

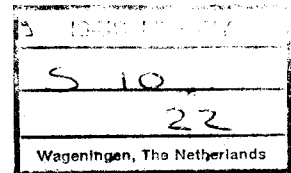
**METHODOLOGICAL GUIDELINES  
FOR FORECASTING THE GEOCHEMICAL SUSCEPTIBILITY  
OF SOILS TO TECHNOGENIC POLLUTION**

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OF SOILS TO TECHNOGENIC POLLUTION**

by  
**M.A.GLAZOVSKAYA<sup>1</sup>**

(1990)

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and Soil Geography**

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<sup>1</sup> This document was edited by N.H. Batjes using the draft English translation of the Russian text by M.I. Gerasimova. It is hoped that the professional aspects and the views of the author and translator respectively have not been altered in the present document which is a "condensed" version of the original translation.



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**CIP-GEGEVENS KONINKLIJKE BIBLIOTHEEK, DEN HAAG**

**Glazovskaya, M.A.**

**Methodological guidelines for forecasting the geochemical susceptibility of soils to technogenic pollution / by M.A. Glazovskaya ; [ed. by N.H. Batjes ; transl. from Russian by M.I. Gerasimova]. - Wageningen; International Soil Reference and Information Centre. - Ill. - (Technical Paper / International Soil Reference and Information Centre, ISSN 0923-3792 ; 22)**

**Met lit. opg.**

**ISBN 90-6672-045-X**

**Trefw.: bodemkunde**

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# 1. ELEMENTAL COMPOSITION OF GLOBAL TECHNOGENIC SUBSTANCE FLOWS AND MODULES OF TECHNOGENIC PRESSURE

## 1.1 Technogenesis, main concepts and criteria

Technogenesis is defined as an entity of geochemical and geophysical processes related to human activities that alter the geochemistry of the environment. As a geochemical phenomenon it includes:

1. Extraction of chemical elements from the environment.
2. Regrouping of elements, including the transformation of the chemical composition of compounds.
3. Dispersion of pollutants, involved in technogenesis, into the environment.

The latter process includes, for instance, the release of industrial and urban pollutants into the atmosphere, hydrosphere and pedosphere. Technogenic contaminants can be dispersed into the environment by accidental and incidental processes. Examples of the latter are the routine application of mineral fertilizers, composts, artificial structure stabilizers and pesticides in agriculture. In addition to having favourable effects on agricultural production, these compounds may disrupt the natural functions of soil systems and interfere with the trophic chains. The negative consequences of technogenesis can be described in terms of the degree of contamination or pollution of soils, water bodies and the atmosphere.

Calculations of the amounts of chemical elements involved annually in technogenic fluxes revealed an increase in elements with low natural *clarks* (element abundance; see Clarke (1924)). The natural ratios between pairs of elements have changed and, as a consequence, the geochemical environment is becoming less "comfortable" for biota.

Perel'man (1975) introduced the concept of "technophylity of an element" as a parameter for the technogenic utilization of this element. The rate of technophylity of an element is defined as the ratio of the annual output of the element and its *clark* in the lithosphere.

It is often difficult to calculate the "technophylity index". Generally, little is known about the total amounts of elements involved in technogenesis alongside the main mineral resources. Moreover, the lithosphere is not the sole source of chemical elements for technogenesis. Other sources are the atmosphere (e.g. as a basis for producing nitrogen fertilizers) and the hydrosphere (e.g. the extraction of salts from seas, oceans and lakes). Therefore, it seems reasonable to compare the amounts of chemical elements involved in technogenesis with their *clarks* in the biosphere.

Glazovskiy (1976 and 1982) proposed five indices to calculate the degree of "technogenic utilization" of elements. These indices are described in the following paragraphs:

- 1) Coefficient of special technogenic utilization or "special technogeneity" ( $T_1$ ):

$$T_1 = \frac{M_1 + F_1}{N_n}$$

with:

$M_1$  the amount of the element (tons) mobilized annually (e.g. from an ore deposit) to extract the element or its derivatives.

$F_1$  the amount of the element (tons) extracted annually from natural flows (e.g. natural waters) through technogenesis to obtain the specified element.

$N_n$  the *clark* of the element in the biosphere.

- 2) Coefficient of total technogenic utilization of the element or "total technogeneity" ( $T_2$ ):

$$T_2 = \frac{M_1 + M_2 + F_1 + F_2}{N_n}$$

with  $M_2$  and  $F_2$  the quantities of the specified elements involved as by-products in the technogenic migration of the immobile state and natural flows, respectively.

The coefficients of special technogeneity and total technogeneity of selected elements are presented in Table 1. They can be used to determine the respective contributions of individual elements to transformations of the geochemical status of the biosphere. Elements with a high total technogeneity are especially active in these processes. Many of these elements are waste-products of the mining industry and as such get dispersed quickly. They include elements with low *clarks* in the biosphere and high coefficients of total technogeneity; these elements belong to the most dangerous environmental pollutants.

- 3) Coefficient of "technogenic rational utilization completeness" or technogenic recovery (R). This coefficient is defined as the ratio of the special technogeneity ( $T_1$ ) and total technogeneity ( $T_2$ ). It is a measure for the amount of an element that is purposefully mined as compared to the total amount of the element involved in technogenesis.

$$R = \frac{(M_1 + F_1) \times 100\%}{M_1 + M_2 + F_1 + F_2}$$

A low R-coefficient is indicative for a high dispersion of polluting elements into the environment.

The comparison of the coefficients of total technogeneity (Table 1) and technogenic recovery rates (Table 2) shows that Ge, Be, U, Se, As, N and S are the most dangerous environmental pollutants. The R-coefficients of these elements range from  $10^8$  to  $10^{10}$ , whereas their coefficients of technogenic recovery (R) are smaller than 20 per cent. B, Cd, Mo, F, Br and Co are also very dangerous environmental pollutants with their total technogeneity of  $10^7$  to  $10^9$  and R-coefficients of 20 to 50 per cent.

Table 1 Coefficients of special technogeneity and total technogeneity for selected elements (After Glazovskiy, 1982).

Order of the coefficients	Special technogeneity ( $T_1$ )	Total technogeneity ( $T_2$ )
$10^{11}$	-	Au
$10^{10}$	Au	Ni, Bi, U
$10^9$	Bi, Pb, Cu, Ag, W, Zr	Cd, W, Pb, Cu, Ag, J Zn, As, Se, Mo, Zr
$10^8$	Cl, Zn, Ba, Na, Mo, Sn, Cr Ca, N, Fe, P, As, U, S, Mn, J, Ni	Cl, Ba, S, Na, Cr, Sn Ca, P, Fe, Be, B, Ge, F, Ti, Ni
$10^7$	Se, Br, Hg, F, B, K, Co, Cs	Br, Mn, Hg, Co, V, Ga, F
$10^6$	U, Mg, Be, Al, Y, Ti	Mg, Li, Al, Ti
$10^5$	Tl	-
$10^4$	Sc	-
$10^3$	Ga	-

Table 2 Coefficients of technogenic rational utilization completeness (R) for selected elements (in %)

Element	R	Element	R	Element	R	Element	R
Cl	98	Hg	77	B,Co	31	Si	n
Na,Ag,Ba	91	Br	71	Bi	25	V	n
Li,Fe,Pb	88	P	55	K	22	J	n
Sn	87	Mn	54	S	20	Ge	0.8
Ni	86	Mo,F	45	N,As	17	Sc	0.4
Cr,Zn	83	W	43	U,Se	7.1	Ga	0.024
Cu	81	Cd	38	Be	2.1		

n stands for negligible

4) The mean module of technogenic pressure ( $P_x$ ) is defined as:

$$P_x = \frac{M_x}{S}$$

with:

$M_x$  the total amount of an element involved annually in technogenesis.

S the area of the region under study.

The mean module of technogenic pressure is a good measure for the technogenic migration of elements at a global level (Table 3). It can be used to compare the impact of technogenic chemicals in different regions of the world.

Table 3 Modules of technogenic pressure for selected groups of elements ( $\text{kg km}^{-2} \text{yr}^{-1}$ ; After Glasovskiy, 1982)

Technogenic pressure module (P)	Elements
500-1000	Na, Cl, Ca, Fe
200-500	S
100-200	N, K
50-100	Al
20-50	P
10-20	Ti, Mn
1-10	B, F, MG, Cu, Zn, Zr, Ba, Pb
0.1-1.0	V, Cr, Ni, As, Br, Sr, Mo, Cd, Sn, J, U
0.01-0.1	Be, Se, Co, Ga, Ge, Se, Bi
0.001-0.01	Li, Ag, W, Au, Hg, Tl
0.0001-0.001	Cs

5) Coefficient of biospherical concentration ( $C_{nx}$ ). This coefficient permits the comparison of the geochemical impact of various industrial products involved in technogenesis on the environment. One coefficient has to be calculated for each of the respective elements of these technogenic products ( $C_x$ ).

$$C_{nx} = \frac{C_x}{N_{nx}}$$

with:

$C_x$  the concentration of a particular element (x) in the product under study (e.g. coal, oil, mineral fertilizers)

$N_{nx}$  the *clark* of this element in the biosphere.



