Chemical Time Bombs: Linkages to Scenarios of Socioeconomic Development

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EXECUTIVE REPORT 20
(CTB Basic Document 2)
April 1992

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International Standard Book Number 3-7045-0115-8

Activities of the Chemical Time Bomb Project are coordinated in the Netherlands by the Foundation for Ecological Development Alternatives (Mondiaal Alternatief), Hoofdorp, The Netherlands.

Cover design by Martin Schobel

Printed by Novographic, Vienna, Austria

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Foreword

Toxic substances are ubiquitous in industrial societies. The sources of these chemicals include atmospheric deposition from multiple point-sources, aqueous emissions from industry, sewage, and storm runoff, solid wastes from industrial and municipal landfills, tailings from mining activities, and the application of agrochemicals, to name a few. The resulting mix of chemicals enters the environment and causes well-known environmental effects. Some of these chemicals are relatively short-lived and their effects are transitory. Others, such as heavy metals and chlorinated organic chemicals, persist in the environment, where they may accumulate in chemical sinks. During the phase of accumulation, the chemicals may be immobilized or biologically inactive. They could be mobilized or activated, however, long after their initial deposition due to changing environmental conditions that diminish the sink's capacity for storing them. Delayed environmental effects may be unrecognized or not anticipated, particularly when policies are directed toward short-term problems.

This report focuses on long-lived chemicals, and, specifically, on how the potential long-term problems they pose are related to socioeconomic activities. Of course, it is well known that emissions resulting from these activities are directly related to the cumulative build-up of long-lived toxics in the environment. What is perhaps less well appreciated is that anthropogenic activities also greatly influence the properties of soils and sediments that regulate the balance between the retention and mobilization of accumulated toxic materials.

The following report attempts to provide a richer context than currently exists for managing the environment with respect to mitigating the effects of toxic chemicals stored over previous decades. The scenario approach is used here to illustrate how land-use changes, climate change, and energy use might affect the storage capacities of soils or sediments. Scenarios also provide a means by which alternative management strategies may be evaluated with respect to such effects. A detailed example is provided regarding the consequences of various land management actions following the abandonment of agricultural lands and their conversion to forest lands.

Currently, decisions about socioeconomic development are generally made without any consideration of its effects on the retention and mobilization of accumulated toxic materials. This "black box" approach to development and environmental management has precluded the formulation of action alternatives that are better integrated and more directed toward the goals of long-term economic and ecological sustainability. We believe the approach given in this report provides a new analytical tool for assisting in the rational prioritization of actions required to meet this objective.

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Preface

The definition of a chemical time bomb (CTB), as provided in the first document of this series, is *a concept that refers to a chain of events resulting in the delayed and sudden occurrence of harmful effects due to the mobilization of chemicals stored in soils and sediments in response to slow alterations of the environment.* The theme of this second report was first conceived at a workshop in the Netherlands in November 1990. It was decided that chemical time bombs must be understood not only in terms of how they are triggered in the environment, but also in terms of the anthropogenic activities that are linked to the triggers. For example, a change in redox potential is a CTB trigger, and activities such as draining of wetlands and implementing sewage treatment have a major influence on redox potential. Thus, this report attempts to connect specific human activities to environmental disturbances that can stimulate CTB phenomena. These connections are made for a range of activities, and matrices linking activities to effects are presented. The analysis is taken a step further by constructing scenarios, of land-use changes for example, and assessing their impacts with respect to CTBs. Thus, scenarios are used here not as a way of predicting the future, but rather for the purpose of presenting possible alternative futures against which the risk of CTB events can be assessed.

This publication is the second in a series of IIASA publications on Chemical Time Bombs. The first, entitled *Chemical Time Bombs: Definition, Concepts, and Examples*, was published in 1991. The next publication in the series will discuss CTBs in landfills and contaminated lands.

The information provided in this report represents the collective judgment of all contributors to the workshop. The Editors organized, condensed, and summarized the discussions. We gratefully acknowledge the Netherlands Ministry for Housing, Physical Planning, and Environment (VROM), Directorate for Chemicals and Risk Management, for providing financial support for the workshop and subsequent publication.

Chemical Time Bombs: Linkages to Scenarios of Socioeconomic Development

1. Introduction and Background

Concern is emerging in Europe and elsewhere that current trends in economic development, and concomitant resource depletion and environmental degradation, will increasingly foreclose the options of future generations to their rightful requirements for economic development (WCED, 1987). Analyzing and assessing developments and different activities and policies from the perspective of ecological and economic sustainability is, however, not always straightforward and uncomplicated. In a long-term perspective many changes might occur that will dramatically alter the dynamics of society and nature as we know them.

Chemical time bombs (CTBs) have been defined as possible chains of events responding to slow environmental alterations, resulting in the delayed and sudden occurrence of harmful effects due to the mobilization of chemicals stored in soils and sediments. This concept was developed in the first document in this series (Stigliani *et al.*, 1991a).

Chemical time bombs might occur over broad geographical areas as the result of large-scale changes in geographical patterns of settlement, land use, and population; and technological and socioeconomic activities. Also to be considered over a longer time perspective are the possible effects of climate change on enhancing or diminishing the probability of CTB occurrences. Awareness of CTB phenomena requires the need for broad and imaginative analysis of the long-term risks of future, present, and past practices related to the accumulation of chemical wastes in the environment.

In this report some possible developments that could affect the loading and triggering of CTBs are discussed. For this purpose a few scenarios of socioeconomic and environmental development are presented. The objective is to give an example of a "CTB risk-sensitivity analysis" for different types of possible changes. This scenario report is a follow-up to Basic Document 1 (Stigliani *et al.*, 1991a) which dealt with definitions, concepts, and examples of chemical time bombs. Future basic documents will deal with the collection, processing, and modeling of data, with data extrapolation and predictive capabilities, and finally with the identification and mapping of vulnerable and sensitive geographical areas.

As an extension of CTB Basic Document 1, the first part of this report discusses the role of scenarios as a tool in the analysis of interactions between socioeconomic development and the environment. Next, the properties of soils, important natural chemical sinks that can control the capacity to retain potentially toxic chemicals, are described. These properties are termed capacity-controlling properties (CCPs). Also included in this section are some potential impacts of socioeconomic activities on CCPs. The following section takes the analysis one step further by linking scenarios to CTBs. Scenarios related to land use, energy use, and waste management, as well as climate change, are presented. A detailed example is provided for the case in which farm land is converted to forests. Various options that may be employed for managing the land during this transition, and the implications of those options with regard to CTBs, are elaborated in the discussion. Finally, recommendations are given for the establishment of an environmental information system for detecting the vulnerability of landscapes to CTBs, incorporating plausible changes due to socioeconomic development.

2. The Role of Scenarios as a Complement to Modeling and Forecasting

There is general agreement that standard means for factoring scientific information into long-term strategies for managing the environment are inadequate. One major problem is the significant information gaps in scientific knowledge that currently preclude the development of rigorous, quantitative analyses for predicting environmental change. Moreover, we do not yet know how to use the information that is available optimally in the formulation of prudent policies that both protect the environment and foster economic development. Another perhaps more fundamental problem is that currently there is no established mechanism by which scientists and senior policy people can exchange ideas on the long-term management of the environment in a way that produces new, useful information. As a result, policy-makers are often disappointed by the lack of "policy relevance" in much of the scientific research, and scientists are often discouraged because their research appears to have no impact on public policy.

