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RESEARCH PRIORITIES FOR SOIL QUALITY ASSESSMENT

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1 INTRODUCTION

Soil is the basis for our life on earth, not only in its literal sense of providing a platform for life. In addition to its load-bearing capacity, it has many other properties and functions which enable mankind to survive.

In recent decades it has become more and more apparent that, in addition to air and water, the soil also needs protection against a growing number of adverse influences and damaging activities.

Legislation aimed at environmental protection in most countries started with water and air. This left the soil increasingly exposed to threats: e.g. by increases in the disposal of wastes on, or in, soil, once this was banned in the other compartments.

The necessity for soil protection, which is now commonly accepted in the member states of the European Community, has renewed the interest in ways and means for soil quality evaluation. This interest arises from the necessity to establish which soil properties and soil conditions should be given protection. For an supra-international organization like the E.E.C., it is of utmost importance that international agreement be achieved on soil protection measures. For this, agreement on soil quality assessment is a prerequisite.

Evaluation of soil quality poses a number of specific problems as compared with the quality of air and water. These are mainly due to the fact that difficulties of defining soil quality are considerably greater than for air and water. During the C.E.C. Conference on "Scientific basis for soil protection in the European Community" in 1987 (Barth and L'Hermite, 1987) agreement was reached that a quantitative evaluation of soil quality should preferably be based on effects that can be expected from the presence and behaviour of pollutants/contaminants in soil. This in turn requires a quantitative risk assessment approach to soil functioning.

Fig. 1, taken from Van Genderen (1987), presents in a schematic way how contaminants may adversely affect humans, plants and animals, including soil organisms. For soil quality evaluation, the following question must be answered: which quantity of a given compound in soil, C_s, is still acceptable in order to safeguard desirable conditions of these three groups of organisms. This question is closely related to risk analysis of health and toxicological considerations. Once the exposure-effect (more strictly dose-effect) relationships are determined, the question is transformed into the assessment of the result of the exposure of the organism of interest.

Sometimes the exposure can be determined in a relatively simple way as in the case of many soil organisms. Usually the concentration (or rather the activity) in the soil solution is of major importance since the exposure dose is the product of the time of exposure and this solution concentration. This means that the relationship between solid phase content and the solution