The geochemical or polluting effects of industrial products can adequately be estimated by adding up the coefficients of biospherical concentration ( $C_{nx}$ ) of their most technogenic elements:

$$\sum \frac{C_{nxi}}{C_{nxi}} = CN = \frac{C_{xi}}{N_{nxi}}$$

The CN coefficient of elements which have *clarks* smaller than  $10^{-3}$  is 1500 for coal, 20 for oil, 510 for natural gas, up to 1300 for mineral fertilizers, and 200 to 3000 for precipitates of sewage waters.

The coefficients of biospherical concentration in technogenic geochemical flows are a measure for the mean concentration of these elements in the accumulating media, viz. the atmosphere, hydrosphere and pedosphere. They are called respectively the atmo-technogenic (Ca), hydro-technogenic (Ch) and pedo-technogenic (Cs) coefficients of chemical element concentration.

## 1.2 Technogenic accumulation of micro-elements and modules of technogenic pressure on the world soil cover

Nriagu and Pacyna (1988) calculated the technogenic flux of heavy metals and other minor elements in the atmosphere, hydrosphere and pedosphere, thereby revealing the magnitude of these fluxes (Table 4). For most micro-elements the rate of technogenic accumulation exceeds the natural rate of atmospheric deposition. This is even true when the lowest estimates are considered for the technogenic fluxes. This is particularly apparent for lead, a waste product in car exhaust fumes. Large amounts of technogenic micro-elements - ranging from 10 to  $10^3$  thousands of tons annually - have accumulated in water bodies and soils over the years. Soils are more severely subjected to pollution by toxic micro-elements than the other accumulating media. The most active micro-elements are Cr, Cu, Mn and V. However, As, Cd and Hg may be added to this list when the highest possible estimates for the technogenic fluxes are considered.

Major sources of soil pollution are listed in Table 5. The main contaminants are residues of coal combustion and residues of agro-chemical wastes.

Table 4 Global technogenic inputs of selected micro-elements into the atmosphere, hydrosphere and pedosphere (1000 tons yr<sup>-1</sup>)

Sources	As	Cd	Cr	Cu	Hg	Mn
Atmosphere, technogenic	12-25.6	3.1-12.0	7.3-53.6	19.9-50.9	0.9-6.2	10.6-65.9
Atmosphere, natural	7.8	1.0	-	19	6	5-6
Water bodies, technogenic	12-70	2.1-17.0	45-239	35-90	0.3-8.8	109-414
Soils, technogenic	52-112	5.6-38.0	684-1309	541-1367	1.6-15	706-2633

Table 4 (cont.)

Sources	Mo	Ni	Pb	Sb	Se	V	Zn
Atmosphere, technogenic	0.8-5.7	24.1-87.1	288.7-376.0	1.5-5.5	1.8-5.8	30.1-141.9	70.2-193.5
Atmosphere, natural	1.8-21	33-194	97-180	3.9-33	10-72	2.1-21	77-375
Water bodies, technogenic	30-145	106-544	497-1113	4.7-47	6.0-76	43-222	689-2054
Soils, technogenic	87	325	806	40	18	182	1372

After: Nriagu and Pacyna (1988)

Table 5 Global technogenic pollution by micro-elements (Nriagu and Pacyna, 1988)

Sources	Total amount (10 <sup>6</sup> tons)	As	Cd	Cr	Cu	Hg	Mn	Mo	Ni	Pb	Sb	Se	V	Zn
Agricultural and food waste	1.5	3	1.5	47.5	20.5	0.75	85	19.5	25.5	14.2	4.5	3.7	12.5	81
Manure	0.2	3.3	0.7	25	47	0.1	95	14	19.5	11.6	0.4	0.9	5.5	235
Forest consumption and waste	1.1	1.6	1.1	10.1	22.7	1.1	61	1.6	12.5	7.4	2.7	1.6	5.5	39
Urban waste	4.4	0.4	4.2	19.3	26.5	0.13	24.5	2.3	6.1	40	0.76	0.33	0.3	59.5
Municipal sewage	2.0	0.12	0.28	6.2	12.4	0.45	7.7	0.2	13.5	5.75	0.12	0.07	0.75	37.5
Organic waste, incl. excreta	2.1	0.12	0.45	0.24	0.32	-	0.35	0.23	1.7	0.81	0.06	0.04	0.43	1.1
Hard waste, incl. scrap	38	0.11	0.04	1.52	4.37	0.04	2.65	0.08	1.67	7.5	0.08	0.09	0.12	10.9
Coal dust and slag	372	21.8	7.2	305	372	2.6	1076.5	44.5	167.5	143.5	12.3	32.5	33.5	298
Fertilizers	16.6	0.01	0.14	20.5	0.31	-	0.48	0.01	0.37	1.35	-	0.06	0.08	0.68
Peat (fertilizers and fuel)	37.5	0.27	0.55	0.11	1.07	0.01	11.6	0.45	17.6	1.5	0.25	0.2	0.9	1.8
Corrosion of metals, chemicals, and pesticides	-	38.5	1.19	457	559	0.68	300	18.8	19.2	292.5	2.4	0.5	1.7	466
Atmospheric fall-out	-	13.2	5.3	21.6	25	2.5	26.7	2.3	24	932	24.5	13.7	12.1	92
TOTAL	-	84	21.3	896.5	954.5	8.3	1670	87.5	325	805	25.8	39.5	181.5	1371.5

About 80 to 90 per cent of the technogenic arsenic and the major part of the technogenic mercury are added to soils with pesticides. Large amounts of selenium are applied to soils with cattle and poultry manure as Se is a widely used additive in fodder. Urban dumps and sludge waters are major sources of Cu, Pb, Hg and Zn as well as of Cd, S and V pollution in soils.

Assuming a regular pattern for the technogenic accumulation of micro-elements in arable soils, Nriagu and Pacyna (1988) calculated that each hectare of arable land receives about 1 g of Cd and Sb, almost 50 g of Cu, Pb and Cr, and at least 65 g of Zn and Mn per annum. Consequently, concentrations of heavy metals in arable soils are already much higher than the contents of these same elements in the pristine analogues of these soils. This is true even without considering the additional pollution produced by industry and traffic.

The mean modules of technogenic pressure (P) decrease in the following sequence: Mn > Zn > Cu > Cr > Pb > V > Mo,As > Se > Cd > Hg (Table 6). The extremes are 11.6 kg km<sup>-2</sup> yr<sup>-1</sup> for Mn and 0.058 kg km<sup>-2</sup> yr<sup>-1</sup> for Hg, corresponding with an order two magnitude difference.

Table 6 Mean modules of technogenic pressure and pedotechnogenic concentration of selected micro-elements for the year 1988

Elements	Total accumulation in soils (10 <sup>3</sup> tons yr <sup>-1</sup> )	Modules of technogenic pressure (kg km <sup>-2</sup> yr <sup>-1</sup> )	Mean conc. in soils* (%)	Modules of pedotechnogenic concentration
As	84.0	0.58	5.10 <sup>-4</sup>	116
Cd	21.3	0.15	5.10 <sup>-5</sup>	3000
Cr	896.5	6.22	2.10 <sup>-2</sup>	311
Cu	954.5	6.33	2.10 <sup>-3</sup>	3315
Hg	8.3	0.058	1.10 <sup>-6</sup>	58.10 <sup>3</sup>
Mn	1670	11.60	8.5.10 <sup>-2</sup>	3.6
Mo	87.5	0.61	2.10 <sup>-4</sup>	3050
Ni	325.0	2.26	4.10 <sup>-3</sup>	565
Pb	805.0	5.59	1.10 <sup>-3</sup>	5590
Se	39.5	0.27	1.10 <sup>-6</sup>	27.10 <sup>4</sup>
V	181.5	1.25	1.10 <sup>-2</sup>	125
Zn	1371.5	9.52	5.10 <sup>-3</sup>	1904

\* After Vinogradov

Data about the technogenic pressure modules alone are not sufficient to estimate the risk of soil pollution. The latter can be assessed by comparing the modules of technogenic pressure with the *clarks* of the relevant elements in the accumulating media. The module of pedotechnogenic concentration (PC<sub>ex</sub>) is defined as the ratio of the technogenic pressure module of an element (P<sub>x</sub>) and its clark in soils (C<sub>x</sub>):

$$PC_{ex} = \frac{P_x}{C_x}$$

The modules of pedotechnogenic concentration permit an evaluation of the partial destructive effects of the constituents of technogenic flows upon the natural soil-geochemical background. The severity of these impacts may be expressed either as absolute figures or as relative concentrations of elements.

