0.001
Fenthion	0.01	Trifluralin	0.10
Flucofenuron	0.10	Triphenyltin acetate	0.01
Hexachlorozene HCB	0.01	Triphenyltin chloride	0.01
Hexachlorocyclohexane	0.01	Triphenyltin hydroxide	0.01

The zero tolerance approach for pesticides in drinking water

A completely different approach is followed by the EU for the management of xenobiotics in drinking water and, in particular, of pesticides. The EU has applied a policy of zero tolerance toward the presence of pesticides in drinking water since 1980. At that time it adopted a policy establishing the maximum acceptable level of pesticides in drinking water at the concentration of 0.1 μg/1 in Directive 80/778/EEC (EEC Council Directive, 1980). This is taken as a '*practically zero*' level of tolerance, considering the analytical detection limit for most pesticides at the time of promulgation of the Directive.

The philosophy of the EU in establishing this zero tolerance standard is based on the following principles.

(1) Xenobiotics are substances not present in nature before the era of synthetic chemicals and, in particular, pesticides are toxic substances by definition. Ideally they should not be present in

the natural environment. In practice, all possible measures of preventive management and of control of emission must be applied in order to maintain the level of these substances 'as low as possible', especially in particularly valuable environmental resources.

(2) The contamination level in drinking water must be more strictly controlled than in food. Usually, every day a person imbibes about two litres of drinking water originating from the same source, and this on a lifelong basis. Thus, in the case of the presence of pesticides, even if at a toxicologically safe level, there is a continuous exposure to the same potentially toxic agent. On the other hand, every day a person may eat different agricultural products that come from various origins and do not contain the same pesticide residues. In this case the possible exposure (again to toxicologically safe levels) is occasional and discontinuous.

This position is often criticized as *arbitrary* and *non-scientific*. It must be emphasised, however, that the methodology for establishing any standard must always contain some level of arbitrariness. For example, the procedure for establishing the acceptable daily intake (ADI) standards, used as the basis for the toxicologically sound World Health Organizaton (WHO) Guidelines, applies a number of safety factors, which contain a large degree of arbitrariness and cannot be considered as a rigorously scientific procedure. Therefore, when compared to the WHO Guidelines, for example, the EU limit is not 'toxicologically incorrect' but 'philosophically different'. Standard-making must always take into account a number of potentially incommensurable factors.

What has been the outcome of the zero tolerance policy?

Despite the use of this policy over a period of almost 30 years, there is none the less a problem of pesticide contamination in groundwater across Europe. In many European countries the concentration levels of specific pesticides (e.g. atrazine) have breached the EU set standard.

What have been the responses to the already existing accumulation of pesticides and the predictable future accumulation of pesticides in the agricultural regions of Europe? First, local derogations to the directive have been allowed up to the concentrations believed to be toxicologically safe (e.g. according to WHO Guidelines) and for the time needed to undertake suitable control measures. Secondly, the local governments have often banned the offending chemical, disallowing its further sale or application in the regions where it has already accumulated. Finally, the EU has now revised its standard, in order to allow further accumulation of pesticides in groundwater. This is the result of the abandonment of the so-called 'cocktail standard', which proscribed aggregate accumulation of all chemicals in drinking water. None of these responses is geared to correcting the underlying problems by using the regulatory approach.

Therefore, irrespective of the desirability of the EU zero tolerance approach, its implementation has clearly been problematic. The proper implementation of the basic objectives of the EU regulatory strategy must be carefully considered, so that the important environmental objectives may be attained.

Outputs: how should chemical accumulation in drinking water be regulated?

According to the opinion of the CSTEE, and taking into account that about two-thirds of the drinking water of the EU comes directly from natural groundwater and consumed without treatment, drinking water should be regulated taking into account three different points of view (CSTEE(1), EEC 1994*b*):

(1) The *ethical and quality-oriented* point of view, which may be summed up as the widely held preference for non-polluted and pristine water sources.
(2) The *technological* point of view, which considers the possibility of controlling the use of chemical substances to avoid their presence in drinking water.
(3) The *scientific* point of view, dealing with the following:
   Consumer health protection: the concentration of substances in drinking water should be such that any consumer can drink the water for a lifetime without risk of adverse health effects.
   Resource protection: measures should be taken so that in future water resources will not be at risk of possible pollution.

The core of this approach is to prevent all unnecessary and unwanted chemical contamination of drinking water. There are many objections, however, to the EU approach, which are based mainly on its potentially high costs (of preventive control measures and their effects on the competitiveness of agricultural products). This indicates that it is important to achieve the correct balance of environmental and agricultural objectives in this area. The regulation of drinking-water quality necessarily involves a balancing of two important but potentially conflicting societal goals: agricultural production and environmental quality.

One of the objects of this volume is to assess this trade-off in the context of a case study concerning one particular agricultural chemical, atrazine. In the course of this case study we hope to demonstrate the methodology that might be used in the balancing of the important but inconsistent objectives.