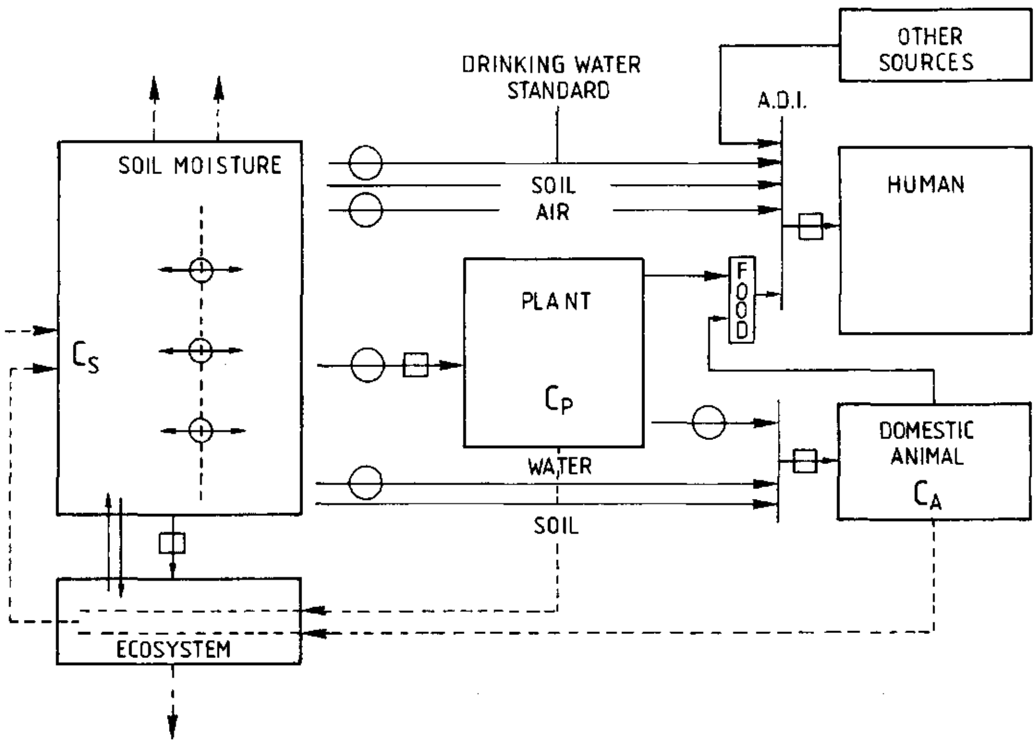

Figure 1. Pathways for contaminants from soil to other compartments and groups of organisms (after Van Genderen, 1987). For most compounds the distribution between solid phase and liquid phase (soil moisture) is of prime concern.
Circles refer to required information about transfer coefficients.
Squares to dose-effect relationships.

concentration is of prime concern. Soil chemistry provides a basis to arrive at such relationships for different contaminants and various soil systems. Adsorption and desorption isotherms are the common form of expressing them, and the distribution coefficient, $K_{s,l}$, provides a useful parameter to characterize interactions between the solid and liquid phases of soil.

The concentration in the soil solution is also highly significant with respect to leaching and hence the resulting composition of surface water and groundwater, and the uptake of compounds by plant roots. For the uptake mechanisms are generally fairly complicated (e.g. preferential or discriminating uptake) so that the content of the compound in plants, C_p, can not usually simply be derived from transpiration fluxes and solution concentration values.

Whereas the liquid phase concentration generally is the most important, there are a few examples where the exposure, or part of it, is directly governed by the content of the solid phase. These are where the exposure results from ingestion of contaminated soil or dust, as is the case with earthworms (Ma Wei-chun, 1983), with grazing animals (Bremner, 1981), and with "pica" (direct soil uptake by children, Brunekreef, 1985). Normally, however, the exposure route is much more complicated, figure 1.

The circles in the connecting lines of figure 1 refer to the need for quantitative information about transfer factors of contaminants from the soil to other compartments and the organisms indicated. The squares indicate a need for quantitative information about dose-effect relationships in order to estimate the eventual effects upon humans, animals, plants and the soil ecosystem. The dotted lines back to the soil indicate that part of the contaminants is recycling within the system as for persistent constituents, e.g. heavy metals and slowly degradable organic compounds.

Ideally, a quantitative evaluation of soil quality requires complete information about all the transfer factors and dose-effect relationships shown in figure 1:

- **for all compounds that can cause malfuntioning or disfunctioning of soil**
- **for all different soil types and soil properties that are found**
- **and for all combinations of the different variables (e.g. pH, redox potential, accompanying compounds) that control compound behaviour in the soil system.**

Because this is an impossible task at the present stage of knowledge, a number of limitations and restrictions has to be made in a first approach.

2 SOIL QUALITY IN RELATION TO SOIL FUNCTIONS

In order to establish methods of soil quality evaluation it is necessary to distinguish between different functions that soil may have.

In the present report the following are considered:

- the filtering function with respect to the composition of surface water and groundwater
- the crop production function, both with respect to yield and plant composition

- its functioning as an ecosystem

The quality of soil for each of the above includes chemical, physical and biological aspects.

A review of different approaches that can be used to assess soil quality for the three functions was obtained by a literature review. The results are presented in five separate State-of-the-Art Reports, each of which reflect the present-day knowledge. These separate reports are entitled:

- The filtering function of soil and aquifers, by A.C.M. Bourg
- Crop yield and crop composition, by S.P. McGrath
- The functioning of soil as an ecosystem, by P.C. Brookes and W. Verstraete
- Chemical aspects of soil quality, by W.H. van Riemsdijk
- Physical aspects of soil quality, by S.E.A.T.M. van der Zee and J.V. Giráldez

The biological aspects of soil quality in relation to the three soil functions are incorporated into the third report.

