Working Paper and Preprint 93/01

PROPOSED ASSESSMENT OF THE VULNERABILITY OF SOILS TO POLLUTION IN EUROPE USING A SOTER-SHELL APPROACH

Batjes, N.H., V.W.P. Van Engelen and L.R. Oldeman

January 1993

ISRIC

INTERNATIONAL SOIL REFERENCE AND INFORMATION CENTRE

PROPOSED ASSESSMENT OF THE VULNERABILITY OF SOILS TO POLLUTION IN EUROPE USING A SOTER-SHELL APPROACH[1]

N. H. BATJES, V. W. P. VAN ENGELEN and L. R. OLDEMAN

International Soil Reference and Information Centre,
P.O. Box 353, 6700 AJ Wageningen, The Netherlands

ABSTRACT

Soils have long been considered to form an 'unlimited' natural resource for buffering, transforming and breaking-down a wide range of chemical contaminants. Following recent unanticipated occurrences of environmental pollution caused by the delayed and sudden release of contaminants previously believed to be held firmly in soils, awareness has increased that soils and the biota they support must be protected. While some soils appear capable of receiving and holding chemical compounds and at the same time retain their ecological flexibility, other soils are readily damaged. The latter soils must be regarded as vulnerable to particular pollution scenarios. Procedures for identifying areas where vulnerable soils occur are presented, with special reference to the minimum soil data sets that would be required in a small scale, GIS-based study at the European level. These data can readily be compiled, stored and processed with the relational database management system developed for SOTER, the 1:1 million World Soils and Terrain Digital database project of the International Society of Soil Science (ISSS) which is coordinated by the International Soil Reference and Information Centre (ISRIC). The proposed, initial soil vulnerability programme would essentially serve to increase awareness on areas prone to chemical soil degradation, and will form the basis for implementing soil pollution assessment programmes at larger scales (1:1 M to 1:250,000). The latter national or regional programmes would include the identification of major sources of soil pollution, the measurement of the accumulated load and rate of loading according to uniform and standardized procedures, and thereby create the conceptual basis for developing process-based models to assess where particular types of chemical time bombs are likely to occur.

KEY WORDS Chemical time bombs Database Pollution Soil vulnerability Europe

INTRODUCTION

Soils are an essential part of natural ecosystems, and are necessary for the growth of food, fibre and timber crops. Until recently it was assumed that they could endlessly absorb contaminants, but it is now generally accepted that 'loading' by some chemical compounds has become such that it is disrupting the natural functions and productivity of soils. Currently, almost 12% of European soils have been degraded to some extent by chemical deterioration. In addition about 52 % have been degraded by water erosion, 19% by wind erosion, and 17% by physical soil degradation (Oldeman *et al.*, 1991 p. 31). Since soils form the essential link between the inanimate rocks and the living world, it is of crucial importance that measures to protect soils from further physical and chemical deterioration be implemented rapidly.

---

[1] Paper prepared for the Chemical Time Bombs session of the joint meeting of the Society of Environmental Toxicology and Chemistry (SETAC) and Aquatic Ecosystem Health and Management Society (AEHMS) in Potsdam (21-24 June 1992).

Some contaminants may detract from the productivity of soils, or reduce their capacity to filter, buffer and transform inorganic and organic substances, diminishing the inherent quality, value and capacity of these soils to support the biota of natural ecosystems and anthropogenic activities. Well known contaminants derived from agricultural and industrial activities are heavy metals, nitrates, phosphates, pesticides and radionuclides to name but a few. In some cases, contaminants (so far) believed to be held firmly in soils can be released suddenly as a result of gradual changes in the biosphere as induced, for instance, by acid deposition, eutrophication, land use changes or climate change. These time-delayed and catastrophic occurrences of pollution have been called 'chemical time bombs' (CTBs) by Stigliani (1988 and 1991).

An example of a CTB is mercury in Sweden. In view of observed toxic effects of Hg-containing chemicals on biota in the 1960s, the industrial emissions of Hg were brought under strict industrial control in the 1970s. Nevertheless human-induced acidification, associated with extensive acid deposition, in the 1980s mobilised the mercury still held in the soil thereby causing severe damage to the inland fish population to the extent of making pike, a carnivorous fish which 'lives' at the top of the aquatic food chain, unfit for human consumption.

In realisation of the possible environmental dangers associated with 'ticking' CTBs, the Netherlands Ministry of Housing Physical Planning and Environment (VROM) and the International Institute for Applied Systems Analysis (IIASA) sponsored a number of workshops to increase awareness and the scientific understanding of the factors and processes that cause chemical time bombs to 'explode' (Smidt, 1990; Csikos, 1991; Stigliani, 1991; Batjes, 1991; Konsten, 1991). Within the framework of this CTB-programme, ISRIC was contracted to organize a workshop on 'soil vulnerability to chemical pollution' (SOVEUR). One of the aims of the SOVEUR workshop was to assess the feasibility of implementing a 1:5 M soil vulnerability mapping programme at the European level to create and strengthen awareness on the need to protect soils from pollution.