As noted by Brewer (1986), the two common means of science/policy synthesis, "Blue Ribbon" panels and large-scale computer simulation models for environment–economic analysis, although quite useful in some contexts, are less so for analyzing long-term, broad-scale ecological changes. Blue Ribbon panels are particularly suited for reaching consensus on complex but well-defined scientific questions. However, the policy aspects, if any, are often overlooked or treated naively.

Large-scale environment–economic models are hindered by the sheer complexity (and non-linearity) of real world phenomena. Wack (1985a and 1985b) has noted that planning based on mathematical forecasts can be reasonably accurate during relatively stable time periods. But precisely for that reason, models fail when they are most needed – in anticipating fundamental changes that require a new way of thinking about and planning for the future. Another important point raised by Beck (1983) is that the need for personal judgment is not eliminated by models. Indeed, if models are used merely to provide answers, then the decision-maker has in effect abdicated much of his power to the model-builders.

Both Wack and Beck have argued forcefully for a scenario approach to managing an uncertain future. They note that the role of scenarios is to enhance the decision-makers' understanding of the future by providing perceptions of several possible future environments against which decisions can be tested and vulnerabilities uncovered. The goal is not to predict the future, but rather to manage the present, learning to live with uncertainty, to factor it into the decision process, and to build bridges between decision-makers and scientists.

A scenario should be easy to understand. Also, a range of scenarios should be examined, including some that might be surprising or "not impossible". At the same time, it is important that a consensus is reached among the analysts or decision-makers participating in or using the analysis on the acceptability of the scenarios presented (Anderberg, 1989). Otherwise, the analysis could be dismissed as meaningless.

Our criteria for choosing scenarios are that they are:

- Interesting from a CTB point of view.
- Easy to understand and to follow, for an outsider and non-specialist also.
- Appropriate for the assessment of important identified "target groups" for which other means of analysis are not applicable.
- Representative of a range of possible future developments, including some surprising, yet plausible, developments.

Advocating such an approach in no way reduces the value of modeling. On the contrary, the complexities of the real world are such that without some assistance in organizing this complexity decision-makers are increasingly helpless and forced to make decisions without any real idea of their consequences. The distinction, however, is that the models must be judged not against the criterion of how accurately they can reveal actual future trajectories, but on how useful they are in enhancing the knowledge and understanding of decision-makers by exploring the dynamic consequences of some of the complex assumptions.

3. The Relationship Between Chemical Time Bombs and the Capacity-controlling Properties of Chemical Sinks

3.1 Chemical time bomb scheme

The input of toxic substances into the environment results in the loading of chemical sinks. Examples of such inputs are heavy-metal emissions from industry into the atmosphere with subsequent deposition on land, land applications of sewage sludge and fertilizers containing heavy metals, biocide spraying, and land deposition of dredge from contaminated waterway sediments. The major chemical sinks are the soil and surface sediments and these have been and will be subjected to chemical loading for decades. Soils and sediments that may pose specific CTB risks can be localized, depending on the type of chemical input. For example, the regions of greatest land deposition of airborne, non-volatile heavy metals might be within a 100 kilometer radius of a point-source industrial region emitting particulates containing heavy metals (Hrehoruk *et al.*, 1991). In contrast, acid rain components that are carried as atmospheric gases can be deposited over a larger geographical region, depending on climatic conditions. In rivers, suspended particles contaminated with heavy metals will be deposited within the flood plain and at the mouth of the river as it enters the ocean. Soils contaminated with pesticides (particularly pesticides of low mobility) will tend to be localized in areas where the pesticide was most frequently used, e.g., intensive agricultural regions. In general, the localized accumulation of toxic chemicals in the environment will depend on the mass balance between inputs to, outputs from, and transformations within the area of concern.

A CTB can occur when a toxic chemical is mobilized because the capacity of the sink containing it is either:

- Exceeded by an excess of toxic chemical input.
- Diminished due to environmental changes influencing parameters that determine the sink capacity; i.e., the CCPs of the sink (Stigliani, 1988).

The aim of this section is to describe the relationship between the sink capacity and possible triggering mechanisms (environmentally induced changes in CCPs) that may shrink it. Chemical inputs pertain to classes of chemicals with the greatest potential for long-term accumulation. In this report we focus on two such classes, namely, toxic heavy metals and persistent organic compounds. This section will also identify some important soil properties that can either: (a) affect the capacity of the soil to retain toxic metals and organic compounds; or (b) are vulnerable to changes by external factors. Starting from the initial event in a chain of events and working upward, a sample matrix is developed showing how CTBs might be detected by determining the effects of socioeconomic scenarios on CCPs.

3.2 Sink capacity and chemical mobility

A sink's capacity for storing toxic chemicals can be influenced strongly by physical and chemical changes in the sink. This can be illustrated from a thermodynamic point of view. *Figures 1(a)* and *(b)* show an example of a common chemical equilibrium relationship (sorption isotherms) between the quantity of a toxic substance sorbed within a given volume of soil (sink) and the substance concentration in the mobile aqueous phase. The effects of either exceeding the soil's maximum capacity through excess chemical input [*Figure 1(a)*] or diminishing the sink's maximum capacity [*Figure 1(b)*], are discussed separately below.

Figure 1(a) illustrates how a soil's capacity for sorption of a toxic chemical can decrease as the soil becomes increasingly saturated with the chemical.