Micro-elements can be ordered according to their modules of pedotechnogenic concentration to provide a measure for their polluting hazard and destructive geochemical activity:

$$\frac{\text{Elements}}{\text{PCs values}} \quad \frac{\text{Hg>Se}}{n \cdot 10^6} > \frac{\text{Pb,Cu,Mo,Cd,Zn}}{n \cdot 10^4} > \frac{\text{Ni,Cr}}{n \cdot 10^3} > \frac{\text{V,As}}{1.2 \cdot 10^2} > \frac{\text{Mn}}{3.6}$$

Hg and Se occupy the first place in this sequence. They have very low *clarks* in soils ( $10^5 - 10^6$ ) and medium modules of technogenic pressure (in the order of  $\text{g km}^{-2} \text{yr}^{-1}$ ). Nevertheless, their relative concentration in technogenic flows is very high (PCs of  $10^6$ ). Cu, Mo, Cd and Zn have PCs of  $10^4$ , while Ni and Cr have PCs of  $10^3$ , and V and S have PCs of  $10^2$ . Mn is the last element in the above sequence, even though it has the highest module of technogenic pressure, because of the relatively high mean concentration of Mn in soils ( $8.5 \cdot 10^{-2} \%$ ). The hazard of Mn polluting soils is therefore rather low at the current levels of technogeneity.

In addition to being altered by global technogenic impacts, soil conditions are being modified by micro-elements dispersed at the regional and local levels. The effects of local air-borne contaminants can be observed within a radius of several tens of kilometres from the source of emission. These contaminants will be deposited on the soil and plant cover, thereby gradually altering the health-status and floral composition of the vegetation. In addition, the concentration of heavy metals and other toxic micro-elements will increase in the soils.

The effects of air-borne pollutants on the geochemical composition of soils are most apparent in the root zone. In these superficial layers the contents of heavy metals are usually 1 to 2 orders of magnitude higher than the normal geochemical background. The reader is referred to the work of Budun (1975), Zvonariev *et al.* (1978), Arzhanova *et al.* (1979), Zhigolovskaya *et al.* (1982), Obukhovskaya *et al.* (1983), Sayet and Smirnova (1983), Sorokina (1983), Lukashev and Simutkina (1984) and Yelpat'ievskiy and Arzhanova (1985) for additional information on this subject. Local anomalies, created by industry and traffic, get superimposed over the "agricultural" technogenic background proper to the region. The spatial pattern of the agricultural background is determined by the land use and land use practices in the specified region.

Data on the regional modules of technogenic pressure, the pedotechnogenic concentration of elements with respect to their *clarks*, and the mean background concentrations of micro-elements in soils are needed to forecast the regional risk of soil pollution.

### 1.3 Atmospheric emissions of selected gases and their acidifying derivatives

During the last decades soil fertility has decreased in many industrialised countries. This decrease has been associated with the widespread application of physiologically acid fertilizers, emissions of potentially acidifying gases, and acid rain. The subject of man-induced soil acidification has been extensively researched (e.g. Acidification today and tomorrow, 1982; Acid rains, 1983; FAO, 1983; Riaboshapko, 1983; Izrael, 1984; Rovinskiy and Yegorov, 1984; Monitoring of long-run transfer..., 1987; Roake and Herera, 1988).

Sulphur, nitrogen and carbon oxides, being water-soluble, can produce acid rain. Table 7 presents data about the volumes of sulphides, nitrogen oxides, carbon oxide, hydrocarbons and hard particles emitted in selected parts of the globe, revealing marked differences in the degree of atmospheric pollution at the regional and international levels. An order 2 to 3 magnitude difference is reported for emissions in the German Federal Republic as compared to those for Finland and Portugal. With respect to continents, total atmospheric emissions are highest in Europe and North America, and lowest in South America. Soils will be most prone to technogenic acidification in regions receiving high inputs of acid deposition.

Table 7 Emissions of selected pollutants into the atmosphere ( $10^6$  Mton yr<sup>-1</sup>)

Continents/ countries	Sulphides	Nitrogen oxides	Carbon oxide	Hydrocarbons	Hard particles
German Federal Republic	8.2	2.4	4.7	0.6	1.6
Finland	0.3	0.1	0.2	0.02	0.2
Portugal	0.07	0.03	0.1	0.02	0.06
Europe (total)	21.6	7.7	21.4	2.6	6.7
N. America	18.1	11.3	77.3	9.0	6.0
Asia	7.5	3.3	8.5	3.3	4.3
S. America	0.3	0.7	2.5	0.3	0.4
Oceania and Australia	2.1	0.7	2.4	0.3	0.32
World (total)	110.4	369.5	1423.8	185.6	256.8

## **2. SUSCEPTIBILITY OF SOILS TO TECHNOGENIC POLLUTION BY CHEMICAL ELEMENTS**

### **2.1 Concepts and general criteria**

Soils are open-ended bio-mineral systems forming an integral part of a more complex natural ecosystem or "biogeocoenosis" (see Fortescue, 1980). They are connected with the atmosphere and hydrosphere through substance and energy fluxes, and form a "harbour" for plants and biota. This is why the "rate of soil resistance to chemical pollution" or susceptibility of soils to chemical pollution can be derived from those soil properties - the so-called "landscape geochemical" framework - that promote/hinder the development of a particular type of soil degradation (Glazovskaya, 1976). A good understanding of geochemical processes is needed to assess the susceptibility of soils to specific pollutants.

Many transport processes in landscapes are regulated by soil properties, such as the buffering capacity. Fluxes of alkaline pollutants may get neutralized in acid soils, whereas acid fluxes may be neutralized in soils containing high contents of Ca-carbonates or Na-carbonates. This means that soils act as selective filters for specific chemical compounds so that they can be compared with chromatographic columns. Unfortunately, it is also the filtering capacity of soils that renders them susceptible to chemical pollution.

Generally, pollutants accumulate first in the organic topsoil. Since this is the section of the soil where organisms are the most active, these pollutants are potentially accessible to these organisms (selective uptake mechanism). Therefore, the role of living organisms must be taken into account when selecting criteria to assess the risk of soil pollution (Vernadiskiy, 1980).

Pollutants will interfere with the natural functions of biomineral systems as soon as they:

1. Disrupt the gaseous, concentrational and redox functions of living organisms in the soil system. These are the very functions which regulate the self "purifying/regenerating" processes in soils, such as the chemical and biological breakdown of technogenic substances.
2. Disrupt the trophic/food chains.
3. Modify the productivity of the system.
4. Alter the "information capacity" or genetic fund of the system.

Upon contamination, the original properties of a soil may change to the extent of getting irreversibly damaged. The quantity and quality of the biomass are good indicators for the normal functioning or stability of soils within complicated ecosystems.

Soil susceptibility should be assessed for defined categories of pollutants, specifying the pollution scenario. A wide diversity of pollutants is added to soils through technogenesis. These compounds can be grouped according to their functional effects on soil properties, i.e. with respect to their pedo-chemically and bio-chemically active components.

Pedo-chemically active pollutants alter the overall geochemistry of the soil environment through their effects on soil reaction and redox conditions. Mineral acids, alkali substances, carbonates, physiologically-acid salts as well as gases, such as methane and hydrogen sulphide, are examples of pedo-chemically active pollutants.

Many elements, such as mercury, arsenic, selenium, lead, cadmium, chromium, nickel, beryllium, vanadium, strontium and barium, as well as radionuclides and "heavy molecular" hydrocarbons (e.g. defoliants, herbicides and pesticides) are bio-chemically active.

The susceptibility of soils to pollution can be derived from the soil properties and soil regimes which regulate the:

1. Physico-chemical and bio-geochemical processes in soils.
2. Bio-chemical degradation/transformation of technogenic compounds and their derivatives.
3. Immobilization/fixation of technogenic substances in compounds which are either available or non-available to plants.
4. Migration of soluble pollutants within and out of the solum.

## 2.2 Criteria for forecasting the susceptibility and response of soils to pollution by toxic micro-elements

### 2.2.1 Water-borne transport of micro-elements in soils and geochemical barriers

The chemical composition of technogenic fluxes varies with the pH and redox condition. Contaminants can form true or colloidal solutions or can be sorbed by solid particles. Smelter plants processing "non-ferrous" metals, for instance, produce often dust particles containing sulphides, sulphates, oxides, metals and arsenites. Evaporates of arsenic, antimony, cadmium and zinc do also occur in gaseous state in the atmosphere. Upon sorption by water droplets, these elements can be deposited on the plant and soil cover.

The chemical characteristics of technogenic elements change upon reaching and infiltrating the soil. The processes regulating the transformation, redistribution and accumulation of technogenic pollutants in a wide range of pristine and polluted soils have been studied by numerous researchers (e.g. Dobrovolskiy, 1980; Methodical recommendations ..., 1982; Razenkova *et al.*, 1984; Sadovnikova and Zyrin, 1985; Migration of pollutants ..., 1986; Glazovskaya and Kasimov, 1989).