In the present paper we first review the relationship between vulnerable soils and chemical time bombs. Then we summarize the methodological procedures developed by the SOVEUR workshop participants to map soils vulnerable to chemical pollution (Batjes and Bridges, 1991 p. 167-171). This encompasses a SOTER-based approach, using a Geographical Information System (GIS). Finally, we present the minimum soil data sets that are considered essential for a wide range of environmental studies at the macro-level. These so-called '1:1 M SOTER-shells' are proposed for rapid implementation at the (sub)continent level, possibly starting in Europe.

CONCEPTS AND DEFINITIONS

Soil vulnerability was defined as the 'capability for the soil system to be harmed in one or more of its ecological functions'. The latter include production of humus, filtering, storage, buffering and transformations (of heavy metals and organic materials). Additionally, the protective role of soil and the genetic reserve of its soil-living flora and fauna were regarded as significant issues by the SOVEUR workshop participants.

Soil conditions vary widely at the European level, ranging from shallow soils over hard rock to deep recent alluvial soils and organic soils (Tavernier, 1985). The 'intrinsic vulnerability' of these soils to various contaminants and pollutants depends to a large extent on their 'relatively stable' soil properties and the nature of the chemicals under consideration. The 'actual vulnerability' of individual soils to a particular contaminant will change with time under the influence of processes such as acidification, eutrophication, salinization, erosion, hydrological changes and land use changes, the so-called 'triggers'. Consequently, each soil (*sensu* soil units of FAO, 1988) will react in a different way to similar scenarios of pollution and environmental change.

So-called 'weak rapid responses' may be observed in soils where chemical compounds are easily lost in continual small amounts through leakage. This is the case, for instance, for sandy soils that are subjected to intensive additions of cattle slurry, which leads to groundwaters being polluted with nitrates. In these situations, delayed responses occur in which there is no trigger effect (at this moment in time). The 'weak responses' therefore do not correspond with chemical time bombs, but with what the SOVEUR workshop participants termed 'more or less' polluted areas. Alternatively, 'strong delayed responses' characteristic of chemical time bombs may be observed in soil systems which can store high amounts of potentially mobilisable chemical compounds. This would be the case for heavy metals, accumulated in clayey sediments, which are suddenly released in a biotoxic form when progressing acidification, associated with industrial pollution, transgresses a certain, element-specific, critical level. Mapping of vulnerable soils thus forms an important step in identifying areas where CTBs may occur.

The chemical time bomb concept stresses the capacity of the soil reservoir to hold/release contaminants and a trigger system. Application of a trigger, such as a change in land use, may cause sudden catastrophic releases of certain pollutants into the environment. The severity, nature and time of occurrence of the resulting impacts will vary with:

a) the *capacity* of the soil system to retain/release a particular chemical;
b) the actual *degree of loading* of the system with these chemicals;
c) the type and intensity of the *triggers* which act upon the soil system, and
d) the *sensitivity* of individual soils to the respective triggers.

In studies of chemical time bombs it is also necessary to consider the *targets* that will be affected by the released pollutants (e.g., human health, biological diversity, soil functions), and the resulting *effects* as determined, for instance, by threshold-levels and dose-response relationships. Erroneously, chemical time bombs often are only perceived as environmental 'problems' when the targets they affect, for instance the groundwater, are considered worthy of protection (Klijn, 1991). In this respect, it is important to take into account the fact that interactions between, and changes in the respective CTB-regulating physical, chemical and biological processes may change with time, and thereby may affect the pathways which lead to a particular type of chemical time bombs (for a discussion see Stigliani, 1991).

MAPPING OF VULNERABLE AND POLLUTED AREAS

Soil contamination

Contamination refers to the presence in the soil of potentially dangerous substances at levels above 'normal' background concentrations (Smith, 1985). Substances giving rise to concern include: organic chemicals such as persistent pesticides; oils and tars; gases of a toxic, explosive or asphyxiant nature;

combustible materials; biologically active elements such as radionuclides; and, certain heavy metals and their potentially biotoxic derivatives (e.g., Cd, Cu, Hg).

Soil contamination occurs basically in two forms, concentrated (e.g., landfills and mine sites) and dispersed (e.g., agro-chemicals, radionuclides and industrial dust). Only the vulnerability of soils to dispersed pollution can be considered in a global mapping programme (Glazovskaya, 1991). Localized chemical time bombs, such as landfills, which are widespread in Europe causing severe environmental and socio-economic problems, must be studied at larger scales. In the context of a GIS-developed for soil pollution oriented applications these would correspond with cartographic windows of higher resolution.

Vulnerable areas

Proposals for identifying physiographically defined mapping units, described in terms of their major soil units (FAO, 1988), on a 1:1 M map and their classification into vulnerability classes were agreed in principle during the SOVEUR workshop (Batjes and Bridges, 1991 p. 170). At the considered scale, soil mapping units are of a compound nature. When assessing the vulnerability of the individual components of these mapping units special attention must be paid to the most vulnerable soils. We should not determine an 'average' vulnerability for the respective components of compound map units, nor look only at the vulnerability of the spatially dominant component.