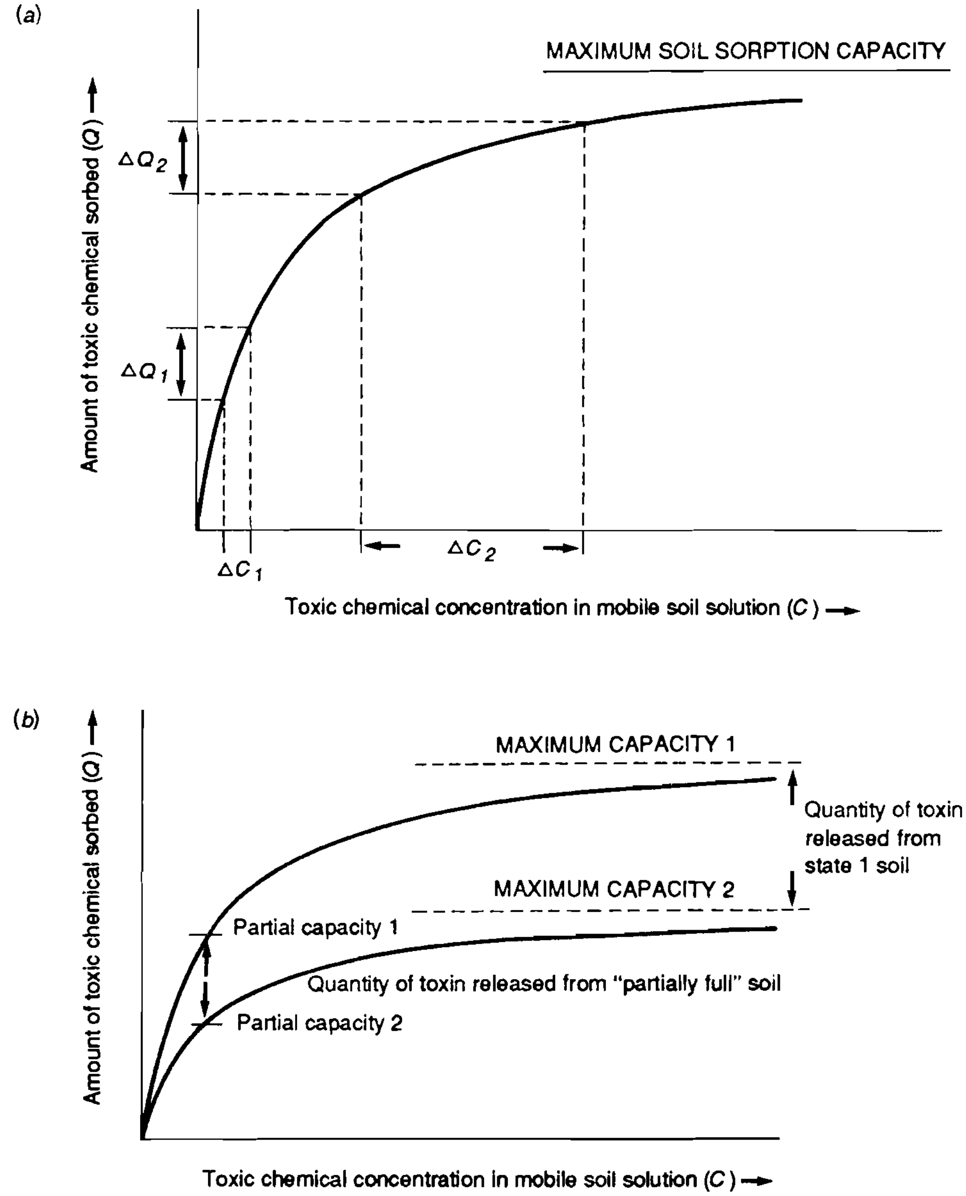

Figure 1. (*a*) The greater the amount of toxic chemical sorbed (retained) in a soil, the lower the soil's buffering capacity for an increased chemical input. (*b*) Reducing the capacity of a soil to retain a toxic chemical, e.g., by altering a capacity-controlling property (CCP), mobilizes the toxic chemical.

Assuming a chemical equilibrium relationship between the amount of sorbed (retained) chemical and the soluble concentration is as shown by the curve in *Figure 1(a)*, it follows that the soil has a higher buffering capacity against an increase in chemical input for a low sorbed concentration. For example, a given change in the sorbed concentration (ΔQ_1) produces only a small change in the mobile phase concentration (ΔC_1). At a high sorbed chemical concentration, a given change in sorbed concentration (ΔQ_2, where $\Delta Q_2 = \Delta Q_1$) produces a relatively large change in mobile concentration (ΔC_2). Conversely, a soil can buffer against increases in toxic chemical inputs, but this buffering capacity decreases as the sorbed chemical concentration increases. Quantitatively, the buffering capacity of the soil equals the tangent at any point on the curve in *Figure 1(a)*. In essence, an increase in toxic chemical input to a soil can produce an equivalent increase in the toxic chemical output from the soil if the soil is at maximum sorption capacity. If this chemical output is environmentally detrimental, then a CTB has been triggered by exceeding the retention capacity of the soil.

Figure 1(b) illustrates how a CTB might be triggered by changing the CCP of a soil and, therefore, its chemical retention capacity. The relationship between sorbed concentration and mobile (soluble) concentration can change due to environmental factors that alter one or more CCP [e.g., organic matter content, cation exchange capacity (CEC), pH, etc.]. Decreasing the retention capacity at a given solution concentration [e.g., from "partial capacity 1" to "partial capacity 2" in *Figure 1(b)*], or decreasing the maximum retention capacity (e.g., from "maximum capacity 1" to "maximum capacity 2"), would (according to thermodynamic principles) cause a release of toxic chemical in order to bring the system to a new state of chemical equilibrium indicated by a different point on any of the equilibrium curves in *Figure 1*. The total quantities of toxic chemical mobilized in the process of changing equilibrium states in the volume of soil considered in the above examples are ΔPC (partial capacity change for unit soil volume) or ΔMC (maximum capacity change per unit soil volume) multiplied by the soil volume. However, the actual rate of toxic chemical release from the sorbed phase into the mobile soil solution (and therefore the chemical concentration in the soil solution at a point in time) is not only addressed by the thermodynamic relationships in *Figure 1*: it will also depend on both the rate (kinetics) of change in the CCP and the kinetics of bringing the system to a state of chemical equilibrium after a given change in the CCP. According to the example given, the potential for a CTB would depend on both the kinetic and thermodynamic aspects of changes in CCPs and whether a

CTB is sensitive to changes in sink or soil solution concentrations of the toxic chemical, or to total amounts of chemical mobilized (released) from the sink over a given time period. Again, a CTB is triggered if the quantity of chemical released is environmentally detrimental.

The shapes of the sorption isotherms in *Figure 1* are qualitatively representative of those for soil macrocomponents (e.g., phosphate) that bind strongly (specifically) to the soil or sediment solids. Isotherms for different toxic substances such as heavy metals (Cu, Cd, etc.) and trace organics vary in shape (e.g., S-shaped or linear), depending on the affinity of the substance for the sorbent relative to the solution phase, as affected by chemical interactions such as competition for surface sorption sites and changes in surface affinity for the toxic substance with increasing surface coverage (see Sposito, 1984a). The general thermodynamic principles discussed in relation to *Figure 1* can be applied to these different-shaped sorption isotherms to evaluate CTB potential, as long as the quantitative relationship between dissolved and sorbed toxic chemical, as affected by soil properties, is known. The feature of the curve's shape that is most important for evaluating the CTB risk depends on the specific chemical. For example, it is unlikely that a heavy metal will reach a level that exceeds the soil's maximum binding capacity (except in extreme situations). But, very small increases in dissolved metal concentration can make the metal dangerous to life: the shape of the isotherm at a sorbed metal concentration well below the maximum sorption capacity would be more important than the maximum capacity itself.

Analogous to the sorption characteristics described above, soil retention of toxic chemicals by precipitation into an immobile solid phase is also affected by CCPs. Changing a soil property (e.g., redox potential or pH) can increase the solubility of a solid and thereby cause a release of a toxic chemical to the mobile aqueous phase of the soil. However, in general, precipitation of a toxic chemical as a solid is environmentally more favorable than sorption because the dissolved concentration of the toxin will remain fairly constant regardless of the total concentration of the solid. The problem comes when the solubility of the solid is altered by a change in a chemical factor such as redox potential or pH.

3.3 Soil properties affecting sink properties

For the identification and prevention of CTBs by detecting them through scenario analysis that uses a bottom-up approach, both the soil-buffering capacity relationships (as shown in *Figure 1*) and the soil volumes (soil thickness) in the geographical area of interest must be quantified. Also, it is important to know (measure) how changes in soil CCPs affect the soil's chemical retention capacity relationships. The CTB potential of a geographical area can then be evaluated by combining this fundamental knowledge of soil properties (from field or laboratory measurements on the soils of interest or on similar soil materials) with measured levels of toxic chemical inputs (e.g., heavy-metal emission data).

Working upward from these very fundamental measurements, one then tries to project how real or assumed long-term socioeconomic changes affect the CCPs. The socioeconomic trends are more speculative than the fundamental soil property measurements.