The second object of this volume is to demonstrate how such a trade-off may be implemented. Clearly, the EU approach to implementation has not yet been successful and alternative approaches must be considered. The implementation of environmental objectives may be pursued through a combination of agronomic, environmental, economic and political means. They may be given effect through a range of different approaches:

The regulation of further chemical usage in regions of already contaminated water sources.

The approval of more 'environmental friendly' compounds in relation to the environmental resources to be protected.

The management of land use and agricultural practices in relation to the protection of particularly valuable and vulnerable natural resources.

We will examine in the context of our case study this range of possible approaches, and how to use each of them most effectively. We will also indicate where we believe the EU approach went wrong, and how it might be rectified.

As a final output we hope to produce a volume that will be instructive in the understanding of how various disciplines must interrelate in the development of policies concerning the environment. Economists, toxicologists and lawyers were all necessary for this research to be undertaken, and for this volume to be its result. Appropriate policy-making in the future must develop these sorts of hybrid endeavours in order to reach the ultimate policy objectives.

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Acknowledgements

This volume is the end product of five years' collaboration between toxicologists, economists and lawyers in the understanding and analysis of the problem of accumulative chemicals, and it represents a truly integrated approach to the subject. The project was funded by the European Science Foundation in order to encourage interdisciplinary cooperation in environmental policy-making and this volume bears witness to that vision. The contributors to this volume wish to acknowledge the efforts and inputs of the other members of the group who participated in the project but who did not author chapters, including Jan Henrik Kock, Michael Pugh and Lars Bergman. We are grateful for their participation in the project. Finally we would like to thank all of those individuals at Cambridge University Press who have helped to see the project through to fruition, especially Sandi Irvine who rendered a rough manuscript readable. We are grateful for all of the support we have received in the accomplishment of this project.

Introduction

1 Regulating chemical accumulation: an integrated approach

Timothy Swanson

The problem under consideration

In July 1980 the European Commission issued a Directive on drinking-water quality (80/778/EEC) setting a maximum admissible concentration for 71 distinct parameters. One of the most strictly regulated substances in the directive was the set of chemical pesticides. The European Commission adopted a 'practically zero' level of permissible contamination for these substances. The limit for any individual pesticide product was set at the trace level of 0.1 μg/l; a 'cocktail' standard for the allowed aggregate level of contamination by all chemical pesticides was set at 0.5 μg/l. These were levels of chemical contamination that were only just detectable under then-existing monitoring technologies. The Commission's standard was intended as a clear and unequivocal pronouncment against the accumulation of chemicals within the drinking water of the EEC.

Despite this pronouncement against chemical accumulation, pesticides have been accumulating in groundwater over the past 15 years to such an extent that several substances have breached the allowed concentration in groundwater in many of the agricultural districts across the European Union (EU) (see, generally, Bergman and Pugh, 1994). This is important because two-thirds of the EU citizenry continue to acquire their drinking-water supplies from untreated groundwater, i.e. directly from the aquifers underlying their communities. In adopting its tough stance against chemical accumulation, it had been the object of the European Commission to stimulate a comprehensive strategy of pesticide management (based on agricultural, land use and pesticide management). However, the continued accumulation of pesticides in European groundwater supplies placed the EU in the position of choosing between two poor options: either the relaxation of its earlier drinking-water quality directive or the costly treatment of groundwater prior to delivery to consumers. The latter option would generate additional costs estimated at around £10 per annum for each consumer of treated water supplies. (Söderqvist, 1994). The former option would entail a substantial loss of political and regulatory credibility. The Commission was caught between two equally unsavoury options.

The EU's approach to the resolution of this dilemma to date has been to do some of each. It has allowed the individual states to select the measures required to meet the directive's standards, in order to allow for cost-effective implementation based upon local conditions (Faure and Lefevre, Chapter 10, this volume). It has also relaxed the 'cocktail standard' for aggregate accumulation, in order to allow for the already observed additional accumulation of chemicals in groundwater sources.

The usual approach of the Member States to the problem of chemical accumulation has been to implement product-specific bans when a specific chemical has breached the EU standards. The disallowance of a market to a chemical found to accumulate in groundwater would seem to be a straightforward method for proscribing chemical accumulation. Once again it would seem to be intended to send a strong and clear signal (at national level) that accumulative chemicals are not to be allowed in use. Nevertheless agricultural chemical accumulation in groundwater supplies continues apace, even in those countries where such bans have already been implemented. The example of groundwater contamination in the maize-growing districts of norther Italy is a case in point (Sbriscia Fioretti *et al.*, Chapter 2, this volume).