The scale of a map determines the detail of information that can be shown, and on soil vulnerability maps it determines the soil-environmental parameters which may be considered meaningful. In the context of a small scale 'soil vulnerability' mapping exercise, it was concluded that pH, clay content, clay mineral type, texture and organic matter content were criteria which are readily available and should be used in the identification of soils at risk from chemical contaminants. In addition, the site's relief, lithology, total depth of soil, water regime and length of growing period were other features, closely related to soils and their capability to resist deleterious changes, which should be considered also. Information on land use, hydrology and climate, for instance, will be derived from ancillary databases such as those developed for the 'Coordinated Information on the European Environment' (CORINE) programme.

Chemical compounds can be grouped according to their functional effects on soil properties, that is with respect to their pedo-chemically and bio-chemically reactive components. Depending on the chemicals and environmental processes, the respective soil attributes (key parameters) must be given different 'weightings'. By implication this means that several vulnerability maps, each of which corresponds to a well-defined pollution scenario, can be compiled with the same base map and set of key attributes. The relevant spatial and attribute data can readily be handled in a Geographical Information System such as SOTER.

A key issue in any mapping/modelling programme will be how to reduce the functional complexity in relation to the proposed scale of mapping (Desaules, 1991). The SOVEUR workshop participants agreed that within the constraints of time, finance and publication scale, it would be desirable initially to focus upon the impact on European soils of a limited number of heavy metals (e.g., Cd, Cu, Pb, Zn) and pesticides and other xenobiotic substances such as fluorine. The chosen chemicals are potential toxicants, mobilisable and persistent, and a source of public concern because of past, present and (possibly) future loading.

Information on the behaviour of inorganic and organic contaminants, as influenced by soil-environmental factors, will be derived from desk studies (Alloway, 1990; Blüme and Brümmer, 1987a and 1987b; Blum, 1990; Briggs, 1990; Halen *et al.*, 1990). Less information seems to be available on how the environmental triggers and key parameters may change over relatively short time scales (decades to centuries) in ways that affect the mobility and biotoxicity of chemicals in soils (Stigliani, 1988; Arnold *et al.*, 1990). Brouwer *et al.* (1991) recently discussed the possible environmental transformations associated with land use changes in Europe.

Areas prone to chemical time bombs

The initial soil vulnerability mapping activities would form the basis for implementing regional programmes at a larger scale (1:1 M to 250,000). The latter national or regional studies would include the identification of major types and sources of soil pollution, mapping of the accumulated load and rate of loading of the soil system, and development of appropriately scaled, process-based models to assess the likely risk of occurrence of specific types of chemical time bombs at the European level.

The proposals for the 'soil vulnerability' and 'soil pollution' studies presented in the preceding paragraphs have been integrated into a comprehensive proposal for developing a project on soil pollution at the European level (EUSOPOL) for which funding is sought. These activities would require that a soil database for Europe be implemented as a matter of priority, using the so-called 'SOTER-shell' approach.

SOTER, A 1:1 M WORLD SOIL AND TERRAIN DIGITAL SOIL DATABASE

Background

Since the early days of pedology numerous soil surveys have been carried out in the various countries of the world according to different field and laboratory methodologies, classification systems and mapping approaches (Brady, 1984; Duchaufour, 1982; Fitzpatrick, 1983; USDA, 1975). Integration of this wealth of information on soil conditions into global soil maps is an intricate procedure, necessitating intensive correlation activities based on well described and uniform procedures (Sombroek, 1990 p. 230). Well known examples of 'world soil maps' include those prepared by the Food and Agricultural Organization (FAO-Unesco, 1971-1981; scale 1:5 M), the United States Department of Agriculture in collaboration with the Soil Conservation Service (USDA-SCS, 1972; scale 1:50 M), and Glazovskaya and Friedland (1982; scale 1:15 M). Of these maps, the 1:5 M Soil Map of the World of FAO-Unesco (1971-1981) is the most widely used internationally because it is the most 'informative' for a wide range of user-oriented applications.

Since the time of production of the FAO-Unesco (1971-1981) maps much new information on soil conditions has been obtained for many areas of the world including the Community of Independent States (V.S. Stolbovoy, Autumn 1991 lecture held at ISRIC) and the European Communities (Tavernier, 1985). Hence the need for incorporating this new information into a global soil data base. In realisation thereof Sombroek (1985) prepared a discussion paper on the possible establishment of an 'International Soil and Land Resources Information Base'. This led to a proposal for developing an attribute-oriented 1:1 M World Soils and Terrain Digital Database (SOTER) linked to a GIS. The

SOTER proposal was officially endorsed during the 13th International Congress of Soil Science at Hamburg (ISSS, 1986 a and b).

World coverage at a scale of 1:1 M in SOTER is scheduled to take from 10 to 20 years in view of the large scientific and logistic magnitude of the task. Meanwhile, updated information on soil conditions is rapidly needed for a wide range of studies of global change (Bliss, 1990; Matthews, 1990; Oldeman and Sombroek, 1990). In this context there is much need for a so-called 1:1 M 'SOTER shells' which only specify the main, readily obtainable, soil and terrain attributes.

The SOTER approach

Within the context of this paper we shall focus on the methodology that evolved for SOTER during a sequence of international workshops and pilot studies. Full references to the studies performed in the context of SOTER are presented in ISRIC's annual reports (ISRIC, 1990).