CTB phenomena depend on complex interactions between source and sink, as well as on many other factors (CCPs) affecting sink capacity (Stigliani *et al.*, 1991a and 1991b). To better understand CTBs it is, therefore, in the initial analysis only practical to consider the most important CCPs. The choice of CCP depends on the sensitivity of the sink capacity to the CCP, and the sensitivity of the CCP to the consequences of important socioeconomic developments or climatic change. Ideally, the CCPs chosen should be measurable properties of the sink.

Seven important soil properties (CCPs) affecting soil buffering capacity and maximum retention capacity for heavy metals and toxic organic compounds are described in *Table 1*. Some of these properties are further discussed by Stigliani *et al.* (1991a and 1991b). For CTBs other than those related to heavy metals or organics, a different set of CCPs may be pertinent. As the descriptions in *Table 1* indicate, CCPs are strongly interdependent (e.g., CEC, pH, organic matter content), and most are measurable parameters. Any scenario causing an environmental change that affects these CCPs will subsequently affect the maximum sink capacity, either unfavorably or favorably.

It is apparent from the above discussion that there are two inseparable aspects to predicting and preventing CTBs. First, it is imperative to know what soil properties will control the toxicity levels of a chemical, and how sensitive the chemical toxicity is to changes in these properties. Second, the relevance of a soil property to a CTB depends on how the soil property is affected by long-term environmental changes, e.g., socioeconomic or climatic changes.

Table 1. Important soil capacity-controlling properties (CCPs) for heavy metals and toxic organic chemicals.

CCP	Detrimental environmental effect
Cation- or anion-exchange capacity (CEC or AEC)	Soil having a low CEC or AEC has a low capacity to retain cations (e.g., metals) or anions (e.g., organic anions) by sorption. CEC and AEC are important soil properties which depend on inorganic clay mineral content and type, organic matter (OM) content, and soil pH.
pH	Lowering pH increases heavy-metal solubility, decreases CEC, and alters soil microbial population.
Redox potential (Eh)	Decreasing redox potential (more reducing conditions) dissolves iron and manganese oxides, which mobilizes oxide-sorbed toxic chemicals (see, e.g., Stigliani, 1988; Stigliani *et al.*, 1991a,b). Increasing redox potential (more oxidizing conditions) mobilizes heavy metals by dissolving metal sulfides.
Organic matter (OM)	Decreasing OM content reduces CEC, soil pH buffering capacity, the sorption capacity for toxic organics, soil water-holding capacity, alters physical structure (e.g., increases soil erodibility), and decreases microbial activity.
Structure	Altering soil structure can reduce drainage and thereby increase redox potential, increase soil erodibility, affect the rate of chemical release to drainage water (could beneficially slow the release), and alter pH.
Salinity	Increasing salinity solubilizes toxic chemicals by altering the ion-exchange equilibrium, increasing soluble complexation, and decreasing chemical thermodynamic activities in solution; it can also decrease microbial activity.
Microbial activity	Altering microbial activity and population ecology can reduce toxic degradation of organics (increase toxic build-up), and alter redox potential and pH.

3.4 Anticipating CTBs

Figure 2 gives a more detailed overview of the CTB problem. Within it, four interrelated levels of events leading up to a potential CTB are identified.

Socioeconomic developments (level 1) not only affect quality and quantity of toxic emissions into the biosphere (sink loading), but also, by causing environmental changes (level 2), influence the CCPs (level 3) that could trigger increased toxicity of a chemical (level 4). A CTB may be anticipated by simultaneously approaching the problem from the top (level 1) down and from the bottom (level 4) up.

To be able to predict and prevent the occurrence of CTBs, relationships between socioeconomic changes and changes in CCPs must be understood. For example, acid deposition caused by power-plant emissions can lower the soil pH, which in turn can mobilize heavy metals (*Table 1*). As another example, climatic warming stimulates microbial activity, which could reduce soil organic matter content by biodegradation. Decreasing organic matter reduces the soil's maximum retention capacity for toxic compounds (*Table 1*) and can change the soil redox potential and drainage characteristics. Toxins might be mobilized through increased solubilization and/or increased soil erosion. The magnitude of such a problem depends on the relationship between soil organic matter, temperature, and other climatic conditions. Past research has shown that the total nitrogen content (related to organic matter content) of surface soils decreases exponentially with increasing temperature, and logarithmically with decreasing moisture content (Birkeland, 1984).

Assessing the potential for future CTBs requires the relation of plausible scenarios of socioeconomic development to their effect on soil CCPs. This might be accomplished by constructing a matrix showing socioeconomic changes in one column and the corresponding changes in CCPs across the rows. An example of such a matrix is shown in *Table 2*. The matrix is of course simplified. In reality, the scenarios for changes in land use, climate, energy use, and industry are interrelated, making the CTB matrix analysis multi-dimensional.

The information provided in the matrix cells represents a synthesis of socioeconomic projections and scientific knowledge, and illustrates the need for a multi-disciplinary approach for identifying CTBs. All too often social and physical scientists operate in their own separate worlds. The result of this separation has been studies focused on one or the other discipline, providing only a limited view of the problems, and offering no solutions, which almost always require the integration of scientific, social, economic, and political knowledge.

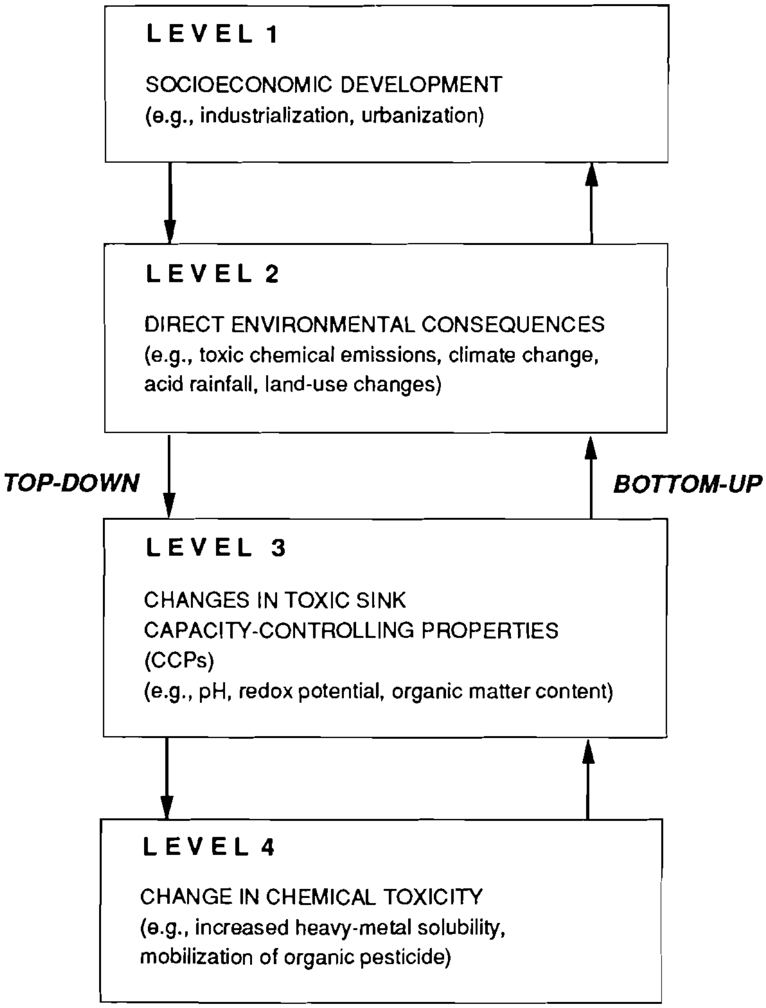

Figure 2. Chain of events leading to potential chemical time bomb situations, and possible directions (top-down or bottom-up) for detecting CTBs through scenario analysis.