The Po River Valley is an important maize-growing district with an aggressive weed problem. In the absence of an active weed control programme, it has been estimated that 31% to 38% of the average maize yield would be lost to weed encroachment. In the 1950s selective herbicide application became the primary mode of weed control, and in 1964 this strategy was extended to maize production in Italy, with the introduction of the chemical atrazine. Atrazine was a stunningly successful pesticide, providing very effective and reliable weed control for many seasons following its introduction. Of course chemical-induced selection implies the need for an evolving weed control programme, and atrazine required supplementation by other chemical products throughout the 1970s. This resulted in increasing volumes as well as increasing numbers of herbicides being applied to the Italian countryside throughout the seventies and into the eighties (see chapter 2, Table 2.3). The level of application of atrazine remained relatively constant throughout this period, even though it was being increasingly supplemented by other chemicals as well.

The Directive on drinking-water quality was finally implemented in Italy on 2 August 1985, and the monitoring of groundwater supplies was initiated on an official basis. As a consequence it was discovered that many of the communities within the agricultural district of the Po Valley were being provided with drinking water containing pesticides (including atrazine) in breach of the EU standard. In order to enforce the standard the relevant authorities (districts) initiated local, then district-level proscriptions on the application of atrazine. These product-specific bans were slow to begin (with 67 000 hectares regulated initially in 1987) but rose to include entire regions (367 000 hectares total) by 1990. Nevertheless these location-specific prohibitions were deemed inadequate and, in 1991, the product atrazine was banned from all sale or use within the state of Italy, both in those areas in which it had accumulated and in those in which it had not. A nation-wide ban of this nature will of course help to reduce the cost of enforcing the prohibition in those areas in which it is most needed. In addition, the perception was that the government was sending a signal to chemical producers and users that accumulative products were not to be tolerated, with the foreclosure of markets to those substances which demonstrably breached these standards. Bans on specific offending chemical products are often hoped to have such broad impacts on the incentives for the use of these and related chemicals (Toman and Palmer, 1997).

Despite the clarity of the policy stance against accumulation, both within the EC Directive and in the foreclosure of markets, there is little evidence that the rate of accumulation of such chemicals is slowing. Continued monitoring identifies wells newly in breach of the guidelines on account of past years of chemical applications; due to prevailing geological conditions, it is possible for maximum concentration levels to be achieved years, even decades, after application has ceased. *Even more alarmingly the newly marketed chemicals frequently exhibit characteristics equally as accumulative as those which they are replacing* (Sbriscia Fioretti *et al.*, Chapter 2 this volume; Mason, Chapter 8 this volume). After the proscription of specified chemical products on the grounds of their accumulative nature, many of the replacement chemicals used in their stead exhibit characteristics which will cause them to appear in groundwater in similar concentrations after an equivalent amount of time. The strong stand taken across and within the EU against chemical accumulation has been having little or no effect on the number or quality of accumulative substances being produced and applied within the Union. This is the primary reason that the EU was forced to relax its 'cocktail standard' on pesticide accumulation. The policy measures preventing the accumulation of specific chemical products are not having the effect of shaping the characteristics of their replacements sufficiently, and one chemical after another is accumulating in the groundwater.

How can it be the case that such strong policy measures have so little impact? It is the object of this volume to explain this conundrum. We hope to demonstrate both the reasons for the inefficacy of existing policies and the essence of an effective approach to regulating chemical accumulation. The remainder of this chapter provides an overview of our approach, and an indication of our conclusions. I recommend that the interested reader read each of the individual chapters to acquire the full story on chemical accumulation and its regulation.

An overview of the volume: empirical studies

Part I of the volume presents two chapters which attempt to dissemble the problematic pesticide into its constituent components. This allows the ensuing discussion to pursue the subject at a more fundamental level. It is not the chemical nature of the products that is problematic nor their widespread use per se, rather it is the specific characteristics of certain chemical products that gives rise to their accumulative nature. Part I of this volume identifies these characteristics, and sets forth an analysis that ascertains their relative contribution to a chemical's use and usefulness. This analysis will then be helpful later in the unravelling of the nature of the policy failures in this area, but initially it provides an excellent introduction to the nature of problematic chemical substances in general and of atrazine (and its substitute substances) in particular.

The first chapter in this section demonstrates both the need for agricultural chemicals and the need for a policy explicitly addressing the contamination resulting from their use (Sbriscia Fioretti *et al.*). Since the 1950s, chemical-based strategies have been the preferred form of weed control, and in their absence it has been estimated that up to a third of crop production would be lost. On the other hand, many agricultural chemicals have been designed in such a fashion as to ensure their accumulation in groundwater. This is because many of these chemicals (herbicides in particular) are designed to use the natural flow of precipitation to transport the chemical from the surface (where it is applied) into the soil. It is within the soil that the chemical then acts upon the germinating seeds and root matter of the weedy plant. In essence, the hydraulic cycle (from atmosphere to surface through soil and other living matter and back into the atmosphere via respiration and evaporation) is used as the transport vector through which the chemical may travel to make contact with the target organisms. For this reason, herbicides have been explicitly designed in order to react primarily with water rather than alternative media (i.e. the atmosphere or organic sphere).