The approach in SOTER is to screen all existing soil and terrain data in a georeferenced area - whether or not registered on official soil maps - and to complement this information with remote sensing where necessary. The collected data is then rearranged according to the procedures of the SOTER manual (Van Engelen and Pulles, 1991). Basic to this approach is the grouping and mapping (vector based) of land areas showing a distinctive, and often repetitive pattern of land form, surface form, slope, parent material, and soils. These areas are delineated on the base map as 'SOTER units'. Each 'SOTER unit' is georeferenced and considered unique with respect to the soil and terrain characteristics of its constituents. Inherently, any given 'SOTER unit' may consist of several polygons of identical composition.

SOTER units are characterized in the GIS by a) their location and topology, and b) their attribute data (Figure 1). In order to store the attributes in a logical and hierarchical manner in the database, each SOTER unit is described in terms of its constituent 'terrain units', 'terrain components' and 'soil components' (Figure 2). The 'terrain units' are differentiated first according to physiography, and lithology or parent material. Each 'terrain unit' is further divided into one or more 'terrain components', each of which have a uniform pattern of meso-relief, slope, and texture of the unconsolidated parent material. Individual 'terrain components' are characterized in the data base in terms of their 'spatially dominant' soils, which form the respective 'soil components'. Each 'soil component', so far, is described using one representative soil profile which has been judiciously selected from a number of similar profiles by regional correlators. The chemical, physical and morphological attributes of this representative profile - for instance, horizonation, texture, organic carbon, cation exchange capacity, structure, stoniness and moisture holding capacity - of necessity are considered to be representative for the whole area represented by the 'soil component' under consideration. The respective attribute data are specified using either descriptive terms or numerical values (Van Engelen and Pulles, 1991).

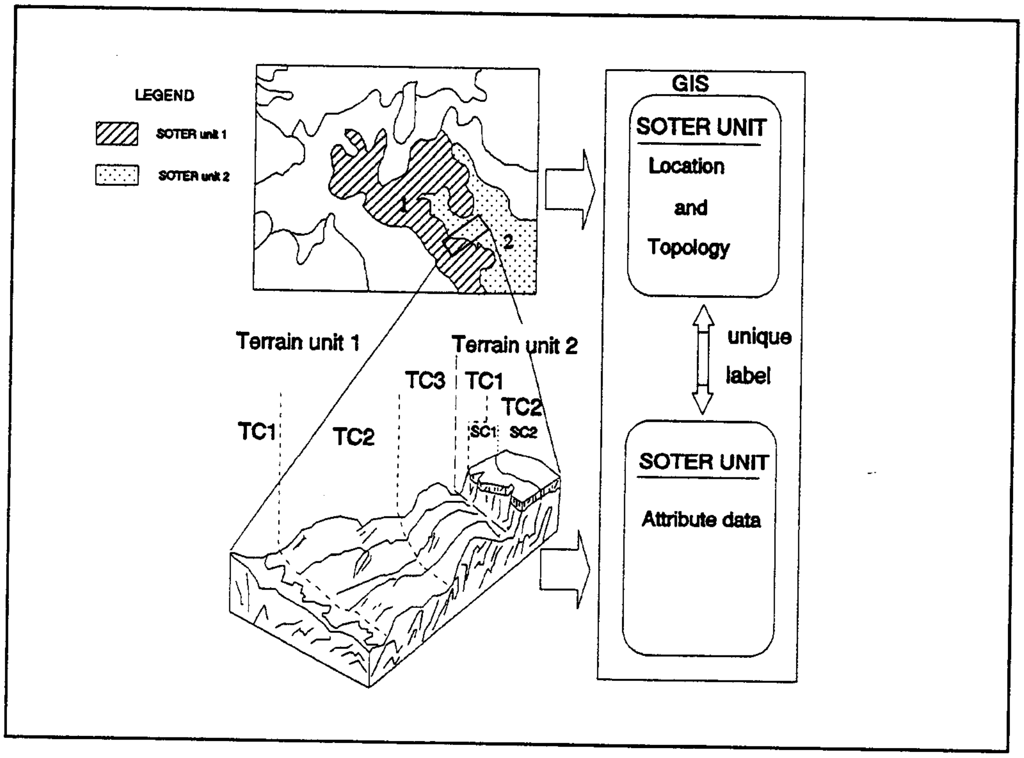

Figure 1. Schematic representation of SOTER units, as represented on a map with their legend, and their constituent 'terrain units', 'terrain components' (TC) and 'soil components' (SC) as specified in the database.

Recently, an ad-hoc expert meeting on SOTER recommended quantifiable attributes be stored both as single values and classes with their limit values and variation. The 'single values' would refer to a representative profile, and the classes would be derived from a number of similar profiles (sensu FAO, 1988). This means that, in so far this is technically feasible at the considered scale of 1:1 M, the aspect of spatial and temporal variability in terrain and soil characteristics is given due consideration in the SOTER procedure. The SOTER methodology should be seen as the best possible compromise between the spatial 'limitations' imposed by a 1:1 M map scale and the amount of information that can be physically and meaningfully incorporated in the attribute data base.