Table 2. An example of a matrix approach to detecting and preventing potential chemical time bombs.

	Soil capacity-controlling properties						
Scenarios	CEC/AEC	pH	Eh	OM	Structure	Salinity	Microbial activity
Land-use changes							
• Low to high input agriculture (major detriment is increased system loading with heavy metals, toxic organics, phosphates, etc.)	CEC/AEC becomes more saturated with toxins	Possibly lowered by, e.g., nitrification (if not compensated by lime inputs)		Could decline if OM inputs (manure) decrease and OM outputs (crop harvesting) increase	Compaction and erosion increase	Could increase, e.g., irrigation with saline groundwater	Microbial population altered
• Wetlands to agricultural land ... etc.	Decreases CEC (OM), mobilizing heavy metals	May decrease, e.g., pyrite sulfide to sulfuric acid	More oxidizing, mobilizes heavy metals	Decreases; lowering CEC, releasing toxic organics	Increased erosion potential		Anaerobic to aerobic population
Climate changes							
• Increased temperature, increased precipitation		Tends to decrease				Reduced	
• Increased temperature, decreased precipitation ... etc.	Decreases; structure degraded	Tends to increase		Decreases, lowers CEC, releases toxic organics	Structural integrity can be degraded by increasing sodium, irrigation	Increased (mobilizes heavy metals)	
Energy-use and industrial changes							
• Increased fossil fuel consumption	Decreases	Decreases (heavy metals mobilized)					Microbial ecology altered, possibly reducing toxic organics degradation
• Increased heavy industry, heavy-metal deposition (major detriment is increased loading of system) ... etc.	CEC more saturated with heavy metals						Microbial ecology altered, possibly reducing toxic organics degradation

4. Interactions Between Scenarios of Socioeconomic Development and Chemical Time Bombs

Listed below are four scenarios of socioeconomic development and their possible linkages to CTB phenomena. It should be stressed that not all development scenarios will trigger CTBs. Some may even serve to mitigate the environmental impacts of CTBs. Also, the scenarios discussed here are only a small subset in a range of possible future developments. A more detailed analysis, in which an expanded number of scenarios was considered, would certainly provide a richer context for exploring the implications of alternative development pathways. However, it is beyond the scope of this report to provide an exhaustive list of scenarios and their consequences for CTBs. As an example of the kind of analysis that needs to be done for each scenario, we describe in some detail the influences that changing from agricultural land to forest land would exert on the capacity-controlling properties of soils and subsequent CTBs, and the opportunities available for prudent land management that would reduce the risk of CTB occurrences.

4.1 General scenarios

1. Land Use. Arable lands are abandoned due to a change in EEC agricultural policy; 30% of the arable land is converted to forest. This increases acidification (lower pH) of the soils due to deposition of acid constituents and the cessation of liming. (See following sections for detailed discussion.)
2. Energy Use. Great progress was made in the 1980s, and is continuing in the 1990s, to reduce SO_2 emissions in Western Europe, mainly from burning coal. However, acidic deposition has not abated because of increasing NO_x emissions from increased automobile use. Forest soils in Central Europe become increasingly acidic, causing problems such as leaching of natural aluminum, minerals, and anthropogenically deposited heavy metals.
3. Waste Management. The EEC Directive against dumping sludge and waste at sea shifts the loading from the marine sink to the choice between disposal in landfills, or incineration. The costs of incineration will encourage land disposal with the corresponding increase in loading of the land with toxic wastes. This policy leads to the construction of more "safe" landfills to accommodate the increased volume of waste. This strategy works for a while, but does not ultimately solve the waste problem as landfill sites become full

and the siting of new landfill areas becomes increasingly difficult. This policy has also discouraged investment in recycling and waste elimination strategies that would prevent generation of the wastes at the source.

4. Sea Level Rise. Increase in sea level by global warming and subsequent thermal expansion causes the loss of coastal wetlands and the intrusion of salinity into coastal soils. Since wetlands are an effective sink for nutrients and some heavy metals, they buffer coastal marine areas from eutrophication and heavy-metal loading. The loss of wetlands will eliminate this buffering function and result in the pollution of the marine environment. Also, changes in the availability of heavy metals will occur due to increases in salinization and changes in redox conditions as a result of inundation.

4.2 A detailed example: scenario 1 analysis – arable lands converted to forest

To analyze this scenario, we first projected likely changes occurring at each level (*Figure 2*) of events between the socioeconomic development of agricultural land abandonment (level 1) and possible changes of chemical toxicity in the environment (level 4). *Figure 3* is a flowchart listing a possible chain of events accompanying scenario 1. Note that the events selected are not necessarily exhaustive; actual events might differ from situation to situation under the general socioeconomic trend projected in scenario 1. In the top-down scenario analysis, we discuss management options that could mitigate or eliminate a CTB event. We also point out uncertainties, where additional research would be beneficial.

Level 1: Socioeconomic development

Based on the socioeconomic projections of Toth *et al.* (1989), arable land could be abandoned in the future due to changes in EEC agricultural policy; in southern and northwestern Europe, 30% of the arable land could be converted to forest. This socioeconomic trend is highly speculative because the prediction is tied to large uncertainties both in future economies and in sociological behavior throughout societies. (High uncertainty is typical of the level 1 (*Figure 3*) socioeconomic trend.) The time scale of such a socioeconomic trend is probably of the order of years after the implementation of an EEC agricultural policy that makes arable farming uneconomical for a certain percentage of farmers. Therefore, it is possible to revise management