2.1 Limitations with Respect to Subjects and Contaminants

Because the subject soil quality is such a complex one, several limitations have to be introduced in order to arrive at an acceptable outline of the problems. Thus, for example, although there is no disagreement about the fact that physical soil degradation by erosion is a serious problem over large areas in the E.C., it has been omitted from consideration here.

Again, there is no disagreement that pollution of groundwater and surface water with nitrate, especially from agricultural practices, is an important problem in the E.C. but because both are already subject of extensive study in the present C.E.C. soil research program, it has been omitted here.

Severe constraints have also had to be made to the number of soil contaminants that could be taken into account: two heavy metals and few organic compounds were selected. The criteria for their selection were:

- high persistence in the environment
- high toxicity and bioaccumulation
- relatively high mobility
- presence in the environment in significant quantities.

For the heavy metals, these criteria are met by cadmium and zinc. Cadmium has high zootoxicity, and a relatively high mobility with respect to uptake and leaching. Moreover, intakes are already at the highest percentage of Provisional Tolerable Weekly Intake (CPTWI) for any toxic metal in the average European diet. Zinc is used in large quantities and has thus been widely spread in the environment, and is of special importance because of its phyto-toxicity. Thirdly interactions between zinc and cadmium may sometimes be important.

For organic pollutants, attention is focused upon polychlorinated biphenyls (PCBs), polyaromatic hydrocarbons (PAHs), and organic solvents like trichloroethylene and tetrachloro-ethylene. These organic compounds do not have the same importance for different soil functions. The first two groups are of special importance for crop production and ecosystem. Organic solvents may relatively easily contaminate groundwater after leaching and are thus of special interest for the filtering function of soils and aquifers. From the group of organic pesticides, atrazine is has been chosen, mainly because of its widespread use.

3 MAIN POINTS FROM THE SEPARATE STATE-OF-THE-ART REPORTS

3.1 The Filtering Function of Soil and Aquifers in Relation to Surface and Groundwater Quality

Contaminants can be filtered, or attenuated, in soils and aquifers by physical retardation, by transformation and by (geo)chemical retardation.

Filtering efficiency should be evaluated not only for its capacity to attenuate, but also for its power to resist significant changes in contaminant mobility.

Physical forms of transport are: as dissolved species, as in a separate liquid phase, as colloids and as gases.

The soil or aquifer structure is very important in determing the filtering capacity, because it controls the solution flow rate, as well as some colloid transport.

Development of simulation models for movement of solutes in soils and aquifers has had extensive attention. In order to be able to test existing or newly developed models reliable field data are needed.

Degradation of organic compounds may follow both abiotic and biotic pathways. Even compounds with long half-lives in the soil may be significant because of the low flow rates in soils and aquifers. Halogenated aliphatics are most probably biotransformed in anaerobic media only, whereas aromatic compounds can be biodegraded under aerobic conditions as well. Transformation of naturally occurring organic compounds is important because of their influence on heavy metal mobility by complexation. Transformation measurements performed in the laboratory cannot simply be translated to field conditions.

All features controlling the redox chemistry of soils and aquifers must be characterized in detail.

The filtering efficiency depends on a network of interactions between transport processes and heterogeneous phenomena like adsorption, precipitation/dissolution and volatilization. All these processes, with their mutual influences, need to be described quantitatively. Approaches used for this purpose are: laboratory experiments (batch and column), lysimeters and field investigation (requiring mass balances and techniques for moisture sampling in the unsaturated zone), and mathematical models.

The retardation factor is the key to determining filtering efficiency.

From measurements of atrazine displacement in soil preferential transport is important. Another mechanism for unexpectedly deep pesticide movement is transport in adsorbed form by soil colloids.

Chlorinated hydrocarbons are extensively leached to the water table even in peat soil.

In order to predict or to prevent further soil and groundwater contamination, it is necessary to develop methods in order to identify high risk places. This can be achieved by using classification systems, based on characteristics that affect the contamination potential. Additional physical, chemical and biological knowledge is necessary to relate pollutant mobility to soil characteristics more satisfactorily.

Understanding at the process level is required before its integration into the system-level functioning can be adequately achieved.