Subdivisions at the level of the 'terrain component' and 'soil component' cannot be visualized on a map at the scale of 1:1 M (Figure 1). The corresponding key attributes, however, can readily be incorporated in a relational database management system. This implies a clear gain in 'resolution' as compared with 'traditional' methods of small scale soil cartography (FAO-Unesco, 1971-1981). Additionally, the SOTER approach allows to update and refine the present knowledge on the spatial distribution and attributes of world soils using uniform procedures.

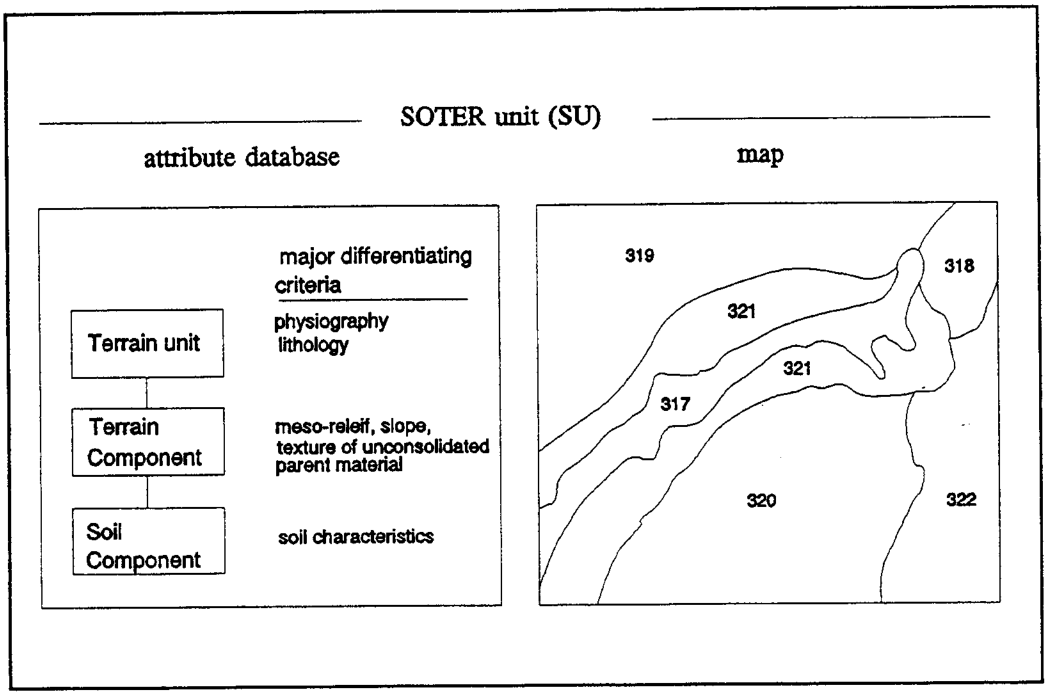

Figure 2. Relationship between a mapped SOTER unit and its constituents in the database (i.e., terrain unit, terrain component and soil component).

Proposed attribute data for a 1:1 M SOTER-shell

Worldwide coverage by SOTER at 1:1 M scale, using the full complement of attribute data specified in the procedures manual (Van Engelen and Pulles, 1991), will require from 10 to 20 years to be completed. Meanwhile, at the global level, there remains an urgent need for generating rapid, accurate and reliable information on a multitude of soil-related environmental threats such as an assessment of the status of human-induced soil degradation, and the role of soils in the 'greenhouse effect'. This consideration has prompted ISRIC to propose that 'SOTER-shells', which only specify the readily available attributes considered in the procedures manual, should be implemented first on a (sub)continent basis. The soil and terrain attributes proposed for inclusion in a SOTER-shell are listed in Table 1. All the input data refer to actual observations; no inferred values are accepted in a SOTER-shell to ensure the integrity of the database. These measured values can be used to derive pedotransfer functions. Collection, processing and storing of the full complement of attribute data, as originally specified by Van Engelen and Pulles (1991), is now seen as a long term objective to be performed at the national or regional level under the supervision of a central coordinating centre.

Table 1. Soil and terrain attribute data proposed for inclusion in the 1:1 M SOTER-shells (Entry of all data is mandatory, unless specified as (O)ptional).

<u>TERRAIN UNIT</u>
- SOTER unit ID
- year of compilation
- regional landform
- relief intensity
- general lithology

<u>TERRAIN COMPONENT</u>
- SOTER unit ID
- terrain component number
- proportion of SOTER unit
- terrain component data ID

<u>TERRAIN COMPONENT DATA</u>
- terrain component data ID
- slope gradient
- texture of unconsolidated parent material
- surface rockiness
- surface stoniness

<u>SOIL COMPONENT</u>
- SOTER unit ID
- terrain component number
- soil component number
- proportion of SU
- profile ID
- classification (FAO, 1988)

<u>PROFILE</u>
- profile ID (unique in SOTER)
- local reference number of representative profile
- latitude, location
- longitude, location
- laboratory ID

<u>Profile (continued)</u>
- date of sampling
- micro-relief
- internal drainage
- soil development/classification