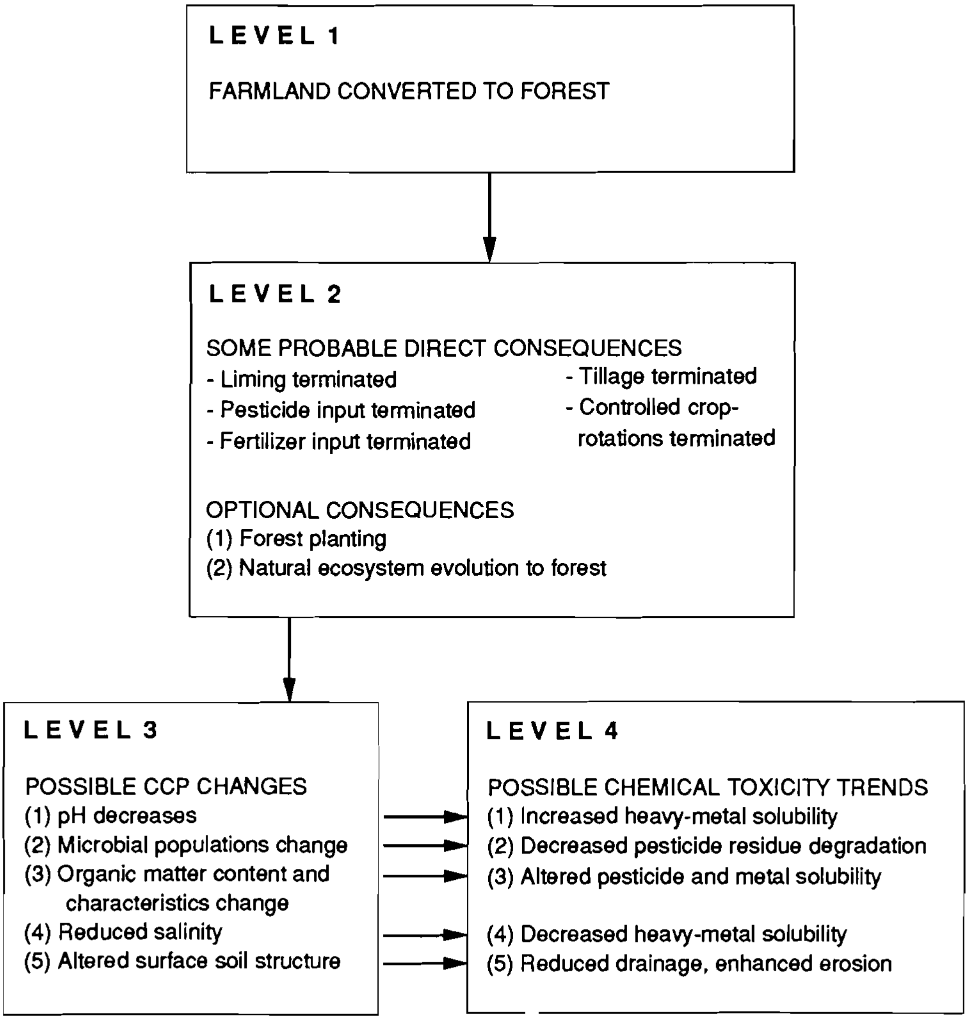

Figure 3. Possible top-down chain of events accompanying arable farmland conversion to forest, including two forest development options.

strategies toward preventing CTB situations as socioeconomic projections are revised in accordance with reality.

Level 2: Environmental (land-management) consequences

Direct consequences

Based on current agricultural practices, it is straightforward (and accurate) to predict what types of changes in land management would accompany the conversion of arable farmland to forest. Some of these changes could lead to changes in soil CCPs and are listed in *Figure 3*. Assuming that farmland-to-forest conversion is dictated by economics, costly inputs (liming, pesticides, fertilizers) to the land will be terminated. Other energy-consuming inputs such as tillage will also cease. Because the land will no longer be subjected to a monoculture of selected crops, the diversity of biological species is likely to increase.

From the CTB standpoint, heavy metals and pesticides are likely pollutants that were put into the soil during the arable farming period. Heavy metals are applied with fertilizers. For example, inorganic N–P–K fertilizers contain trace levels of cadmium (Cd). In the past, animal manures contained copper (Cu) and zinc (Zn) in levels exceeding those required for plant nutrition. Over time, applications of inorganic or manure fertilizers for plant nutrition (or land disposal) cause a build-up of heavy metals in the soil. Organic pesticides are used to a large extent in most arable agricultural systems. Depending on the resistance of the various pesticides to biological degradation and on pesticide mobility, these potential organic micropollutants can build up in the soil.

The soil acidification rate depends on soil buffering properties such as the presence and type of soil minerals and organic matter, and climatic conditions such as rainfall and leaching rate. Data presented by Birkeland (1984) can be used as the basis for a reasonable estimate of the time frame for acidification of abandoned agricultural soils. These data show that after calcite was depleted in an Alaskan soil, the pH of the top 5 cm of soil decreased one pH unit from pH 6.5 to 5.5 in 15 years, while a further decrease of 0.5 pH units (from pH 5.5 to 5.0) took an additional 20 years. Thus, soil acidification rates occur in times of the order of tens to hundreds of years, are non-linear (and therefore depend on the pH at the time of farmland abandonment), and depend on soil buffering capacity, e.g., unbuffered sandy soils should acidify more rapidly than clay soils under the same climatic conditions.

Optional consequences

The optional consequences listed in *Figure 3* are two different management strategies for the conversion of arable farmland to forest.

1. Forest planting. Selected species of trees are planted on the land, probably for a specific economic (e.g., lumber) or societal (e.g., recreational land) benefit. Some management expenditures to prevent detrimental environmental consequences are probably justifiable.

2. Natural ecosystem evolution. In this case, the arable land is abandoned and allowed to grow wild. It is probably uneconomical to justify large expenditures to manage this land for preventing environmental problems. Therefore it is even more important to consider the environmental consequences of this land-use change. In this system, ecological communities evolve naturally according to the general ecosystem-maturation trend of agricultural land to grassland to forest (depending on geography).

Level 3 and Level 4: CCP changes and their effects on chemical toxicity

Figure 3 lists five potential changes in the soil's CCPs (level 3) that would accompany a conversion from arable farmland to forest, either by forestation or by natural ecosystem evolution. Corresponding important effects of each of these CCP changes on heavy-metal or pesticide toxicity are listed under level 4.

pH decrease

On agricultural soils that are limed to maintain soil pH at a level beneficial to crops (about pH 7), cessation of liming will cause the pH to decrease over time (years). The rate of pH decrease will be most rapid on sandy soils that are leached because of annual rainfall in excess of evaporation and plant evapotranspiration. Clay soils will be more buffered against pH reductions.

A direct result of soil acidification (pH decrease) is that heavy-metal solubility increases. For example, Buffle (1988) compiled the results of laboratory studies showing that the ability of dissolved organic material (fulvic acids) to bind (complex) Cu, Zn, and Pb decreases about one order of magnitude (five- to ten-fold) for each unit decrease in pH. Assuming that solid-phase organic matter, which is typically more abundant than dissolved organic matter in soil, behaves like fulvic acid with respect to metal binding, then reduced binding strength with decreasing pH would increase metal solubility. Metal solubility also increases with decreasing pH when metals are bound to inorganic solids (Buffle, 1988; Dzombak and Morel, 1990). Naturally occurring minerals such as aluminosilicates also increase in solubility with decreasing pH. Thus, the natural tendency for the pH of soils which were previously limed to decrease from pH 7 to about pH 5 will increase the solubility of heavy metals such as Cd, Zn, Pb, Cu, and Al. Depending on the possible mitigating effects of other CCPs (e.g., reduced salinity – discussed below), and on land use (e.g., the toxicity level of the wildlife species in the ecosystem), the heavy metals can reach toxic concentrations in the soil solution or be mobilized to an extent that causes an environmental problem.

Considering the two land conversion alternatives proposed – forest planting and natural ecosystem evolution – it is difficult to predict which mechanism will cause the most rapid soil acidification. If a large part of the acidification results from CO_2 production by plant roots (Bohn *et al.*, 1979), one might expect that the soil of the natural ecosystem, with its high root density in the grassland phase of evolution, would (at least initially) acidify faster than a soil having a sparse population of young, planted trees. However, organic matter tends to build up in grassland, while in a young forest organic matter might be depleted by mineralization, thereby decreasing some of the soil buffer capacity (and possibly enhancing acidification) in the conversion to forest. Alternatively, acidification might be dominated by regionalized influences such as acid rainfall.

Microbial population changes

Changes in soil properties such as pH, nutrient level, aeration, and specific crop residue inputs will induce changes in the numbers and types of soil microbes such as bacteria, fungi, etc. (Alexander, 1977). Different microbial species require different environmental conditions for optimum growth. For example, as the soil pH decreases, bacteria that can thrive at a lower pH will compete better than other bacteria and therefore become the dominant bacterial population. Also, under nutrient-limiting conditions, soil fertilization can stimulate microbial activity.