The groundwater contamination problem arises because some of the natural flow of water leaks out of this cycle, and becomes relatively stagnant within various substrata. In these so-called 'sinks' the chemical substance accumulates under circumstances (out of contact with light, air or organic substances) in which it is difficult for further biodegradation to occur. The chemical's natural affinity for water has led it down a dead-end, where it will continue to accumulate so long as degradation and recharge rates are low. Groundwater aquifers are one of those dead-ends in which chemical substances are capable of being found.

For these reasons the two traits of a chemical that are most likely to determine its rate of accumulation within groundwater are: (1) its relative affinity for reacting with water relative to the other basic media (the organic sphere, the atmosphere), and (2) its absolute rate of reactivity or persistence. 'Affinity' is measured by virtue of partition coefficients which determine the rate at which the substance will react with alternative media when simultaneously exposed to them; for example, the K_{oc} coefficient states a chemical's relative affinity for organic carbon and water media. 'Persistence' is usually measured by the amount of time required for the loss of half of the original mass of the chemical substance through reactivity (the chemical's 'half-life'). The product of these two measures is combined into something termed the 'GUS index': a measure of a chemical's in-built propensity for accumulation within groundwater. Clearly, chemical substances with longer half-lives and higher relative affinities for water will have a greater proportion of their initial applications finding their way into groundwater sinks.

Of course both water affinity and persistence are in-built characteristics of useful chemicals. Water affinity provides the substance with its transport vector – to take it where it needs to be. Persistence reduces the need for multiple applications because it allows for the correct amount of the chemical to be on hand at the time that its action is needed. It does this by reducing the rate at which the chemical reacts with non-target substances; i.e. by reducing its general rate of reactivity or biodegradation. Hence, it is no accident that these chemicals accumulate in groundwater; the propensity for accumulation is a by-product of the same characteristics that render the chemical useful. This point is pursued further in an empirical analysis of the demand for the various characteristics of pesticides (Söderqvist, chapter 3, this volume). This study looks more closely at atrazine and its various substitute chemicals, and assesses the relative demand for the various characteristics which distinguish them from one another. The characteristics of useful chemicals examined there include:

(1) Persistence (half-lives).
(2) Reliability (GUS index for pre-emergents).
(3) Effectiveness (kill rate).
(4) Toxicity (lethal dose).
(5) Regulation (banned status).
(6) Age (years on market).

Unsurprisingly, this study demonstrates that the effectiveness (kill rate) of the chemical is the single most important facet of the substance; users are clearly willing to pay more for chemical substances which are more effective in removing the targeted organisms. There are other, more surprising, results from this study, but these will be addressed in the discussion later in this chapter concerning the policy studies regarding atrazine.

At this juncture, the importance of the studies in Part I is to demonstrate the nature and object of chemical design: it is a matter of in-built chemical characteristics related to very specific targets and objectives. The contest between crops and their competitors is an important and continuing one. Agricultural chemicals are not blunt instruments; they are carefully designed to perform specific functions along charted routes through the environment. This section of the volume demonstrates the complex nature of chemical design, and the range of characteristics across which chemical manufacturers must operate (persistence, affinity, toxicity, kill rate). The choices that manufacturers make regarding these various parameters are determined by what makes for a useful chemical substance in the context within which they are used. This implies that chemical accumulation is a linked outcome, not an unintended consequence, of chemical production and application. It is probably incorrect to view the societal objective as the prohibition of all accumulative substances (unless the entirety of the benefits of chemical applications are to be foregone), as opposed to the calibration of chemical design (and application) in order to balance the benefits of chemical usefulness against the cost of chemical accumulation. Part I of this volume details how the various traits of a chemical are demanded in agriculture, and how these same traits can contribute to various forms of unintended, but necessarily linked, consequences such as accumulation in the groundwater. It demonstrates the basic nature of the social problem of regulating the traits that cause chemical accumulation: the trade-off between groundwater purity and chemical effectiveness.

The valuation of resource contamination

Part II of this volume then launches into the problematic region of environmental valuation. In a previous volume (Bergman and Pugh, 1994), we discussed the importance of undertaking a cost–benefit analysis of the EU drinking-water standard for pesticide accumulation, in order to calibrate the cost of the EU policy concerning chemical accumulation against its benefits. In that volume we reported a rough estimate of the cost of the EU policy; as mentioned previously, the cost of removing pesticides from groundwater by the use of granular activated carbon filters in the Po Valley region was estimated to be around £10 per consumer per annum (Söderqvist, 1994). Now we turn to the task of estimating the benefits.

The benefits of removing these trace chemicals are more difficult to calibrate. On account of their extremely low levels of concentration in groundwater, it will require many years of continuous exposure before that exposure accumulates to levels which are toxicologically meaningful. The toxicological procedure for extrapolating an acceptable daily intake (ADI) for any given chemical based upon various indicators such as its acute toxicity is widely accepted and not under examination here, but a large amount of uncertainty must remain in a context such as this one. This is because toxicologists must operate in laboratory environments and on time scales much shorter than a normal human life-span; they are simply unable to replicate the conditions which are prevalent in the environment in assessing their likely impacts. The low level conditions of contamination prevailing in groundwater are hence not discernibly costly under standard toxicological measures; yet a large degree of uncertainty remains, precisely because these measures are not suited to the problem of long-term low dosage induced responses.