<u>HORIZON</u>
- profile ID
- horizon number
- upper depth
- lower depth
- structure form
- structure size
- total carbon content
- total nitrogen content
- CEC soil (pH7 in NH_4OAc)
- exchangeable Ca^{++} (O)
- exchangeable Mg^{++} (O)
- exchangeable K^{+} (O)
- exchangeable Na^{+} (O)
- exchangeable H^{+} (O)
- exchangeable Al^{+++} (O)
- $pH\text{-}H_2O$
- coarse fragments (volume %)
- texture class (USDA)
- % clay
- % silt
- % sand
- Soil moist. at field capacity (O)
- Soil moist. at wilting point (O)
- bulk density (O)
- $CaCO_3$ content
- diagnostic horizon
- diagnostic property

Hierarchical structure of SOTER

The hierarchical structure of the files in the SOTER data base is shown in Figure 3. The SOTER attribute files are compatible with widely used commercial database management systems such as dBASE, INFO and ORACLE. Different Geographical Information Systems, ranging from relatively simple systems such as IDRISI to increasingly advanced systems such as ILWIS and ARC/INFO, have been linked with the databases of three pilot areas, thereby demonstrating the versatility of SOTER (ISRIC, 1990). In February 1992, at the end of a joint meeting in Nairobi, FAO, ISRIC, ISSS and UNEP, mutually agreed to endorse and adopt the principles of the SOTER methodology, with minor revisions, reflecting the international recognition of soil scientists and policy makers of the developed methodology.

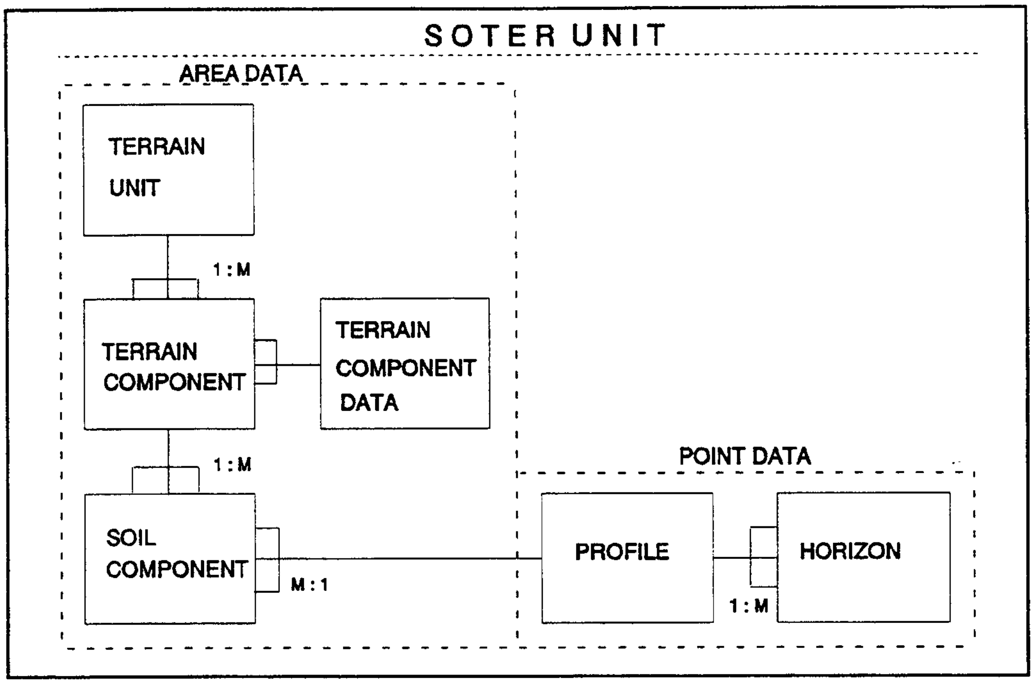

Figure 3. Schematic representation of a SOTER unit, and structure of the attribute database with its area data and point data (1:M stands for one to many relations, and M:1 for many to one relation; see Table 1 for listing of attributes of SOTER-shells).

CONCLUSIONS

There is a widespread recognition for the need for coordinated action on soil protection at the international level (UNEP, 1982; Barth and L'Hermite, 1987; Council of Europe, 1990; Oldeman *et al.*, 1991). Although most European countries are acutely aware of the need for, or are in the process of establishing computerized national resource data bases of one kind or another, attempts to set up a system which will specifically support 'soil vulnerability mapping' are still quite rare. Implementation of a 1:1 M 'SOTER-shell' would improve upon the limited ability of European governments to access, combine and utilize all available data on agro-climatic conditions, geology, hydrology, land and water resources and land cover to assess the vulnerability of soils to chemical pollution. It is time planners fully realize the need for tested and operational environmental geographic information systems to study the possible consequences of a wide range of processes of global change. The SOTER-shells would provide the essential minimum soil data for such analyses. The recent endorsement of the SOTER procedures for small scale digital map and database compilation by the Food and Agricultural Organization (FAO) and the United Nations Environment Programme (UNEP) shows the applicability and usefulness of the SOTER methodology.