3.2 Crop Yield And Composition

A good quality soil may be defined as one that does not have a negative effect on crop yields, nor produce harvested materials of a composition that could be harmful to animals or humans. The risk of the occurrence of negative effects upon crop yield or crop quality requires the establisment of a quantitative relationship between exposure (more effectively dose) and the corresponding response, either a decrease in yields or an increase in the content of an undesirable substance.

A fundamental question is how substances are taken up by and translocated within plants, and how this can be related to the presence of the substances in the soil. Establishing such relationships would enable a link to be made between food and soil quality. There is usually no simple relationship between the total amount of a substance in soil and its biological action. Hence, the term 'bioavailability' is used to define the availability of a substance to a living organism.

The bioavailability of hazardous compounds is crucial. It is related to a large number of soil properties and system conditions, which are fortunately not all of equal importance. The most critical ones for cadmium and zinc are: the values of soil pH, proportion of organic matter, CEC, type and amount of clay, oxides and redox potential. However, for most conditions, pH and organic matter are of paramount importance.

For PCBs and PAHs, the type and amount of organic matter constitute the most important factor in controlling mobility and hence the bioavailability.

Atrazine at its usual application is not a threat for plant uptake, but may leach to groundwater.

Unfortunately, bioavailability is apparently not only controlled by soil properties and system conditions, but also by plant specific factors. The cadmium content of different crops grown on the same soil may vary two orders of magnitude for different crop species. The concentration at which toxic effects, e.g. a certain yield depression, occur also differs considerably for different crop species. Even the age of plants may play a role.

Plants may directly influence the chemical conditions present in the rhizosphere. They can influence, for example, the pH and the redox conditions in the immediate environment of the roots affecting the distribution of chemicals over the soil solution - solid phase and plant root. Other factors influencing the speciation of pollutants in the rhizosphere are the root exudates produced by the plant, wich may not only alter the pH, but also serve as complex forming agents for pollutants, leading to an increase of the amount present in the soil solution. However, the activity of the uncomplexed species may be decreased by the action of the root exudates. The plant itself thus influences the bioavailability of pollutants.

Fungal symbioses (mycorrhizas) may be influenced by soil pollution with metal ions. At present little is known about to the sensitivity of mycorrhizas to pollutants and the effect on plant uptake.

It is believed that simple extractants like calcium chloride solutions may indicate the bioavailability of certain pollutants.

It is emphasized that a good insight into the speciation of pollutants is needed in order to be able to interpret bio-availability. The concentrations of the various species present of the same chemical have to be established and this speciation needs to be interpreted by a conceptual model. Only an understanding of fundamental processes will allow progress towards the generation of concepts of general validity.
For cadmium too high concentrations in crops may cause zootoxicity, whereas the problem for zinc is mainly its phytotoxicity.

It may be possible to express uptake of Cd and Zn by different species of food plants relative to a reference crop. This, if true, would enable most effort to be put into understanding of metal uptake by a few species, in many different soils and different types of contamination.

Observations made in pot experiments can not be translated usually simply to field conditions.

3.3 The Funtioning of Soil as an Ecosystem

A mature ecosystem exhibits persistence and resilience. Soil organisms mainly depend on energy inputs from organic matter. Damage to energy turnover, and hence to the soil ecosystem, may occur by inhibition of biological activity and by decrease of quality and quantity of organic matter. Biological functions and activities usually depend on networks of biological interactions, which therefore must be maintained.

The present state of soil quality, as well as the rate and risk of its deterioration, can best be assessed with the use of "benchmark" non-degraded soils.

Spatial variability of soils and aquifers must be taken into account. This can lead to the identification of high risk areas. Spatial variability is also important at micro scale.

For good ecosystem functioning, the natural (micro)-biological processes should proceed normally, which implies that the relationships between microbial biomass, activity and soil organic matter are at predictable levels.