Part II describes the toxicological and the economic approaches to risk assessment under conditions of uncertainty. In addition to the uncertainty related to the definition of a toxicologically based ADI, the extremely low levels of the EU standard for drinking water (much lower than any estimated ADI) renders it technically impossible to estimate the risks of such levels of contamination based upon toxicologically relevant considerations. The toxicologists frankly admit that the EU standards are based on foundations other than the toxicological; they are 'philosophically different' from the World Health Organization (WHO) toxicology-based standards, relying upon ethical, technological as well as scientific precepts. The economists, on the other hand, advance the willingness-to-pay criterion for use in this region of profound uncertainty. If consumers are concerned about little-understood hazards such as low level groundwater contamination, then perhaps the best measure of the cost of these hazards is the willingness of consumers to pay to undertake efforts to avoid them. Willingness to pay (WTP) for avoidance of a risk is the preferred measure used by economists to calibrate the magnitude of these sorts of preference across individuals, and the economic analysis of this problem in Part II studies a range of different approaches to the estimation of this measure.

Part II includes two chapters presenting two distinct economic approaches to the assessment of the benefits of avoiding groundwater quality deterioration: (1) a survey of *indirect method* studies for quantifying individual responses to risk (Johannesson and Johansson, Chapter 5, this volume) and (2) a *contingent valuation survey* for the same purpose (Press and Söderqvist, Chapter 6, this volume). The survey on the indirect method studies reports on several different markets which contain risk assessments implicitly, e.g. workers accepting jobs with less risk exposure at lower wages. Empirical studies across such markets once again break down the marketed product or occupation into its constituent characteristics, and then ascertain the relative contribution of each characteristic to the differences in prices between the products. In this fashion the implicit price assessed by consumers to a characteristic such as potential hazardousness may be derived. Several studies have discussed this value with regard to the willingness to pay to avoid an incremental hazard resulting in the loss of one additional life, and found a range of estimates of between US$1 million and US$20 million. This approach is valuable when the relative risks of the alternatives are already known, as it is then possible to weight this risk according to the value that individuals are observed to place on risk avoidance. This is not so helpful in circumstances, such as this, where the risks are relatively low but uncertain.

Another indirect approach to valuing risks that is more applicable in this context is to use observed expenditures that individuals undertake in order to avoid the risk. For example, the risks and uncertainties of groundwater contamination may be avoided in part by, for example, drinking bottled water, installing a water filter or moving to an area with better water supplies. Obviously, some of these are better indicators of the willingness to pay for pure water, and all of them are actions replete with mixed motives. Nevertheless, avertive expenditures provide a market-based indicator of willingness to pay, and useful indicators of the potential value placed on the risk by individuals. Three studies regarding avertive behaviour towards groundwater contamination are reviewed in this volume, indicating WTP values regarding water contamination risks in the neighbourhood of US$1–10 per individual per week. (Johannesson and Johansson, Chapter 5, this volume).

The problem with these market-based indicators is that the willingness to pay measure should be geared as closely as possible to the actual environmental good that is being valued – in this context, pristine groundwater quality. Health risks (actual and perceived) are only one facet of this environmental good. For many centuries Europeans have been able to drink untreated groundwater piped directly from the aquifers, and then into their houses. The advent of intensive agricultural production and the introduction of chemical methods of weed control have now changed this for the first time. The continued application of large volumes of chemical pesticides will make it necessary to introduce drinking-water treatment, as is now the case in the most intensive agricultural districts, and it has denied Europeans something that was part of their natural heritage.

In addition, the loss of the pristine resource is something that the individual citizen might value for reasons other than health risks and uncertainty. There are also its effects on wildlife and other biota, general ecosystems, and general environmental degradation. For these reasons the market-based indirect methods of estimation are far too narrow. The true willingness to pay for pristine groundwater quality must allow for the inclusion of this wider range of characteristics and motivations that might be included in a willingness to pay for the underlying resource. This calls for different sorts of valuation technique.

Economists attempt to estimate the broadest range of values inherent in an environmental good by means of the construction of artificial or imaginary markets for the good. This is done by constructing an imaginary mechanism for maintaining the environmental good – in our experiment we used a groundwater management fund established through water taxation – and then a random sample of individuals are asked what tax they would be willing to pay into such a fund for the purpose of maintaining groundwater quality (Press and Söderqvist, Chapter 6, this volume). This form of study is known as a contingent valuation exercise, because it asks the individual to give a valuation of the good that is contingent upon his or her acceptance of the vehicle identified as its mode of provision (here, the groundwater management fund). This volume reports a contingent valuation study undertaken in Milan, Italy, in which the average stated willingness to pay for the maintenance of groundwater quality was about ITL640 000 (aprox. £320) per household per annum. This is a very large figure relative to average household income or average household expenditures on bottled drinking water. It indicates in part that there are many broader values at stake in the preservation of pristine resources such as groundwater than simply the narrowest measures of health risks and uncertainties.