The soil database and derived cartographic output can serve as the basis for identifying problem areas for inclusion in more detailed follow-up studies of higher resolution (1:1 M to 1:250,000) which would be run in succession of the proposed, initial Europe-wide soil vulnerability mapping programme (publication scale of 1:5 M). Many countries of Europe which participate in the Chemical Time Bombs project, and particularly those of the Balkan and Central sections, have already expressed their interest for implementing '1:1 M SOTER-shells' in the context of regional soil pollution studies in the framework of the proposed EUSOPOL project. A SOTER-shell for Europe would provide critical input for independent projects on mapping of 'critical loads' (Sverdrup *et al.*, 1990; De Vries and Kros, 1991 p. 42), the sustainable use of groundwater resources (RIVM-RIZA, 1991 p. 73) and modelling of emissions of greenhouse gases from soils (Bouwman, 1990 p. 13). Results of such studies in turn would provide policy makers with a better scientific basis for selecting abatement scenarios for a remedying suite of environmental problems.

REFERENCES

Alloway, B.J. (ed.), 1990. *Heavy metals in soils*. Blackie, Glasgow and John Wiley and Sons, Inc., New York.

Arnold, R.W., I. Szabolcs and V.O. Targulian, 1990. *Global soil change*. Report of an IIASA-ISSS-UNEP task force on the role of soil in global change. International Institute for Applied Systems Analysis, Laxenburg.

Barth, H. and P. L'Hermite (eds), 1987. *Scientific basis for soil protection in the European Community*. Elsevier Applied Science, London and New York.

Batjes, N.H. (ed.), 1991. *Mapping of soil and terrain vulnerability to specified chemical compounds in Europe at a scale of 1:5 M. Report of working group discussions* (Wageningen, 20-23 March 1991). International Soil Reference and Information Centre, Wageningen.

Batjes, N.H. and E.M. Bridges (eds), 1991. *Mapping of soil and terrain vulnerability to specified chemical compounds in Europe at a scale of 1:5 M*. Proceedings of an International Workshop organised in the framework of the Chemical Time Bomb Projects of the Netherlands Ministry of Housing, Physical Planning and Environment and the International Institute for Applied Systems Analysis (Wageningen, 20-23 March 1991). International Soil Reference and Information Centre, Wageningen.

Bliss, N.B., 1990. 'A hierarchy of soil databases for calibrating models of global climate change', pp. 523-529 *in* A.F. Bouwman (ed.) *Soils and the greenhouse effect*, John Wiley and Sons, Chichester.

Blum, W.E.H., 1990. *Soil pollution by heavy metals: Causes, processes, impacts and need for future action*. Sixth European Ministerial Conference on the Environment (Brussels, 11-12 October 1990). Council of Europe, Men 6 (90) 4, Strasbourg.

Blume, H.-P. and G. Brümmer, 1987a. 'Predicting the behaviour of heavy metals in soils using simple field methods' (in German). *Mitteilungen Deutsche Bodenkundliche Gesellschaft* **53**, 111-117.

Blume, H.-P. and G. Brümmer, 1987b. 'Predicting the behaviour of pesticides in soils with simple field methods' (in German). *Landwirtsch. Forsch.* 40, 41-50.

Bouwman, A.F. (ed.), 1990. *Soils and the greenhouse effect*, John Wiley and Sons, Chichester.

Brady, N.C., 1984. *The nature and properties of soils (Ninth edition)*, MacMillan Publishing Company, New York.

Briggs, G.G., 1990. 'Predicting the behaviour of pesticides in soil from their physical and chemical properties'. *Phil. Trans. R. Soc. Lond.* **B239**, 375-382.

Brouwer, F.M., A.J. Thomas and M.J. Chadwick (eds), 1991. *Land use changes in Europe: Processes of change, environmental transformations and future patterns*. GeoJournal Library Volume 18, Kluwer Academic Publishers, Dordrecht.

Council of Europe, 1990. *European Conservation Strategy (Draft Recommendation)*. Sixth European Ministerial Conference on the Environment (Brussels, 11-12 October 1990). MEN 6 (90) 5, Strasbourg.

Csikós, I. (ed.), 1991. *Report of the international workshop on long-term environmental risks for soils, sediments and groundwater in the Danube Catchment area* (Budapest, 13-15 December 1990). Foundation for Ecodevelopment 'Mondiaal Alternatief', Hoofdorp.

Desaules, A., 1991. 'The soil vulnerability mapping project for Europe (SOVEUR): methodological considerations with reference to conditions in Switzerland', pp. 23-28 *in* N.H. Batjes and E.M. Bridges (eds) *Mapping of soil and terrain vulnerability to specified chemical compounds in Europe at a scale of 1:5 M*, International Soil Reference and Information Centre, Wageningen.

De Vries, W. and J. Kros, 1991. *Assessment of critical loads and the impact of deposition scenarios by steady state and dynamic soil acidification models*. Report 36, Winand Staring Center, Wageningen.

Duchaufour, P., 1982. *Pedology: Pedogenesis and classification* (translated by T.R. Parton). George Allen and Unwin, Boston.

FAO, 1988. *Soil map of the world* (Revised legend). World Soil Resources Report No. 60, FAO, Rome.

FAO-Unesco, 1974-1981. *Soil Map of the World, 1:5,000,000*. Vols. 1-10, Unesco, Paris.

Fitzpatrick, E.A., 1983. *Soils: Their formation, classification and distribution*. Longman, London.