Complex formation of heavy metals with organic ligands is an important factor in metal mobility and general bioavailability. Availability and resulting toxicity is controlled by comparable factors which govern plant uptake. Organic matter and nitrogen transformations can seriously be hampered by Cd and Zn, thus damaging the ecosystem functioning. Soil microbial biomass can be used as an "early warning" for undesirable changes. Biomass reduction can be induced by direct toxic effects, and by possible reduction in plant yield and plant residues. The ratio between biomass C/soil organic C can be used as an indicator of the quality of the soil ecosystem.

Mycorrhizae are important organs for absorption of substances by vascular plants. Observations of increased as well as decreased metal uptake by vescular-arbuscular (VA) mycorrhizae are reported in the literature. Sensitivity to heavy metals may thus be very different for different species of VA mycorrhizae.

Soil enzyme activity can also be markedly influenced by heavy metals. Microbial communities in soil may develop resistance to heavy metal exposure.

The use of other soil organisms like invertebrates as indicators for soil contamination with heavy metals is sometimes proposed.

The bioavailability of organic pollutants is governed mainly in addition to their binding on the soil solid phase, by decomposition, volatilization and leaching. The latter three processes are of importance because they control the persistency and even the presence of the compounds in the soil system.

Atrazine must be considered as relatively recalcitrant towards physico-chemical and biological breakdown compared with other s-triazines.

Biological degradation of PCBs depends on the evolution of microbial groups with the capacity of performing dehalogenation reactions. Some soils may have evolved microbial communities that can degrade PCBs at accelerated rates. Microbial degradation of two- and three-ringed PAHs has been reported, but degradation of 4 rings (and above) is exceedingly slow. For PCBs with 5 or more chlorine atoms per molecule, biodegradation seems insignificant.

The high stability of chlorinated hydrocarbons, such as organic solvents, is probably due to the absence of the enzymes necessary to degrade them. Soil already polluted for some time may adapt microbial populations capable of biodegradation. It seems likely that even the most recalcitrant organic pollutants will, in time, undergo biodegradation. The rates, however, may be very slow.

3.4 Chemical Aspects of Soil Quality

Measuring, understanding and modeling the interaction of dissolved species with the soil matrix is one of the central tasks of soil chemistry. This branch of science is thus of direct relevance to the study of the relationships between soil quality evaluation and the filtering function.

For crop production the availability of a pollutant either with respect to plant uptake or with respect to toxicity effects is important. The availability depends, amongst other factors, on the form (species) in which an element is present. For a proper definition of soil quality and possibilities for crop growth, it is necessary to assess, understand and ideally to predict the various forms in which a pollutant may be present in the soil system as a function of variables like pH, salt concentration, soil type e.g. organic matter content, clay content, metaloxide content, pollutant concentration, temperature.

Pollutants do not only interact with the various reactive surfaces of the soil such as soil organic matter, metal oxides and clay, but also with the biota living in the soil, such as soil microbes and plant roots. The interactions of pollutants with the surface of biota and with (dead) soil organic matter can be studied using physical chemical methods. In addition to the interaction of pollutants with the surface of soil biota or exudates produced by the biota, active or passive uptake mechanisms play a role. Cooperation between soil chemists and biologists is required for progress in this field.

Soil chemistry may also play a vital role in relation to the development of soil quality standards. In principle from standards that have been set for water quality or product quality, soil quality standards could be derived for different soil types. To make this 'translation' requires much fundamental physical, chemical and biological knowledge which at present is lacking.

In order to be able to interpret the effects of soil pollution on the various soil functions and thus be able to define soil quality, the bio-availability of a pollutant and its concentration in the soil solution as a function of the pollution load for **any soil** has to be determined. For these purposes, in a detailed and quantitative manner the distribution of a chemical over all its likely forms in the soil systems has to be predicted. These various forms include its presence on the various reactive surfaces in the soil, both living and dead, and include the whole range of probable species present in the soil solution. That present knowledge is limited is understandable given the complexity of the problem.