A possible detrimental effect of microbial population changes is that the detoxification or degradation rate of organic pesticides is reduced. For example, if the microorganism that degrades a certain toxic pesticide has optimum growth at pH 6–7, typical for bacteria (Alexander, 1977), soil acidification after farmland liming ceases could decrease the population of this microbe and thereby reduce the pesticide degradation rate. Also, nutrient limitations after farmland fertilization ceases could impede microbial growth. If the pesticide normally has a long residence time (i.e., is slowly degraded) under near-optimum microbial growth conditions, then its residence time in the soil would increase under non-optimum growth conditions. A CTB-type situation might occur if the pesticide residue is either mobilized and carried to a sensitive ecosystem, or changes in land use cause immigration of biological species that are sensitive to the pesticide.

The choice between forest planting or natural ecosystem evolution as management systems to ensure favorable conditions for pesticide degradation depends on the particular types of pesticides and degrading microbes. For example, certain types of slime molds (fungi) are more common in forest soils than in grasslands (Alexander, 1977). If these fungi enhance pesticide degradation, then the pesticide would be degraded more rapidly on abandoned farmland if a forest is established by tree planting instead of by natural evolution through a grassland stage to forest. In general, soil factors such as pH, fertility, and moisture content which influence microbial growth will probably differ between the two types of forest development systems and therefore will influence pesticide degradation. These types of uncertainties should be investigated by research directed toward specific potential CTB situations.

Organic matter altered

Converting farmland to forest can affect both the characteristics and quantity of organic matter in soil. Other than the effect of pH on organically complexed metals, an organic matter characteristic that appears important for heavy-metal (and possibly pesticide) solubility is the generation of strongly complexing (chelating), water-soluble organic ligands. In young forests, leaf litter is sparse and therefore organic ligands in leachates might not be important. However, as a forest matures, a rich organic leaf-litter layer develops at the soil surface. Water leaching through this layer becomes laden with dissolved organic matter that can complex metals. Evidence of this is in the Al- and Fe-rich soil horizon that often develops in forest soils as soluble Fe–organic complexes leach down the soil horizon (Birkeland, 1984). Research has shown that organics in leaf-litter leachates also form complexes with Cu (Blaser and Sposito, 1987). It follows that the presence of dissolved organic ligands in forest soils is an important factor in increasing the solubility and mobility of heavy metals accumulated during arable farming. The significance of this toxic chemical transport mechanism in soils depends on the amount and nature of the organic material, as well as pH and leaching rates.

By increasing heavy-metal or pesticide solubility, dissolved organic ligands may cause leaching of these toxic chemicals into a more sensitive ecosystem or into groundwater aquifers, thereby creating an environmental hazard. Alternatively, increased metal and pesticide solubility at the soil surface might detrimentally affect wildlife species that inhabit the forest. Organic materials could also influence the longevity of a trace-metal pollution problem in forested farmland. One could speculate that after a long time period (years), metal uptake by resistant tree species could significantly lower the total soil concentrations of metals applied in excess during the previous agricultural period. However, research shows that the uptake of Cd and Al by selected plants increases with increasing activity (approximately equal to the concentration) of free (uncomplexed) metal ions in solution (Sposito, 1984b). If this is also true for trees, then complexing dissolved organic ligands could deter uptake and immobilization of metals in forest land. Again, this is an example of the type of research needed to prevent CTB situations.

Reduced salinity

The conversion of farmland to forest would eliminate periods of increased soil salinity due to manure or inorganic fertilizer additions. For short time periods after fertilizer application, increased salt concentration in the soil solution could increase heavy-metal solubility. This effect is caused by dissolved cations competing with heavy-metal cations for soil cation-exchange sites, and dissolved anions complexing metals in the soil solution (Salomons and Foerstner, 1984). Increased salinity might be an important mechanism for metal mobilization in agricultural land, but would probably not occur on forested land.

Altered surface soil structure

Surface soil structure will be altered during a conversion from arable farmland to forest because of the elimination of tillage and changes in plant species. Farming operations can either loosen the surface soil (tillage) or compact the soil (heavy machinery traffic). Once these operations are terminated, the soil structure will depend on natural processes such as root growth, organic matter content, and freezing and thawing cycles.

During the conversion of farmland to forest, the soil structure can go through both favorable and unfavorable changes relative to chemical toxicity. Early in the life of a planted forest, plant cover over the soil may be sparse. Since plant cover is a very important factor for reducing soil erosion (Brady, 1974), erosion could be high during the early stages of forestation (unless preventative measures are implemented). Surface crusting, the breakdown of soil aggregates at the soil surface that often occurs from raindrop impact on bare soils, can reduce water infiltration (enhance water runoff) and reduce soil aeration.

The detrimental environmental effect of soil erosion and surface-water runoff is the mobilization of potentially toxic agricultural chemicals (e.g., pesticides) that reside at the soil surface. (Note that this erosion should *not* be any worse in young forests than during periods of conventional farming when crop cover is sparse.) Reduced soil aeration can cause reducing (redox) soil conditions that increase metal (e.g., Fe) solubility. After a mature forest is established, high inputs of organic matter, a dense tree canopy, and increased soil cover (leaf litter) improve soil structure and reduce erosion.

In contrast to planted forest systems, erosion and surface runoff should be less in a naturally evolving ecosystem. The grassland stage of evolution provides dense ground cover and a high root density that minimizes soil erosion (Brady, 1974) and improves soil structure.

4.3 Prevention of a CTB

From the above discussion it is apparent that environmentally detrimental events could occur during the conversion of arable farmland to forest. It is also evident that actual chemical toxicities can be controlled to some extent by foresight and sound management strategies. To illustrate how foreseeing potential CTB situations and practising sound environmental management can be beneficial, there follows a comparison of two management scenarios for the same environmentally sensitive situation. Both scenarios are purely hypothetical.

Background scenario

An area of sloping arable farmland is abandoned abruptly after years of intensive farming. Large inputs of inorganic fertilizers and manures over the previous 20 years added excess Cu, Cd, and Zn to the soil. The farmland traditionally required liming every three to four years. Over the last three years of farming operations, as the economics of farming worsened, the landowner grew the same crop each year because it seemed the most profitable. However, a lack of crop diversity (no crop rotation) caused several types of pests to become especially problematic as their populations became increasingly resistant to the applied pesticides. Each year, the landowner applied greater amounts of (expensive), high-residence-time pesticides to keep the crop from being overtaken by insects and weeds. Finally, it was no longer profitable to farm this land. Government regulations had changed and price protections eliminated, causing this year's crop prices to decrease by 30%. The farm was sold off as part of a recreational land development project. The development agency built a lake in the basin drained by this and similar farms on the watershed.

Management scenario resulting in chemical time bombs

The land development agency wants to take full advantage of the existing soil fertility of the basin farmland by planting trees. A softwood tree species is selected that grows quickly to help establish the recreational area. The land is tilled to overturn the fall harvest residue, and young trees are planted. The tree population density is moderately sparse to ensure that the forest is better suited for hiking.