The relationships between pH and redox conditions and the chemical speciation of heavy metals in soils, and the impact of these metals on soil properties and plant nutrition have been studied by Zyrin and Chebotareva (1979), Obukhov *et al.* (1980), Vorobieva *et al.* (1980), Bineyev *et al.* (1982), Pervukhina (1983) and Obukhov and Bab'ieva (1980). These topics are also discussed in the work on "Landscape geochemical fundamentals of environmental monitoring" by Glazovskaya and Kasimov (1989) and in the review on "trace elements in soils and plants" by Kabata-Pendias and Pendias (1986).

Yelpat'ievskiy and Arzhanova (1985) studied the effects of air-borne pollution in lysimeters situated in a "brown forest mountain soil" located in proximity of a smelting plant. Subsequent to their transport and deposition, the major part of the "emitted" heavy metals were retained in the uppermost soil horizons which functioned as "mechano-sedimentative" barriers. The fraction of water-soluble micro-elements that leached out of these upper horizons was shown to account for a greater fraction of the total amount of micro-elements than the atmospheric deposition. This points at a partial mobilization of the heavy metals in the upper horizon. In the soil under consideration, the concentration of water-soluble metals increased by 2.4 times for Cu, 2.1 times for Zn, 4.8 times for Cd, 3 times for Mn and 2.5 times for Fe.

Heavy metals, contained in free moisture, infiltrate into the soil as metal-organic compounds or as colloidal solutions. The respective quantities and ratios of metals recorded in the soil solution change considerably during the infiltration process (Table 8).

Table 8 Intensity and composition of techogenic input of heavy metals to the brown forest soils of Sikhote-Alin' mountains (Yelpat'ievskiy and Arzhanova, 1985).

Medium	Elements (mg m <sup>-2</sup> yr <sup>-1</sup> ) and types of migration											
	Cu		Zn		Pb		Cd		Fe		Mn	
	1*	2	1	2	1	2	1	2	1	2	1	2
Flow from the atmosphere	5.1	8.5	32.4	77.4	87.4	383.4	0.86	1.29	12.9	373.1	9.1	12.3
Soil run off at:												
2 cm	12.5	0.5	69.3	2.3	49.2	2.3	4.3	0.06	32.6	43.3	27.2	0.4
40 cm	6.6	0.2	15.9	1.7	8.1	0.6	0.94	0.02	14.0	58.4	12.3	0.9
90 cm	2.4	0.05	4.4	0.17	2.7	0.17	0.29	0.006	4.9	4.9	4.7	0.05

\*: 1: soluble forms; 2: insoluble forms

More than 55 per cent of the water-soluble lead, deposited with the precipitation, was retained in the 0 to 2 cm layer, and more than 90 per cent of it in the humus profile (0 - 40 cm). The percentages of heavy metals mobilized in the 0 to 2 cm layer were 47.2% for Cu, 77% for Zn, 85.4 for Pb, 77.2% for Cd, 56.3% for Fe and 55% for Mn. Metals further accumulated in the illuvial horizons (40-90 cm). Below a depth of 90 cm the following amounts of metals were removed from the soils: 19.2% for Cu, 6.3% for Zn, 5.5% for Pb, 6.7% for Cd, 15% for Fe and 17.3% for Mn. The most mobile elements in this experiment were Mn, Fe and Cu, while Pb was the least mobile.

The solubility of trace metals varies with the pH, redox potential and chemical composition of the soil solution. On the basis of this knowledge, Perel'man proposed a scheme, consisting of main categories of geochemical barriers, to describe the migration of chemical elements in landscapes. This scheme, which was revised by Glazovskaya (1976; see Table 9), shows that the solubility and mobility of trace metals changes with the pH and redox regime of the soil. This means that genetic soil horizons can form selective barriers for specific contaminants contained in technogenic fluxes. Consequently, soils can be viewed as matrices of genetic horizons. Each column of these matrices corresponds with a particular type of geochemical barrier.

The work of Perel'man (1975) on geochemical barriers is widely used in geochemical studies of landscapes. Perel'man distinguished three main categories of geochemical barriers:

1. Bio-geochemical barriers, in which a wide range of elements can be sorbed biologically.
2. Physico-chemical barriers (e.g. "oxidative", "gley reductive", "sulphidic reductive", "sulphate-calcareous", "alkaline-acid", "evaporate", "adsorptive" and "thermodynamic")
3. Mechanical barriers.

Perel'man (1972) mainly developed his scheme for the zone of hypergenesis. Geochemical barriers, however, frequently coincide with soil horizons, each of these horizons having their peculiar characteristics. Some additional criteria, considered useful to characterize geochemical processes in soils, were incorporated in Perel'man's scheme by the author.

When rain first reaches the surface of a soil it is saturated with oxygen, and the pH-values range from 2.5 to 8.5, depending on the amount and nature of the contaminants. The pH and redox potential of the "rain" will change upon infiltrating into the soil. If the initial soil pH is higher than the pH of the technogenic flux (e.g. acid rain falling on calcareous soils), some elements may precipitate in an alkaline barrier. However, if the soil is more acidic than the technogenic flux an "acid barrier" may be formed. The latter will selectively retain those elements that are poorly soluble under acidic conditions. Similarly, "gley", "hydrogen gley" and "hydrogen-sulphide" barriers will selectively retain those metals that are poorly mobile under anaerobic conditions.

The redox and pH conditions vary widely within and between soils. Nevertheless, certain redox and pH combinations can be associated with specific geochemical fields. Each of these fields will have its peculiar physico-chemical and thermodynamic barriers. The soil-geochemical barriers most commonly observed in soils are listed in Table 10.

Many genetic soil horizons form complex geochemical barriers. Superficial soil horizons with a high organic matter content primarily act as mechanical barriers for technogenic suspensions. In addition, they can function as "chemosorptive" organo-mineral barriers. In situations where there is a net upward water flow, "evaporative" barriers may occur simultaneously. Illuvial horizons (e.g. B, Bh, Bt, Bca) often function as "sorptive" (Cm) and "chemo-sedimentative" barriers, e.g. "calcareous", "sulphitic" and "hydroxidic" barriers. Illuvial Bt-horizons, commonly form "mechano-sedimentative" (incolmatative) barriers within the solum. Similar barriers are observed in horizons with permafrost and plinthite, as well as in impermeable parent rocks.

Micro-elements which are poorly mobile under reducing conditions often accumulate in gley horizons, functioning as "chemo-sedimentative" barriers. Alternatively, "evaporative" barriers are commonly observed in the uppermost soil horizons in arid and subarid regions. "Sedimentative" barriers may also be formed in these soils upon drying.



Table 9 Main classes for the migration of chemical elements in water in landscapes (Modified after Perel'man (1972) by Glazovskaya)

Soil reaction	Typomorphic		Redox conditions	
	water migrants	air migrants	O <sub>2</sub> -oxidative medium	CO <sub>2</sub> , partially CH <sub>4</sub> -reductive medium
Strongly acid	H <sup>+</sup> , SO <sub>4</sub> <sup>2-</sup> , Al <sup>3+</sup> , Fe <sup>3+</sup>		1. Sulphate (H <sup>+</sup> -SO <sub>4</sub> <sup>2-</sup> )	H <sub>2</sub> S - reductive hydrogen sulphide medium 2. Sulphate sulphidic (H <sub>2</sub> S - Fe <sup>2+</sup> )
Acid	H <sup>+</sup> - organic acids, HCO <sub>3</sub> <sup>-</sup> , Fe <sup>2+</sup> , Al <sup>3+</sup>		3. Organo-acid (H <sup>+</sup> -Ch <sup>+</sup> )	4. Organo-acid gley (H <sup>+</sup> -Ch <sup>+</sup> -Fe <sup>2+</sup> )
Weakly acid	H <sup>+</sup> , HCO <sub>3</sub> <sup>-</sup> , Fe <sup>2+</sup>		5. Acid (H <sup>+</sup> ) 7. Weakly acid transitional to Calcic (H <sup>+</sup> - Ca <sup>2+</sup> )	6. Acid gley (H <sup>+</sup> -Fe <sup>2+</sup> ) 8. Weakly acid gley (H <sup>+</sup> - Ca <sup>2+</sup> Fe <sup>2+</sup> )
Neutral and weakly alkaline	Ca <sup>2+</sup> , Fe <sup>2+</sup>		9. Calcic (Ca <sup>2+</sup> )	10. Calcic gley (Ca <sup>2+</sup> Fe <sup>2+</sup> )
Alkaline	Ca <sup>2+</sup> , Na <sup>+</sup> , Cl <sup>-</sup> , Na <sup>+</sup> , SO <sub>4</sub> <sup>2-</sup>		11. Calcic-sodic (Ca <sup>2+</sup> -Na <sup>+</sup> ) 13. Saline (Cl <sup>-</sup> , Na <sup>+</sup> , SO <sub>4</sub> <sup>2-</sup> )	12. Calcic-sodic gley (Ca <sup>2+</sup> - Na <sup>+</sup> - Fe <sup>2+</sup> ) 14. Saline gley (Na <sup>+</sup> - Cl <sup>-</sup> - Fe <sup>2+</sup> ) 15. Saline sulphidic (Na <sup>+</sup> -H <sub>2</sub> S)
Strongly alkaline	OH <sup>-</sup> , Na <sup>+</sup> , HCO <sub>3</sub> <sup>-</sup> , SiO <sub>2</sub>		16. Soda (Na <sup>+</sup> - OH <sup>-</sup> )	17. Soda gley (Na <sup>+</sup> - OH <sup>-</sup> - Fe <sup>2+</sup> ) 18. Soda sulphidic (Na - OH-H <sub>2</sub> S)