Clearly all of these methods for risk assessment and resources valuation have their own failings and presumed biases toward underinclusiveness and overstatedness. The object of including in this volume all of these various approaches to the valuation of the risks and uncertainties associated with chemical accumulation is to demonstrate the range of methods available and the kinds of result they provide. A balanced assessment of the costs and benefits of chemicals and chemical contamination will have to consider all of these various approaches to risk assessment and environmental valuation; however, our study makes clear that individual health risk from contaminated groundwater is only one part of the overall rationale for environmental regulation. Individuals are willing to pay for regulation that takes into account the broader sets of values (wildlife, heritage, etc.) that are affected by the fact of continuing environmental degradation.

Existing market and regulatory failures

Part III of this volume concerns the failings of the existing systems of regulation regarding accumulative chemical substances. The first issue discussed is whether markets will fail to generate the correct characteristics within chemical products from the overall societal perspective. The answer to this appears to be straightforward. Intuitively it might seem that the average pesticide user would be interested in maximising water affinity and persistence, in order to enhance the overall effectiveness of the chemical. Since these two traits are related directly to the rate at which the substance will accumulate in groundwater, it would then be the case that the chemical users' (i.e. the farmers') demands for chemical characteristics would be in direct conflict with those of the groundwater users. This would be the classic form of 'externality' – where some decision-makers take choices that maximise their own objectives without regard to the implied impacts on others.

There is more than a grain of truth to this paradigm as it applies in the context of agricultural chemical usage; however, as in most instances of simple generalisation, there are many complicating factors. This is because the user's objective with respect to chemicals is not so uncomplicated as it was depicted. The user clearly does not want the chemical to exhibit the largest possible persistence, for instance. This is because land use changes over time, and desirable chemicals in one context become highly undesirable in another. Pesticide residuals are cited as a major problem of chemical usage (Sbriscia Fioretti *et al.*, Chapter 2, this volume) even by their own users, so to some extent chemical and groundwater users' objectives are aligned.

This limited appeal of persistence as a chemical characteristic is evident in the results of the hedonic analysis undertaken by Söderqvist (Chapter 3, this volume). In that study there was no clear link found between the trait of persistence and the farmers' willingness to pay for the chemical. This was one of the more surprising results from that study.

Even more surprisingly that study also found a significant but *negative* relationship between what is termed 'reliability' (estimated by the use of the GUS index in the case of pre-emergents) and the users' willingness to pay. Once again this is evidence that the conflict between chemical and groundwater users is not so clear-cut as might have been thought to be the case. This finding might have been cast off as some sort of a statistical anomaly but for the fact that there is only one other empirical study on this point, and it came to the same conclusion (Beach and Carlson, 1993). It is not at all apparent that the problem of groundwater contamination is simply the result of accumulative characteristics being chosen by chemical producers in order to satisfy the demands (for water affinity, persistence and effectiveness) of chemical users. This is part of the problem, but not the whole of it. What else can explain the in-built characteristics that contribute to the accumulation of pesticides in groundwater?

Part III describes another category of explanations for excessive accumulation as 'regulatory failures' (Mason, Chapter 8, this volume). Unlike market failures, regulatory failures do not represent conflicts between the preferences of various user groups: they are instead the strategic response by concentrated industries to various forms of regulatory structures. Sometimes a regulation, ostensibly adopted for one public purpose, may instead be turned to affect the objects of the industry it was intended to regulate. This is because an industry with one or a few firms is capable of responding to the regulator in a carefully conceived and strategic manner. Since the chemical industry is one of the world's most concentrated (in the sense that a small number of firms control a large proportion of the global market), and the markets are further subdivided through patent claims and licenses, it would not be too surprising if the industry responded strategically to proffered regulations. This means that regulations must be drafted extremely carefully in anticipation of such reactions, in order to have their intended effect.

The drinking-water Directive of 1980 and its subsequent implementation is an excellent case study to illustrate this point. This Directive (as described earlier) was intended to convey the disapproval of the community regarding all accumulative chemical pesticides – their use was not to be allowed if they were found to accumulate in groundwater above trace levels. It has already been mentioned that this is an illogical objective: it implies the prohibition of many substances precisely for those characteristics that render them useful. Unless the EU means to render entirely unlawful the use of the natural hydrological cycle as a transport vector (implying the use of natural organic and atmospheric media in its stead), then the objective as stated makes little sense.

If the EU régime is instead interpreted to imply that chemicals should be used and designed in such a manner that they are less rather than more accumulative, then this makes more sense as an objective but it remains largely unattained. The study by Mason, Chapter 8, this volume, demonstrates that the replacement chemicals for those which are specifically banned are equally as accumulative (as measured by their GUS indices) as those which they are replacing (atrazine).