During the next 5 to 15 years, the following events were environmentally disastrous. Because the soil was not well-buffered and the rainfall was moderately acidic, the pH of the soil decreased from pH 6.5 to 4.5. This increased the solubilities of Cu, Cd, and Zn by between 25- and 100-fold. Because the tree species selected was not very tolerant to elevated Cu and Zn levels, the forest stand and ground cover were poor. No special measures had been implemented to prevent soil erosion, so sediment loads to the lake were high. Because the surface soil contained high levels of pesticide residues, plant growth in and around the lake was retarded, and certain species of birds common to these areas did not flourish. The combination of high sediment loads and pesticide residues made the lake much less biologically diverse than similar lakes in the surrounding area. Finally, heavy metals occurring in high concentrations in watershed soils were transported into the lake with drainage water, rendering it unhealthy for human recreation. Many wildlife species common to the area vanished from the watershed. The recreational objective was not satisfactorily fulfilled and the environmental impact on the watershed ecosystem was disastrous.

Scenario for ecologically sound management

To maintain soil cover and prevent erosion during the winter, the land development agency left the fall harvest residue intact (no tillage). The soil, which was pH 6, was limed with an inexpensive limestone of coarse particle size. Although the lime did not provide an immediate pH increase, its slow dissolution decreased the rate of soil acidification over the next several years until a dense population of trees was established. A mix of perennial grasses was initially planted on the basin farmland to help ensure that at least one grass species could proliferate under the existing conditions of high pesticide-residue levels. A tree species was selected and planted that was tolerant to both acidic soil conditions and elevated levels of heavy metals, grew rapidly, and could establish dense stands. The tree-planting density was moderately dense to try to maximize tree biomass production on the land.

Over the next several years, the following events were environmentally favorable. Although the soil was not well-buffered and the rainfall was moderately acidic, the coarse lime at the beginning of forestation maintained the soil pH above 5.5 for several years. Heavy-metal solubility was still at acceptable levels. As the soil pH continued to decrease and heavy-metal solubility increased, tree growth was concurrently in a stage of maximum biomass production. A significant portion of the dissolved metals was taken up by the trees and immobilized. This had the effect of mitigating heavy-metal transport within the watershed and to the lake. For a period of years, the stand of trees was continually thinned out to help make the forest more suitable for hiking. Cutting and removal of mature trees from the watershed helped to disperse the heavy metals and to initiate rapid growth of new trees that could immobilize metals.

The high pesticide residues on the land were reduced by microbial degradation. This was especially rapid during the first two years after forestation when grass roots and residues provided an additional carbon source for microbial growth. The delay in soil acidification was also beneficial to microbial degradation. A diversity of wildlife in the watershed and tolerable levels of sediment and heavy-metal deposition in the lake helped to fulfill the recreational objectives of the watershed.

5. Recommended Procedure for Detecting Vulnerabilities to Chemical Time Bombs

As the above detailed analysis demonstrates, CTB detection and prevention require an understanding of complex interactions between chemical inputs to the environment, and sink capacities as influenced by yet unknown socioeconomic changes. The following is a recommended procedure for establishing a comprehensive early-warning system for the detection and identification of CTBs. Note that the occurrence of CTBs depends on the vulnerability of the soil receiving the chemical load, and on the magnitude of the inputs to the soil of the chemical in question. Over a given geographical region (the size depending on the chemical input mechanism), soil vulnerability will be patchy; that is, the great spatial variability in soil type means that there will be significant differences in the responses of different soils to a given chemical input. However, the variability in the response of soils to chemical inputs offers the opportunity for detecting CTBs at the local level. Detection at the most vulnerable locations will hopefully prevent larger-scale environmental disasters.

Recommendations

1. Develop an environmental information system (EIS) containing the spatial distribution of land use, soil parameters most relevant to CTB vulnerability (defined above as CCPs), and inputs of chemicals most likely to cause CTBs. Because the model must be dynamic, it must reflect changes in these components over time. The chart in *Figure 4* shows the components an EIS might have.
2. Land-use changes must incorporate possible changes owing to land-use policies and climate change.
3. Changes in CCPs over time must be monitored or estimated by soil models. Priority should be given to areas deemed to be most vulnerable to CTBs. The development of large-scale soil vulnerability maps and

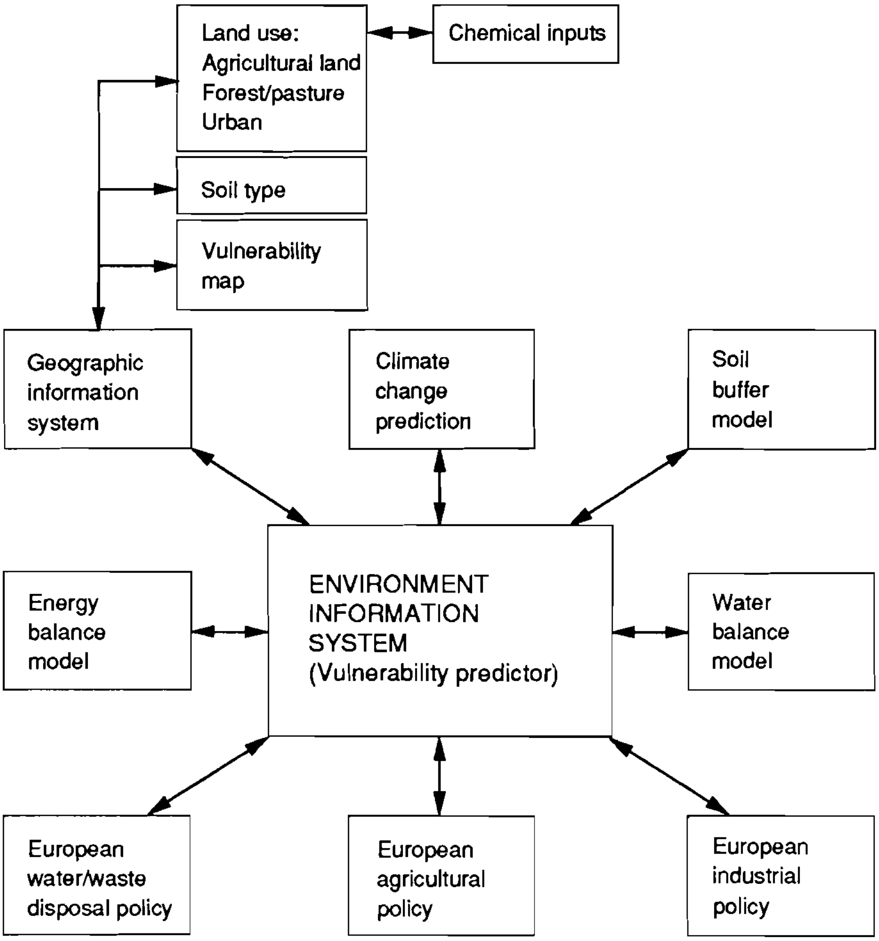

Figure 4. Components of an environmental information system for uncovering vulnerability to chemical time bombs in Europe.

maps indicating inputs of chemical deposition to the soil can be helpful in deciding on the areas on which to focus.

4. Having selected localized hot spots, detailed analysis on a much finer scale can be conducted. The goal of such an analysis would be to determine the processes working to trigger the CTBs and to define the impact and duration of the explosion. The results of this analysis may be useful in assessing the potential for CTBs to occur on a much larger geographical scale in regions yet unaffected by CTBs.
5. As a first step to illustrating the method's practicality, a case study of a CTB in the Netherlands will be conducted using emission scenarios, GIS, and soil modeling. The results of such an analysis will be a CTB vulnerability map.

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