Table 10 Common combinations of geochemical barriers in soils

	A-O	A-G	A-S	N-O-E <sub>1</sub>	N-G-E <sub>1</sub>	N-O-E <sub>2</sub>	Al-O-E <sub>3</sub>	Al-S-E <sub>3</sub>
C <sub>3</sub> -M <sub>1</sub>		+						
C <sub>3</sub> -M <sub>2</sub>		+						
C <sub>3</sub> -M <sub>3</sub>	+							
C <sub>2</sub> -M <sub>1</sub>	+				+			
C <sub>2</sub> -M <sub>2</sub>	+			+		+		
C <sub>1</sub> -M <sub>1</sub>	+	+			+			
C <sub>1</sub> -M <sub>2</sub>	+	+				+	+	
C <sub>1</sub> -M <sub>3</sub>	+	+				+	+	
M <sub>1</sub>							+	
M <sub>2</sub>							+	
M <sub>3</sub>			+				+	+

Indices for soil-geochemical barriers:

- A = acid
- N = neutral and weakly alkaline
- Al = alkaline and strongly alkaline
- O = oxidative
- G = gley reductive
- S = hydrogen sulphide reductive
- E = evaporative (E<sub>1</sub> = seasonal weakly evaporative; E<sub>2</sub> = seasonally evaporative; E<sub>3</sub> = intensively evaporative)
- C = organic and organo-mineral sorptive and chemo-sorptive (C<sub>1</sub> = low capacity; C<sub>2</sub> = medium capacity; C<sub>3</sub> = high capacity)
- M = mineral-sorptive and chemo-sorptive (M<sub>1</sub> = low capacity; M<sub>2</sub> = medium capacity; M<sub>3</sub> = high capacity)

### 2.2.2 Soil properties determining the mobility of micro-elements and their risk of accumulation

The chemical composition of the polluting fluxes as well as the properties and regimes of the soils basically determine the form/speciation of micro-elements in a particular soil. The accumulation and mobility of micro-elements and their availability to plants varies widely between soils, irrespective of the modules of technogenic pressure and the pedotechnogenic concentration of the elements.

The following soil properties and regimes have been used to assess whether soils are prone to pollution by technogenic micro-elements:

1. pH and redox conditions
2. Occurrence of carbonates, Fe- and Al-hydroxides, as well as other inorganic substances capable of chemisorption.
3. Content and composition of organic substances, controlling the mobility and chemisorption of micro-elements.
4. Clay content and mineralogy (sorption properties).
5. Hydro-thermic regime of the soil.

The speciation, solubility and toxicity of many micro-elements in soils is pH and redox dependent. The latter conditions are easily changed by agricultural practices (e.g. liming, drainage) and upon the addition of technogenic compounds.

Scherbina (1972) reported five redox facies under "hypergenic" conditions namely, (1) bivalent iron, (2) bi-valent and tri-valent iron, (3) trivalent iron, (4) chromates and vanadates, and (5) tetravalent manganese oxides. The first three facies occur in a wide range of soils, while the fourth facies (Cr<sup>6+</sup> - V<sup>5+</sup>) is mainly observed in freely drained, alkaline desert soils with a low humus content (Perel'man, 1972; Kaurichev and Orlov, 1982). The facies of highest Mn oxidation has not been found in soils.

Table 11 Mobility of selected micro-elements in soils with different water migration classes\*

Water migration class	Mobility of micro-elements		
	Poorly mobile	Moderately mobile	Easily mobile
Organo-acid ( $H^+ - Ch^+$ )	Mo	Se/Co/Ni, Cr	Hg/Cd, Cu, Zn, Pb/As, V
Acid ( $H^+$ )	Mo	Se/Pb/Co/Ni, Cr, V, As	Hg/Cd, Cu, Zn
Organo-acid and acid gley ( $H^+ - Ch^+Fe^{2+}$ )	Se/Mo/As, V	Hg/Cd, Cu, Zn, Pb/Ni, Cr, Co	-
Weakly acid ( $H^+ - Ca^{2+}$ )	Pb	Hg/Cd, Cu, Co, Zn/Ni, Cr, V	Se/As
Weakly acid gley ( $H^+ - Ca^{2+}Fe^{2+}$ )	Pb, Mo	Se, Hg/Cd, Cu, Zn, Co/Ni, Cr	-
Weakly alkaline calcic ( $Ca^{2+} - HCO_3^-$ ) ( $Ca^{2+} - Na^+$ )	Pb, Co	Hg/Cd, Cu, Zn/Ni, Cr	Se/Mo/As
Calcic and sodic calcic gley ( $Ca^{2+}-Fe^{2+}$ ) ( $Ca^{2+}-Na^+-Fe^{2+}$ )	Pb, Cd, Cu, Zn, Co	Se/Mo/V, As	Hg/Ni
Strongly alkaline soda ( $Na^+ - OH^-$ )	Pb	-	Hg, Se/Mo/Cu, Zn/As, V
Soda gley ( $Na^+-OH^-Fe^{2+}$ )	Pb, Cd, Cu, Zn, Co	Se/Mo/V, As	Hg/Ni
Soda gley sulphuric ( $Na^+ - OH^- - H_2S$ )	Se, Hg/Cu, Pb, Zn, Co, Cu/Ni	Mo/As, V	-

\* Only for micro-elements with "high" modules of pedotechnogenic concentration ( $P_{cs}$  of:  $n 10^6 / n 10^4 / n 10^3$ )

The mobility of many elements varies with the soil's oxidation status.  $As^{5+}$ ,  $Se^{6+}$  and  $Mo^{6+}$ , for instance, are highly mobile in an oxidizing environment, yet practically immobile under reducing conditions. Similarly, the mobility of micro-elements varies with the pH of the soil solution. The pH of non-polluted soils ranges generally from 3.0 to 9.5.

Soils can be grouped into geochemical-associations with respect to their pH and redox conditions (Table 11). The nature of the geochemical fields has been used to predict the mobility of various micro-elements in a particular geochemical-association.

In the association of "organo-acid" and acid soils, the cations Hg, Cd, Cu and Zn are very mobile, whereas the anion Mo is only poorly mobile. In the association of "acid gley" soils, Se, As and V also become immobile, while the overall mobility of heavy metal ions decreases. There are no easily mobile elements under these conditions. In the association of neutral and weakly alkaline soils of the "transitional ( $H^+ - Ca^{2+}$ ), calcic ( $Ca^{2+}$ ) and calcic-sodic ( $Ca^{2+} - Na^+$ ) water migration class" most elements are moderately mobile. Selenium and arsenic are readily mobile in an "alkaline-oxidative" medium. Lead and cobalt are practically immobile under reducing (gley) conditions.

Cu, Zn, Be, Y, Se and Zr form complex radicals and soluble carbonates in strongly alkaline soils, particularly in the presence of soda. In this form, these elements are highly mobile. In neutral and weakly alkaline soils, however, the above elements will form moderately mobile compounds (Perel'man, 1989).

Most elements which occur in acid and neutral soils become less mobile upon reduction of the soil. Perel'man (1972) distinguished two types of natural reducing media: "less reductive - gley" and "strongly reductive - hydrogen sulphide".

Technogenic fluxes generally contain a wide range of sulphur compounds. Sulphur is oxidized to its six-valent form in freely aerated soils, forming mainly soluble metal-sulphates except for barium-sulphate. Hydrogen sulphide will be formed when technogenic sulphur compounds reach a reduced soil layer and all processes will be operative in a "hydrogen-sulphide" medium. Chalcophilous elements will be reduced to their bivalent forms, forming non-soluble sulphides or poorly soluble hydro-sulphides (e.g. Cu, Zn, Pb, Co, Ni, and Hg). Elements that are mobile under both aerobic and anaerobic conditions will be immobilized in the presence of hydrogen sulphide. The latter process is commonly observed in poorly drained, saline soils containing sulphates of sodium and calcium. Under these conditions, a water-soluble complex of mercury-sodium and sulphide is formed.