How can it be that the EU régime does not generate incentives to design even marginally less accumulative chemical substances than those which have been banned? Consider the simplest case as an illustration, the case in which the industry is effectively monopolised by a patent-holding firm. How would that firm respond to the prospect of a ban being placed on its patented product should it accumulate in groundwater to the proscribed level? Would it respond by creating substitute chemicals which are less accumulative? Not necessarily. If the firm perceived itself as the most likely recipient of a patent for a substitute product, then it would perceive the threatened ban simply as a mechanism for determining when it would switch from one patented product to the other. A strategic reaction to the threat of a ban would be precisely the opposite of that which was intended. The firm would instead plan to sell quantities of the accumulating chemical so as to *ensure* that the patented chemical *did* reach the level that would engage the ban on its further sale or use. This strategy would provide the firm with the capability of choosing the time at which all further sales of the first product were disallowed. Why would it care about disallowing the future sale of this product? On the expiration of a patent, the product is then available for production by any and all firms in the industry. Banning the future use and production of the now-generic chemical makes room in the market for the newly patented product.

This is a 'pre-emption' sort of strategy. It disallows general entry into the firm's monopolised market by reason of that firm's exhaustion of an ancillary but necessary resource. Here, the EU's proscription of specific chemical products unless specified stocks of groundwater remain uncontaminated implicitly renders that groundwater supply a necessary input into chemical production and use. Once that quantity of groundwater is exhausted so is the right to manufacture the chemical. Firms with market power (e.g. current patents and the prospects for replacement patents) could respond to threatened product-specific bans by strategically exhausting the resource rather than conserving it.

Regulatory failures occur whenever regulatory mechanisms are inadequately planned and implemented within the context of market power. It is predictable that regulations will have unintended consequences when the regulated firms are not naïve in their responses. There is evidence for regulatory failure underlying these problems in the hedonic analysis by Söderqvist (Chapter 3, this volume). Two of the variables demonstrating significant relationships with market prices of chemical products are the extent of product regulation and the time that the product has been on the market; both are inversely related to the market price of the chemical. This implies that the newer, replacement chemicals are more expensive than the previous generation of chemicals (in addition to being equally as accumulative). This finding is consistent with the use of product-specific regulations as a method to phase out older increasingly inexpensive chemicals (whose patents are expiring) for replacement by the newly patented more expensive chemicals.

Part III discusses a wide range of reasons that might underlie the inefficient choice of chemical characteristics, and the inefficient accumulation of chemicals in groundwater. The most obvious explanation is the straightforward problem of externality between agricultural producers and water consumers. One group wants to use the water resource as a vector to transport its pesticides to the targets; the other wishes to consume water uncontaminated by such a use. Obviously there is a societal conflict inherent in these uses that must be taken into account in the regulation of agricultural chemicals. Less obvious is the problem that regulation itself can engender. The chemical industry is a concentrated one, and typified by producers of patented goods. These conditions are likely to give rise to relatively complicated responses to regulation. The EU's attempt to discourage chemical accumulation by banning products which accumulate is a case in point. Our empirical studies indicate that the continued production of accumulating chemicals in this context (i.e. the replacements for atrazine) is less likely to be a straightforward response to agricultural users' demands than it is a strategic reaction by producers to the product-specific regulation. If this is the case, this means that it is the form that the EU regulation has taken that has resulted in its ultimate ineffectiveness (and now the relaxation of the standard). This indicates the importance of making policies correctly in order to make them effective, and this leads us into the subject of the next part of the volume.

Optimal policies for accumulative chemicals.

Part IV outlines our suggested approach to regulating chemical accumulation. It is based on the idea of internalising the externalities inherent in the design and use of chemical characteristics, but doing so in a manner that anticipates the most obvious outlets for strategic responses.

The chemical characteristic most closely linked to chemical accumulation is persistence. A chemical that reacts slowly will persist in the same environment for a longer period of time, existing through more cycles and allowing more opportunities for its leakage into some sink. For example, a persistent chemical with an affinity for water will remain where it is applied while successive waves of the hydraulic cycle pass over it. Since there is little breakdown of the substance in the interim, it continues to flow into the hydraulic system over time, with some fraction always leaking out of the system and into a sink (such as an aquifer). Once there, its general reticence for reactivity will maintain it and allow it to accumulate. Hence the trait of persistence will always generate increased accumulation in the sinks with which it has an affinity.

Since persistence can be measured, it is possible to internalise the cost of such accumulation by means of a penalty on persistence. The idea here is to cause the design of chemicals to shift toward a level of persistence that balances both the chemical benefits of that trait as well as its accumulation-based costs. This implies the need for a value-based penalty on persistence, i.e. a quantitative penalty that recognises that persistence generates both benefits and costs for society. For this reason we suggest an instrument termed the 'accumulation tax'. The accumulation tax is a unit production tax that is equal to the product of: (1) the anticipated proportion of that unit of production that will accumulate ultimately within groundwater, and (2) the cost of an additional unit of chemical contamination in the groundwater resource.