Glazovskaya, M.A., 1991. *Methodological guidelines for forecasting the geochemical susceptibility of soil to technogenic pollution*. Technical Paper No. 22, International Soil Reference and Information Centre, Wageningen.

Glazovskaya, M.A. and V.M. Friedland, 1982. *Soil Map of the World* (1:15 M). GUGK, Moscow.

Halen, H., R. Van Bladel and P. Cloos, 1990. 'pH-dependence of copper, zinc and cadmium adsorption by some soils and clay minerals' (in French). *Pédologie* XLI, 47-68.

ISRIC, 1990. *Annual report*. International Soil Reference and Information Centre, Wageningen. p. 39-45.

ISSS, 1986a. *Proceedings of an international workshop on the structure of a digital Soil Resource Map annex Data Base* (20-24 January 1986, ISRIC, Wageningen). Edited by M.F. Baumgardner and L.R.Oldeman, SOTER Report No. 1, International Society of Soil Science, Wageningen.

ISSS, 1986b. *Project proposal 'World Soils and Terrain Digital Database at a scale of 1:1 M (SOTER)'*. Edited by M.F. Baumgardner, International Society of Soil Science, Wageningen.

Klijn, F., 1991. 'Environmental susceptibility to chemicals: from processes to patterns, with special reference to mapping characteristics and spatial scales', pp. 9-22 *in* N.H. Batjes and E.M. Bridges (eds) *Mapping of soil and terrain vulnerability to specified chemical compounds in Europe at a scale of 1:5 M*. International Soil Reference and Information Centre, Wageningen.

Konsten, C.J.M. (ed.), 1991. *Report of the international workshop on delayed environmental effects of chemical pollution with focus on the Nordic countries* (14-15 September 1991, Uppsala, Sweden). Foundation for Ecodevelopment 'Mondiaal Alternatief', Hoofdorp, the Netherlands.

Matthews, E., 1990. 'Global databases for evaluating trace gas sources and sinks', pp. 311-325 *in* Bouwman A.F. (ed.) *Soils and the greenhouse effect*, John Wiley and Sons, Chichester.

Oldeman, L.R. and W.G. Sombroek, 1990. 'Use of the SOTER database to model global change'. *Transactions 14th International Congress of Soil Science, Kyoto* V, 136-141.

Oldeman, L.R., R.T.A. Hakkeling, and W.G. Sombroek, 1991. *World map of the status of human-induced soil degradation: An explanatory note (Second revised edition)*. ISRIC-UNEP, Wageningen.

RIVM-RIZA, 1991. *Sustainable use of groundwater: Problems and threats in the European Communities.* Report No. 600025001, National Institute of Public Health and Environmental Protection (RIVM) and Institute for Inland Water Management and Waste Water Treatment (RIZA), Bilthoven.

Smidt, G.R.B. (ed.), 1990. *Report of a European workshop on Chemical Time Bombs* (De Bilt, 21-23 June 1990). Foundation for Ecodevelopment 'Mondiaal Alternatief', Hoofdorp.

Smith, M.A., 1985. 'Background', pp. 1-11 *in* M.A. Smith (ed.) *Contaminated land: Reclamation and treatment*, NATO, Challenges of modern society Volume 8, Plenum Press, New York.

Sombroek, W.G., 1985. *Establishment of an International Soil and Land Resources Information Base*. Discussion paper for the ISSS Working Group on Digital Mapping of Global Soil Resources. ISRIC, Wageningen.

Sombroek, W.G., 1990. 'Geographical quantification of soils and changes in their properties', pp. 225-244 *in* A.F. Bouwman (ed.) *Soils and the greenhouse effect*, John Wiley and Sons, Chichester.

Stigliani, W.M., 1988. 'Changes in valued 'capacities' of soils and sediments as indicators of non-linear and time-delayed environmental effects'. *Environmental Monitoring and Assessment* 10, 245-307.

Stigliani, W.M. (ed.), 1991. *Chemical time bombs: definition, concepts and examples*. Executive Report 16, International Institute for Applied Systems Analysis, Laxenburg.

Sverdrup, H., W. de Vries and A. Henriksen, 1990. *Mapping critical loads: A guidance to the criteria, calculations, data collection and mapping of critical loads*. Miljørapport 1990:14, Nordic Council of Ministers, Copenhagen.

Tavernier, R. (ed.). *Soil map of the European Communities 1:1 M*. Directorate General for Agriculture, Coordination of Agricultural Research. Office for Official Publications of the EC, Luxembourg.

UNEP, 1982. *A world soils policy.* United Nations Environment Programme, Nairobi.

USDA, 1975. *Soil Taxonomy: A basic system of soil classification for making and interpreting soil surveys.* Agric. handbook 436, Soil Conservation Service, US. Dept. of Agriculture, Washington D.C.

USDA-SCS, 1972. *Soils of the world: Distribution of orders and principal suborders (1:50 M).* Soil Geography Unit, Soil Conservation Service, Hyattsville.

Van Engelen, V.W.P. and J.H.M. Pulles, 1991. *The SOTER Manual: Procedures for small scale digital map and database compilation of soil and terrain conditions.* Working Paper and Preprint 91/3, International Soil Reference and Information Centre, Wageningen.