Soluble mercury compounds as well as other soluble salts can accumulate in the reduced horizons of saline soils with an "exudative" moisture regime. Cinnabar (HgS) may be formed in the upper part of the profile upon oxidation of the sulphides. Soluble and toxic Na-borates may be formed in alkaline saline soils. In acid soils, however, boron is not very mobile as it is sorbed by iron and especially aluminium hydroxides.

Many elements can be sorbed in organo-metallic complexes in poorly drained, humus rich, alkaline soils, forming toxic products. Complexes of mercury and organic compounds are extremely toxic. These compounds are very stable under anaerobic conditions in view of the reduced microbiological activity. Particularly poisonous forms of methylated mercury have been observed in irrigated rice fields in Japan. Many micro-elements are sorbed by peat. Uranium accumulates in some "humus-gley" soils (Perel'man, 1989).

From the preceding discussion it follows that several types of "landscape-geochemical" barriers may occur under reducing soil moisture regimes, namely "gley", "sulphide", "sorptive" and "biochemical" barriers. This is why technogenic elements may occur in various forms in soils. The repercussions of technogenic pollution by heavy metals are likely to be most severe in soils with an oxidative regime. Many toxic elements are easily mobile in the anaerobic horizons of alkaline hydromorphic soils so that large amounts of toxic precipitates may be deposited upon evaporation.

A wide variety of complex, toxic technogenic compounds may occur in geochemical associations comprising soils with variable redox regimes. In these soils the mobility/speciation of each compound will vary during the year.

A group of moderately mobile micro-elements occurs in most acidic-alkaline and redox soil-geochemical media. Generally, the elements of this group are not easily leached out of the solum. They tend to accumulate in the humus or illuvial horizons and often partake in the nutrient cycle and biological cycle. The group under review comprises elements that can be retained by "sorptive mineral" (Cm) barriers as well as by "organo-mineral" (Ch) barriers. The sorptive capacity of the latter barriers varies with their texture and mineralogy as well as with the composition and content of the organic materials. The sorption capacity of clay minerals decreases in the sequence: allophane > montmorillonite > smectite > kaolinite. Zn, Mn, Cu are preferentially sorbed by allophane, and Ni, Cu, V, Pb and Zn by clay minerals.

Humic acids are very prone to form poorly mobile complexes with metals, particularly with Cr, Co, V, Se and Mo (Stepanova, 1976; Tkachenko *et al.*, 1978; Saprykin, 1984). Complexes of metals and fulvic acids are even more mobile. The sorptive properties and stability of these organo-metallic complexes increase as the pH of the medium increases. In one study, the average ratio of sorbed zinc over water-soluble zinc was 24 in podzolic soils as against 2400 for chernozems (Zyrin, 1973). The concentrations of micro-elements present in moderately mobile forms are higher in the illuvial horizons of acid textural soils (e.g. podzolic soils and soils lessives) than in the humus horizons of neutral chernozems.

Micro-elements may accumulate in poorly mobile forms in some soils upon co-precipitation with iron and aluminium oxides. In amorphous ferruginated neo-formations of low moor, for instance, the concentrations of As, Mn, Zn, Se, Co and Ti were 1 to 2 orders of magnitude higher than the *clarks* of these elements in the lithosphere (Taisayev, 1981).

Summarizing, it can be said that a high content of clay minerals - particularly montmorillonite and allophanes -, a high content of amorphous oxides of aluminum and iron, a high content of organic compounds - particularly humic acids-, and a neutral soil reaction facilitate the accumulation of micro-elements in moderately mobile forms in soils. Consequently, these features must be taken into account when estimating the risk that these mobile toxic micro-elements will accumulate in the pedosphere. It should be noted that some micro-elements may get sorbed or bounded in organo-mineral complexes upon the application of organic fertilizers, composts and lime.

Micro-elements which occur in poorly mobile forms in soils, generally are not toxic for biota. These compounds are often produced in soils following exchange reactions with carbonates, phosphates (e.g. Pb, Zn, Mo) and sulphates (e.g. Sr, Ba) (Vorobieva *et al.*, 1980).

Some minor elements may get immobilized in the lattices of clay minerals upon isomorphic substitution. About 15 per cent of the micro-elements were found to be isomorphically substituted in Trans-Caucasian krasnozems as against about 30 per cent in brown forest soils. The isomorphic substitution of heavy metal ions by clay minerals is a preferential process:  $\text{Co}^{2+} > \text{Cu}^{2+} > \text{Zn}^{2+} > \text{Mn}^{2+}$ . The affinity for isomorphic substitution is clay mineralogy dependent: montmorillonite < nontronite < kaolinite < halloysite < illite.

The hydro-thermic regime strongly influences the mobility of water-soluble micro-elements in soils and thereby whether they will be precipitated in the soil or be leached out of it. In humid climates, with net downward water fluxes, water-soluble elements are readily leached out of the profile. In soils of subhumid regions possessing an "impermacid" water regime, water-soluble elements may be precipitated upon evaporative concentration. These evaporates may dissolve again upon wetting of the soil.

### 2.3 Criteria for assessing the susceptibility of soils to technogenic acidification

The susceptibility of soils to acid deposition is determined by the intensity and duration of the acidifying flux, as well as by the initial buffering capacity of the soils. The latter can be derived from titration curves. The effects of technogenic acidification upon the buffering capacity of soils have been studied by many researchers (e.g. Tanaka, 1968; Tamm, 1976; Brinkman, 1977; Ulrich, 1981; Loucks, 1982; Kauppi *et al.* 1984; Glatzel *et al.*, 1988; Gobrand and Bosota, 1988; Roake and Herera, 1988; Tamm and Haldbacken, 1988; Patil *et al.*, 1989; Stefanovits, 1989).

For Hungarian soils, Varallyay *et al.* (1989) showed that the buffering capacity for acids is mainly determined by the original reaction (pH-H<sub>2</sub>O and pH-KCl), the CaCO<sub>3</sub> content, the hydrolytic acidity, the cation exchange capacity, the humus content, the percentage of exchangeable bases and exchangeable Al respectively, as well as soil texture. Statistical analyses of the experimental data combined with the interpretation of titration curves were used to derive a number of empirical relationships between the buffering capacity for acids ( $\Delta\text{pH}$ ; decrease in initial soil pH upon addition of a known amount of acid) and selected soil characteristics. In the experiments, soil samples of 10 g were treated with HCl solutions having pH values similar to that of acid rain. The following empirical equations were developed:

HCl conc.                      Decrease in soil pH ( $\Delta\text{pH}$ ) upon addition of HCl  
( $\text{mmol l}^{-1}$ )

0.1	$\Delta\text{pH} = 1.8 - 0.2E$	( $r_E^2 = 0.737$ )
0.2	$\Delta\text{pH} = 3.1 - 0.05E - 0.01H$	( $r_E^2 = 0.855$ ; $r_H^2 = 0.916$ )
0.5	$\Delta\text{pH} = 3.9 - 0.07C$	( $r_C^2 = 0.914$ )
1.0	$\Delta\text{pH} = 4.2 - 0.08C + 0.01G$	( $r_C^2 = 0.900$ ; $r_G^2 = 0.954$ )

with:

- E the organic matter content (%)
- H the content of clay fraction (%)
- C the hydrolytic acidity ( $\text{me l}^{-1}$ )
- G the content of silt fraction (%).

According to Stefanovits (1989) the buffering capacity of soils is determined not only by the total clay content, but also by the mineralogy of the clay size minerals. With reference to Hargitai's work, Stefanovits (1989) proposed the following equation:

$$\text{EBC}_S = \text{EBC}_A + \text{EBC}_H + \text{EBC}_C$$

with:

- $\text{EBC}_S$  the total buffering capacity of the soil,
- $\text{EBC}_A$  the buffering capacity due to the initial calcium carbonate content of the soils (acidity or alkalinity) of the soil,
- $\text{EBC}_H$  as above, but for the organic matter,
- $\text{EBC}_C$  as above, but for the clay size fraction.

The repercussions of technogenic acidification are most severe in non-calcareous, acid and strongly acid soils. The buffering capacity of non-calcareous soils is mainly determined by the rate at which acid fluxes replace the exchangeable bases with hydrogen ions or protons of acids. Base saturated soils with a high cation exchange capacity have the highest buffering capacity for acids.

Upon the addition of acidifying compounds to soils, the pH will first decrease markedly when the exchangeable bases get depleted. The hydrolytic acidity of the soil solution will increase gradually, while the cation saturation level decreases. Sulphates and nitrates of calcium, magnesium and potassium, produced by exchange reactions, may be leached out of the solum so that the soils may get impoverished in bases and the groundwater may become polluted. In strongly acid soils, aluminium ions will be released gradually into the soil solution, ultimately reaching concentrations toxic for organisms.