What would determine the optimal level of the accumulation tax? The unit value of the water resource is equal to its 'opportunity cost', i.e. its value for its alternative use. In this context, the groundwater aquifer is being allocated between two uses: sink for chemical wastes or source for drinking water. The opportunity cost of groundwater contamination is the loss of drinking water purity and this may be estimated via the various methods introduced in Part II.

How does an accumulation tax address the problem of appropriately constructed regulation? In effect, this approach to regulation allows the chemical producer to choose between designing the chemical so that less of it will accumulate in the groundwater and designing the chemical for more accumulation with a penalty equal to the cost of each unit of groundwater use that design implicitly entails. Such an approach allows for regulation to achieve a balance between the costs of accumulation and the benefits that accumulative characteristics imply. It also gives the regulator a straightforward mechanism for shifting chemical products away from persistence: higher accumulation taxes will result in reduced overall accumulation in groundwater.

Taxing the implicit use of groundwater is an important step toward the rational regulation of this environmental resource; however, the problem of strategic response remains in regard to the other environmental media. The issue in this instance concerns the obvious avenues by which a firm might substitute other, untaxed resources if the tax on water resources is implemented. One such problem concerns the choice of the trait of affinity. If the use of groundwater is regulated, then this means that the relative incentives to exploit other unregulated media are enhanced. For example, the chemical might be designed for affinity with air rather than water, leading to accumulation in the atmosphere rather than in the groundwater. This suggests the need for an integrated accumulation tax, balancing the relative cost of contamination of various media.

Finally, it is important to note that much of this volume has been addressed to regulating chemical accumulation *vis à vis* the chemical industry, while there are admittedly many other agents who are able to determine the final cost of chemical accumulation (chemical users, water users, public water providers). This is not meant to imply that the problem is ultimately sourced with the chemical designer alone, but rather to pay some attention to a previously neglected facet of a complete chemical accumulation policy. Chemical characteristics such as persistence and affinity are endogenous to the production process, and thus subject to regulation. Properly constructed regulation must take this possible route of intervention into consideration.

Other routes to intervention are also available, e.g. chemical users. There is no question that the local users of chemicals are also important agents in determining the ultimate extent of chemical accumulation. An accumulation tax must be supplemented by other instructments that work through these other agents. The accumulation tax proposed here will necessarily apply to the average conditions existing across large swathes of territory, and perhaps, on account of economies of scale, the entire globe. Local communities with larger-than-average valuations of their groundwater supplies may wish to supplement this general producer-level accumulation tax with a supplementary local-level accumulation tax on users. Alternatively, they might not make use of their groundwater for any other purpose, and hence wish to subsidise the use of agricultural chemicals in their region. Clearly, the accumulation tax on producers might be supplemented by a completely different tax/subsidy schedule on users in all of the various regions in which it is applied.

The problem with a heterogeneous tax schedule within an area of ready mobility is, of course, the problem of enforcement. How can it be ensured that the users do not acquire all of their supplies from within the region with the most beneficial user tax schedule? Under such circumstances (as in the EU) where heterogeneity is important but mobility is mandatory, a supplementary layer of 'zoning' may be preferable to a supplementary tax schedule (Fauve and Lefevere, Chapter 10, this volume).

In essence, the overall objective of chemical regulation is to minimise the aggregate cost of: (1) agricultural losses due to weeds and weed control, (2) consumer risks and welfare losses due to water contamination, and (3) governmental costs due to administration and evasion. The first two objectives are balanced by means of an appropriately determined accumulation tax. The third objective may have to consider introducing alternative forms of instruments such as zoning or standards.

Conclusion

This volume is intended to demonstrate how science, economics and policy may all be integrated to address an important environmental problem. It is arguable that in this context the problem is insoluble in the absence of an integrated approach.

We demonstrate here that the EU's approach to groundwater regulation is based on a fundamentally flawed approach. It has attacked accumulation as an unmitigated bad thing rather than recognising it as the linked outcome of useful chemical production and application. It seeks to impose 'bans' rather than 'balance' and in the process achieves neither objective. Chemicals have continued to be manufactured and applied with the same in-built capacity for chemical accumulation. Groundwater contamination continues to escalate as a problem both in those areas where it is already present and increasingly where it has not been before.

Real and effective regulation of chemical accumulation requires an understanding of: (1) the characteristics of chemicals that contribute to accumulation, (2) an understanding of why they are demanded and by whom, (3) an even-handed objective that balances the benefits of these chemical characteristics with the costs of the accumulation that they imply, (4) an understanding of the values implicit in resource contamination, and

(5) an understanding of the instruments necessary to implement the desired balance between costs and benefits. This volume provides illustrations of how to think about and how to implement these various considerations. Most importantly it demonstrates the value of an integrated approach to policy-making in the area of environmental resources. It requires a collaborative effort between natural, social and policy scientists to bring the nature of the fundamental problem and the optimal policies to light.

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