A characteristic of soils is their heterogeneity, both in a physical and a chemical sense. The chemical composition of a soil varies not only with soil type (e.g. clay, peat or sandy soil) but also within one soil type, and even within one field, the chemical composition is not uniform. Because of the complexity of the soil matrix, it is difficult to define the nature and extent of the reactive surfaces present in a soil sample. The chemical heterogeneity of reactive surfaces influences the adsorption behaviour of chemicals. The chemical heterogeneity is characterized by the distribution of sites, with respect to their affinities for a chemical, over the total number of sites. Such a distribution is called the affinity distribution. For a limited number of affinity distributions analytical heterogeneous adsorption equations are available. The advantage of these heterogeneous equations is that they have only one extra parameter compared with a comparable homogeneous case. This extra parameter characterizes the width of the distribution function, the wider the distribution function the more heterogeneous is the reactive surface.

Competition between its various species for the same sites may play a very important role in the effect a pollutant has in the soil system. For soil organic matter, protons and various metal ions compete for the adsorption sites. For a given total concentration of cadmium in a given soil, the resulting cadmium concentration in the soil solution may vary considerably depending on the concentration of for instance calcium and zinc and the pH (proton concentration). Physical chemical models need to be developed that can cope with this complexity. Another factor influencing the distribution of a pollutant over the soil solid phase and the solution phase is the possibility of formation of soluble complexes in solution. These complexes can be formed both with inorganic and organic ligands.

The natural variation in both solution composition and the composition of the solid matrix causes a very large variation in the distribution behaviour of one and the same chemical in different locations. It is thus far from simple to obtain information that has general validity. Obviously for purposes of a European policy on soil quality, soil chemical information is required that is of general validity.

3.5 Physical Aspects of Soil Quality

Soil physical behaviour plays an important role in soil quality. The dynamics of water, gas and heat affect among others plant and micro-flora growth and activity. The dynamics of these phases, and their effects on biota, have also consequences for the chemical environment, e.g. through the redox potential and sources and sinks for compounds in the soil solution.

One of the basic problems associated with soil physics and soil science research is related with methodological aspects. The governing processes and the system at hand should either be considered on related or equal scales, or appropriate averaging procedures must be developed for the transition from one scale to a larger one.

Soil water physics has been mainly devoted to theoretical and experimental studies concerning the Richard's equation, taking the matric and gravitational water potential terms into account. Much progress has been made in this line of work. On the practical side temporal changes of e.g. the soil matrix, usually assumed to be rigid, may be of profound importance. However, these changes have received only a limited interest in soil water research.

The transfer of gasses in the soil pore system may occur convectively as well as by diffusion. While the mathematical side of modeling is advanced, the assessment and the understanding of dependencies of transport coefficients on a variety of soil properties, such as volumetric water content, is still limited. An additional problem that has hardly been dealt with is the multicomponent nature of gaseous diffusion and appropriate averaging to scales of interest, that are usually larger than the process level.

During the past decade much emphasis was given to multifluid transport problems as may be encountered in non-aqueous phase transport through soil. Theory has been based heavily on advances made in petroleum engineering. Both the numerical solution of such two or three phase fluid transport problems and the experimental assessment of constitutive relationships require emphasis in the near future, in view of the many problems still encountered in this field. The specific problem of non-uniform flow, e.g. due to viscous or density fingering deserves emphasis in research programs, as much of its phenomena are still only understood on the qualitative level rather than operationally.

The displacement of solutes and contaminants in soil is confronted by two main problems that need to be adressed in future. Conceptually, advances are needed to account for the multicomponent nature of transport. This statement holds both for transport involving microbiological interactions and for purely physico-chemical interactions. Guidelines justifying a simple monocomponent approach of transport, taking simple adsorption equations or rate expressions into account, are of practical interest. Technically, advances are needed concerning the solution of complicated non-linear sets of equations. Among others numerical considerations with respect to the stability, convergence, etc. of the usually non-linear problems are needed.

For a number of years stochastic analyses of transport in spatially variable flow domains are being emitted into the literature, which show the potential to understand this complicated problem using stochastic theory. While theory steadily grows, field data are lagging considerably behind. Different sources of heterogeneity and spatial variability, their level of variability, and practical approaches to deal with these phenomena in transport modeling and risk assessment are important for evaluations of soil and ground water quality, their vulnerability to contamination, and other environmental hazards.