Upon the technogenic acidification of acid soils - with high contents of fulvates, chelates and humates of Fe or Al - organo-mineral compounds become readily mobile. Similar processes occur in permanently or seasonally flooded soils containing significant amounts of easily-reducible iron and manganese compounds (e.g. Tanaka, 1968; Brinkman, 1977). Toxic concentrations of water-soluble iron and aluminium compounds are commonly observed in poorly drained soils.

In the humid subtropics and tropics as well as the seasonally humid tropics there are extensive areas of soils developed on fersiallitic and ferrallitic weathering crusts or in their weathering products (denudation and redeposition). The buffering capacity of these soils is generally low because of the nature of the clay minerals - mainly kaolinite/halloysite, low content of primary silicate clay minerals -, low reserves of bases and low humus content (Roake and Herera, 1988). These soils generally contain a wide range of Fe-, Al- or Mn-hydroxides and display variable charge properties. Sulphate- and phosphate-anions may be adsorbed by the mineral particles in these soils, particularly under acid conditions.

Soil acidification can be so severe under anaerobic conditions (e.g. paddy fields) that the Fe and Al contained in amorphous hydroxides is mobilized. The resulting concentrations of Fe and Al in the soil solution are often toxic for plants.

The buffering capacity of calcareous, strongly alkaline and sodic soils will not decrease rapidly upon addition of acidifying compounds. These soils have a high buffering capacity for acids in view of their high calcium carbonate content. The pH of these soils will not drop sharply until the carbonate reserves become exhausted. Gypsum may be formed in some calcareous soils upon acidification. Gypsum crystals are often formed in the uppermost horizons of soils with an "impermacid" or "exudative" moisture regime. Alternatively, gypsum may be leached out of the solum if there is a net downward water flow.

The alkalinity of solonetzic soils and solonchaks decreases upon acidification. Exchangeable sodium ions will be replaced by calcium in calcareous soils and by hydrogen ions in acid soils. Acidifying materials have a beneficial effect on the properties of this group of soils; their alkalinity will decrease and the solonetzic properties become less pronounced.

### **3. PROGNOSTIC WORLD MAPS OF SOIL SUSCEPTIBILITY TO CHEMICAL IMPACTS**

The global distribution of soils with similar levels of "potential stability" or susceptibility to "pollution by toxic micro-elements" and "technogenic acidification" respectively are presented in this study. To the author's knowledge, this is the first time that this kind of global maps have been prepared. The maps can serve to increase the awareness of the general public and policy makers about the ever increasing damaging effects of technogenesis upon soils.

#### **3.1 Cartographic base**

The 1:60 M reduction of the 1:15 M World Soil Map produced by Glazovskaya and Friedland (1982) served as the topographical basis for the prognostic maps. This map was prepared using the polyconic projection, developed at the Central Research Institute for Geodesia, Aerial Photography and Cartography. The 1:60 M World Soil Map is to be published in the "Atlas of World Natural Resources" by the Institute of Geography (USSR Academy of Sciences).

A tabular legend is used on the map. Soils with similar "moistening" or precipitation surplus/deficit are grouped in the columns. The considered "moistening" classes are: "very humid and humid", "moderately-humid and moderately-dry" and "dry and very dry". Within each "moistening" class, soils are grouped according to their "water regime": 1) "percolative", 2) "percolative with periodical surface or ground water excessive moistening", 3) "stagnant", 4) "periodically non-percolative", 5) "pulsating (alternating non-percolative, stagnant, poorly exudative)", 6) "non-percolative", 7) "exudative" and 8) "strongly non-percolative (superficially-exudative)".

Three classes of "heat reserves and temperature regimes" are listed in the rows of the tabular legend: 1) "soils of very cold and cold regions with permafrost", 2) "soils of moderately-cold and temperate regions subjected to seasonal freezing" and 3) "soils of warm and hot regions, with or without a cool season, and not subjected to freezing".

Associations of soils with similar hydro-thermic regimes as well as similar redox and pH conditions occur at the intersections of the columns and rows.

In addition to this grouping by hydro-thermic parameters there is also another one. The 104 soil types and subtypes form 21 genetic groups displaying similar pedogenetic features. These properties are reflected in the names of these genetic groups. The latter groups can be correlated with the "family level" of the soil classification system of Glazovskaya (1966), and with the "order level" of the classification scheme of Friedland (1984). The original soil names - mapping unit symbols of the 1:15 M World Soil Map - are given in the following sections together with their Russian indices. Whenever possible, these Russian names have been correlated with the 1:5 M FAO/Unesco Soil Map of the World (Appendix I).

In spite of its low resolution the 1:60 M World Soil Map presents fairly comprehensive information about global soil features and regimes. Therefore, it can be used to compile low resolution prognostic maps on the susceptibility of soils to technogenic fluxes of micro-elements and acid deposition.

#### **3.2 Prognostic maps of soil susceptibility to technogenic pollution by toxic micro-elements**

##### **3.2.1 Grouping of the soils of the world according to their susceptibility to pollution by micro-elements**

The properties of heavy metals and other toxic micro-elements (e.g. As, Se), contained in technogenic flows, change when passing through the soils (e.g. solubility/speciation/mobility/bio-toxicity). As observed earlier, the pH and redox conditions strongly influence the transformation of chemical compounds in soils. This means that the highest category in a classification scheme to assess the susceptibility of soils to pollutants should be the geochemical soil-association. The latter consist of soils with similar redox and pH features (Glazovskaya, 1966 and 1979). The assumption is that technogenic flows of micro-elements will show similar



behaviour in a given geochemical association. The soils of a particular geochemical association that have similar genetic profiles, functioning as geochemical barriers, form a "family". The characteristics and indices of the respective geochemical barriers are shown in Table 10, and the soil families are listed in Table 12. The soil families are useful prognostic tools to compile low resolution soil susceptibility maps.

### 3.2.2 Contents and possible uses of the map

The legend of the soil susceptibility map consists of two tables (see Appendix II). In the first table, the soil families are placed in rows according to:

1. The predominant soil water regime and redox condition which determine the potential rate of removal, accumulation or evaporative concentration of the most mobile fraction of micro-elements.
2. The water migration class and, consequently, the soil geochemical association.
3. The mobility of the respective micro-elements at the pH and redox conditions proper to the considered soil family.

The respective water migration classes are depicted on the legend using indices (see Table 11). The relative mobility of the respective micro-elements within a given "water migration" class is shown using the following format:

poorly mobile elements	moderately mobile elements -----
	easily mobile elements

In the calcic water migration class ( $\text{Ca}^{2+} \cdot \text{HCO}_3^-$ ) the relative mobility of micro-elements can be expressed as follows:

Pb Hg, Cd, Cu, Co, Zn  
Se, As

In the soda class ( $\text{Na}^+ - \text{OH}^-$ ) the sequence is as follows:

Pb -  
Hg, Se, Mo, Cu, Zn, As

Only the micro-elements with a coefficient of pedotechnogenic concentration of at least  $10^4$  have been considered in this study.

The soil families are grouped in a particular row taking into account the nature and capacity of the sorptive, chemisorptive and chemo-sedimentative barriers in which the moderately and easily mobile elements accumulate in the upper horizons (most directly subjected to pollution). Soil families with similar susceptibility to pollution by toxic micro-elements occur at the intersections of the columns and rows. Three categories of "risk" have been mapped; very high, high and moderate (Figure 1). The basic mapping units for making the interpretations are shown in Figure 2. For the sake of convenience these figures have been incorporated in Appendix III which also includes the legend.

The second table in Appendix II lists the combinations of soil-geochemical barriers most commonly observed in the soil families considered in the first table of the legend. The lay-out of the second table is as follows. Possible combinations of "acid", "neutral" and "alkaline" barriers with "oxidative", "gley reductive", "hydrogen sulphide reductive" and "evaporative" barriers are shown in the columns. The rows list the possible combinations of "organic sorbtive", "organo-mineral sorbtive" and "chemisorptive" barriers. Commonly occurring combinations of soil-geochemical barriers are found at the intersections of the columns and rows.

The rate of soil pollution by toxic micro-elements can be slowed down by reducing the input of polluting substances. Alternatively, it is possible to develop procedures to clean-up polluted soils. This will require a thorough understanding of the processes which regulate the breakdown and mobilization of pollutants in soil systems. The prognostic map (Fig. 1 in Appendix II) provides general information with respect to the nature of these processes. The map may be used to formulate guidelines for soil conservation and soil pollution management at the global level. The map may also be used to formulate broad research priorities relevant

to the various regions of the globe. Additionally, the susceptibility map can be used as the basis for estimating the risk of soil pollution by overlaying it onto the relevant chemical loads map.