4 RESEARCH PRIORITIES

The research priorities derived in the separate State-of-the-Art Reports are briefly reviewed. A number of co-operative research projects of the highest priority are then recommended.

4.1 Research Priorities Evolved from Separate Reports

4.1.1 Filtering function

- For a realistic understanding of the retention of pollutants through soil and aquifers it is not sufficient to measure equilibrium adsorption in batch experiments, desorption, and adsorption and desorption reaction rates also need consideration. Translation of behaviour of pollutants in closed systems (batch) to open systems (column and field) is required.
- Aspects of heterogeneity, both for soil profiles and aquifers should be studied.
- Better connections between coupled processes (e.g. adsorption and transport), as well as the relations between these processes and land use (e.g. irrigation and redox condition) should be obtained.
- Scientists should restrict the multidisciplinary efforts to a few selected soil/aquifer systems, using (and probably improving) state of the art sampling.
- Scaling up laboratory observations to field behaviour (including the effect of heterogeneities and of dual porosity) is needed.

4.1.2 Crop yield and composition

- Techniques for measuring and predicting solution concentrations of heavy metals in soil and the evaluation of extraction methods with dilute neutral salts like $CaCl_2$ are needed urgently. These must be linked with plant uptake, in cooperative efforts between soil chemists and plant physiologists.
- Measuring and predicting chemical species in solution, in combination with plant uptake response to different chemical species, is of high importance.
- Studies on effects of metals on ecosystem interactions, particularly on nitrogen fixation by free-living blue-green algae and by legume-Rhizobium symbioses, and on mycorrhizal symbioses should be performed.
- Insight into the relationship between extent of contamination of soil with Cd and the uptake under field conditions by potatoes and grains (the principal components of the European diet) is required.
- Broad scale modelling in sustaining (Cd containing) waste disposal planning is desired.
- The influence of organic pollutants on mycorrhizas deserves more attention.
- More information is required on the (mechanisms of) uptake of organic compounds of moderate K_{oc} by plants and their movement to edible portions of the plant.

4.1.3 Ecosystem functioning

- Biological indicators for heavy metal toxicity in soil ecosystems should be developed; emphasis must be given to methods useable in all E.C. member states, with a high degree of standardization of methodology between member states.
- Soils containing heavy metals at, or even below, current recommended concentrations may contain significantly less biomass than found in uncontaminated soils. The implications for ecosystem functioning, which metals (or combinations) cause these effects, and which specific groups of organisms in the biomass are affected needs to be studied.
- The relationship between soil metal content and biological N_2-fixation needs further study (cf. also 4.1.2).
- Mechanisms of adaptation of populations to heavy metal enrichment in soil should be studied.

- The reason why the soil ecosystem is not capable of degrading recalcitrant xenobiotic chemicals, and the possible mechanisms to improve the soil ecosystem capacity in this respect both warrant detailed research.
- In order to know whether highly halogenated TCBs and PAHs are decomposed in soil, whether the concentrations of hazardous compounds will increase, or decompose at higher concentrations needs further investigation.
- Standardization of methods for measuring heavy metal-effects on soil N mineralization and nitrification is required.
- Bioavailability of metals to soil invertebrates must be studied by comparing uncontaminated and contaminated soils.
- Identification and conservation of "bench-mark" soils throughout Europe where pollution is low or non-existent should be stimulated.
- The possibility of using earthworms and other higher organisms as indicator species, for organic pollutants, deserves attention.

4.1.4 Chemical aspects

- In the long run only a fundamental approach will facilitate real progress in the area of soil quality (research). Cooperation between the more fundamentally oriented disciplines like soil chemistry, soil physics and soil (micro) biology with the more effect oriented disciplines that deal with soil functioning is considered to be essential.
- In order to be able to apply knowledge surface chemistry of metal oxides to soil systems, conditions more representative of soil systems should be studied. The theory of metal ion adsorption on metal oxides should be further developed. Very recently some progress has been made in applying physical chemical models to the binding of ions to soil organic matter. Since soil organic matter is believed to be one of the most important reactive surfaces in soils this area needs much more attention.
- Four areas have been defined **of reseach into whole soil** . First, the development of new techniques to study desorption of metals already present in the soil is greatly needed. These techniques may help to evaluate the potential risk of soil pollution. Second, there is a need for a better characterization of the type and quantity of reactive surfaces in soils. Third, a large data set on the interaction of chemicals (metals) with soils of different composition needs to be collected. The soils should be characterized as closely as possible by the type and quantity of reactive surfaces present. Such a data set would give the opportunity to

test how far existing or newly developed physico chemical models can describe the variations present in the data set. The challenge is to describe those variations with as few adjustable parameters as possible. The fourth is the study of the interaction of hydrophobic organic pollutants: the missing soil chemical knowledge is mainly related to the physical chemical behaviour of soil organic matter.

- The research priorities identified are summarized as: first research into soil organic matter, second the collection of a data set for a range of soil type and solution conditions and the third related to metal oxides.

4.1.5 Physical Aspects

- Development of numerical approaches to multicomponent transport in soil water and gas, and development of guidelines to justify monocomponent approximations.
- Development of operational averaging procedures to relate processes as well as measurements on different scales, and the assesment of the effects of heterogeneity on different scales of interest on environmental risks.
- Development of numerical, experimental and parameter estimation techniques for multifluid transport in soil, and the study of the behaviour of this system.
- Characterization of the soil/atmosphere interface in terms of physical properties and processes, related to the water, gas, and heat dynamics of this interface and their temporal changes.
- Quantification and description of non-uniform or multidimensional flow through heterogeneous soil systems.

4.2 Clusters of Research Priorities

Since all individual State-of-the-Art Reports demonstrate research that many interconnections reveal between the various research areas, it is recommended that forthcoming research proposals directed to soil quality should be combined into 'clusters'. Clustering provides possibilities for cooperation and exchange of knowledge, both between the different disciplines and between research institutions of the E.C member states.

Clustering might be achieved by several groupes, submitting joint proposals. Another possibility is that separate research proposals should combine into a new cluster, or assigned to existing clusters. In any case, the coordination of the research activities within each cluster, although extremely difficult to do properly, is decisive for the kind of synergistic effects, which should result in the whole being greater than its parts.

From a methodological point of view it seems appropriate to have at least three clusters, each related to one of the three distinghuished main soil functions. Within each, the different disciplines: chemistry, physics and biology should be represented.

The State-of-the-Art Report focuses attention on the heavy metals Cd and Zn, and organic pollutants. Because the research is partly compound specific, it is suggested that the three clusters are split into six, each whith a heavy metal and organic pollutant cluster for each soil function. In the opinion of the authors, a "critical mass" is required of a cluster in order to obtain for the results to be adequate for the effort required. Hence the amount of money available for the research programme is important in determining the actual number of clusters.

Since, for all three soil functions under consideration chemical, physical and biological aspects are of concern, the research programme can be set out in tabular form (matrix structure).

One matrix for metal related soil quality research is given in table 1 (note: this is not intended as a research proposal, but a general indication; for the specific topics, see section 4.1).

Table 1: RESEARCH MATRIX/METALS (Cd, Zn)

	filter	**crop**	**ecosystem**
chemical	speciation/mobility ad-/desorption data set	speciation/rhizosphere desorption techniques data set	speciation/microbes data set
physical	water transport/fieldscale gastransport/redox transport models	transport/rhizosphere	water-heat-gas exchange
biological	?	uptake/availability toxicity/availability	toxicity/availability indicator organisms (C/N cycles)

Similar matrices can be constructed for organic pollutant-related soil quality research. The main difference with that of metals is that now the biological aspects of the filtering function are of paramount importance. Because the biodegradation of organics as well in topsoil as in aquifers is probably the critical effect.

As set out in table 1, the chemical, physical and biological aspects are of importance in relation to each of the three soil functions. This means that coordination of research activities for the vertical direction of the matrix has also to be arranged in the horizontal direction for each of those three aspects also.

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