Table 12 Soil families showing similar response to pollution by toxic micro-elements

Index on prognostic map	Translation of soil families (literal)	Members of the soil families*	Combinations of soil geochemical barriers**
1	Flow-accumulative alumo-ferric humus-rich	Ва, Во, ф <sup>Г</sup> , АП <sup>Г</sup>	A-O/C <sub>3</sub> -M <sub>3</sub>
8	Humus-accumulative non-saturated	Тпр, З <sup>Г<sup>II</sup></sup> , З	A-O/C <sub>2</sub> -M <sub>1</sub>
15	Flow- and eluvial-illuvial ferric humus	Пб <sup>М</sup> , По <sup>М</sup> , Пб, По, По <sup>Ж</sup> , ГТ <sup>М</sup> , По <sup>СТ</sup>	A-O/C <sub>2</sub> -M <sub>2</sub>
9	Siallitic non-saturated	ЗТ, Гр <sup>Ж</sup> , Б <sup>Ж</sup> Б, Б <sup>СТ</sup>	A-O/C <sub>1</sub> -M <sub>1</sub>
20	Siallitic clay-differentiated (lessivated and podzolized)	П, П <sup>Ж</sup> Б <sup>Ж</sup>	A-O/C <sub>1</sub> -M <sub>1</sub>
16	Ferrallitic and weakly ferrallitic non-saturated and differentiated	Ж, ф <sup>Ж</sup> , ф, ЖК <sup>О</sup> , ф <sup>О</sup> фК	A-O/C <sub>1</sub> -M <sub>2</sub>
21	Gley eluvial non-saturated	ГЭ <sup>М</sup> , ГЭ, П <sup>Г</sup> , ГЭ <sup>Ж</sup> , ГЭ <sup>СТ</sup>	A-G/C <sub>1</sub> -M <sub>2</sub>
2	Peaty-gley and peaty frozen and seasonally freezing	Т <sup>М</sup> , Т <sup>В</sup> , Т <sup>Н</sup>	A-G/C <sub>3</sub> -M <sub>1</sub>
10	Gley non-saturated	Г <sup>М</sup> , Г, ГТ, ГЛ	A-G/C <sub>1</sub> -M <sub>1</sub>
17	Gley and peaty-gley non-saturated, locally with laterite	ГЛ <sup>СТ</sup> , Б <sup>СТ</sup> , Т <sup>СТ</sup> , А (БЛ, ТРОП)	A-G/C <sub>3</sub> -M <sub>2</sub>
7	Boggy solonchakous acid	М, МГ	A-S/M <sub>3</sub>
11	Humus-accumulative weakly unsaturated and neutral, clay-differentiated	Зк <sup>М</sup> , Зк, ЖС, ЖГ <sup>С</sup> , Л, ЧВ, ЧП, ЧПК	N-O-E <sub>1</sub> /C <sub>2</sub> -M <sub>2</sub>
4	Vertisols and vertic	Ч <sup>СТ</sup> , ЧС, СС	N-O-E <sub>2</sub> /C <sub>1</sub> -M <sub>3</sub>
13	Humus-accumulative saturated	Ч <sup>Г</sup> , Ч <sup>ОЮ</sup> , Ч <sup>МУ</sup> , К, К <sup>СН</sup>	N-O-E <sub>2</sub> /C <sub>2</sub> -M <sub>2</sub>
18	Weakly ferrallitic and ferrallitic weakly unsaturated and neutral, locally lessivated	Тр, Зк <sup>СТ</sup> , Кр, К <sup>Ж</sup> , КБ, КБ <sup>Ж</sup> , Кч	N-O-E <sub>2</sub> /C <sub>1</sub> -M <sub>2</sub>
3	Gleyed humus-accumulative neutral and weakly alkaline	ЛГ <sup>М</sup> , ЛГ, ЛГ <sup>СТ</sup>	N-G-E <sub>1</sub> /C <sub>2</sub> -M <sub>1</sub>
12	Gleyed weakly alkaline and alkaline differentiated solonetzic and solodized	СЗ <sup>М</sup> , ПП <sup>Ж</sup> , СЗ, СЧ <sup>Л</sup> , СЗ <sup>СТ</sup> , СЧ <sup>СТ</sup>	N-G-E <sub>1</sub> /C <sub>1</sub> -M <sub>1</sub>
5	Meadow-solonchakous and solonchaks	Ск <sup>М</sup> , Ск, Ск <sup>СТ</sup> , Тк, А	Al-S-E <sub>3</sub> /M <sub>3</sub>
14	Low-humus calcareous	Ар, Ар <sup>Л</sup> , БП, КсБ, СБ, С, С <sub>КУ</sub>	Al-O-E <sub>3</sub> /M <sub>3</sub>
19	Low-humus solonetzic and gypsic	КсБ <sup>СН</sup> , Сн, СБ <sup>Т</sup> , Кб <sup>СН</sup> , СБ <sup>СН</sup> , С <sub>КУ</sub> <sup>СН</sup>	Al-O-E <sub>3</sub> /C <sub>1</sub> -M <sub>2</sub>
23	Low-humus ferruginated	Кб, Кб <sup>ЖТ</sup> , СБ <sup>СТ</sup>	Al-O-E <sub>3</sub> /C <sub>1</sub> -M <sub>3</sub>
6	Humusless desertic stony, frequently gypsic	Пк, Пк <sup>Г</sup>	Al-O-E <sub>3</sub> /M <sub>2</sub>
22	Humusless desertic sandy	Пп, П <sup>Ж</sup>	Al-O-E <sub>3</sub> /M <sub>1</sub>

\* See Appendix I, II

\*\* See Table 10

### 3.3 Prognostic map of soil susceptibility to technogenic acidification

#### 3.3.1 Grouping of soils according to their buffering capacity and response to acidification

The following sources have been consulted to group the soils of the world according to their susceptibility to anthropogenic acidification:

1. Basic, theoretical studies of the probable relationships between the buffering capacity of soils and their susceptibility to acidification (e.g. Glasovskaya, 1976; Muranyi, 1977; Ulrich, 1981).
2. Results of laboratory experiments in which the effects of acid rain and physiologically acid fertilizers on soil properties were studied. Soils with widely differing initial pH values, texture, clay mineralogy and humus content were included in these studies (Gobrand and Bossata, 1988; Stefanovits, 1989; Varallyay *et al.*, 1989).
3. Results of long term (20-50 years) field experiments in which physico-chemical changes in the soil properties caused by inputs of physiologically acid fertilizers and/or acid rain were measured (Tamm, 1976; Rosen, 1989; Jacks *et al.*, 1989; Puxbaum *et al.*, 1989).
4. The mapping procedure developed to assess the susceptibility of Hungarian soils to acidification (Varallyay *et al.*, 1989).
5. Information about the "initial" properties of the soils shown on the 1:60 M World Soils Map.

In the current study the soils of the world have been divided into 3 main categories based on their anticipated response to acidification:

1. "Originally acid soils", in which further acidification will considerably deteriorate the physico-chemical properties and the soil fertility will decrease.
2. "Soils with weakly alkaline or neutral A horizons and calcareous B horizons (by origin)". Upon acidification, the original properties of these soils will deteriorate less rapidly than is the case for the soils of group 1.
3. "Soils, originally alkaline-calcareous or strongly alkaline and solonetzic". Upon acidification the prevailing alkalinity will be reduced, thereby improving the properties of these soils.

The soils of the above categories are subsequently subdivided with reference to their contents in acid neutralizing agents, such as carbonates, exchangeable bases, bases included in organo-mineral compounds or Fe, Al and Mn hydroxides. One of the criteria for differentiating subgroups is the "ease" with which the products of exchange reactions can be removed from the soil or will accumulate in the uppermost soil horizons.

There is a general lack of data about the effects of acid loads on soil properties. Consequently, it is somewhat difficult to assess quantitatively how soils will respond to acidification. Nevertheless, the anticipated changes in the buffering capacity of particular soils upon acidification have been tentatively derived from the "initial" properties of these soils. The overall characteristics of the considered soil groups and their general response to acidification are described in Appendix IV in general terms.

#### 3.3.2 Contents and possible uses of the map

The legend to the map on soil susceptibility to technogenic acidification is presented in Appendix III. The soil families in a given row have similar buffering capacity. The columns are used to differentiate between soils which are initially calcareous or non-calcareous - with similar pH values and profiles - and thereby respond similarly to acidification. Soil families with similar susceptibility to acidification, i.e. composing similar groups of risk, are mapped in Appendix III (see Figure 3), while the basic mapping units for making the risk-assessment are shown in Figure 4.

## ACKNOWLEDGEMENTS

The author is grateful to Prof. V.O. Targulian for his encouragement in preparing this text, and thanks Dr. M.I. Gerasimova for translating the original text and Ing. M. Bogdanova for drawing the maps<sup>2</sup>.

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<sup>2</sup> The original, hand-painted 1:80 M maps can be studied in ISRIC's map collection.

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**Appendix I Correlation of the Russian map unit symbols and soil names used on the 1:60 M World Soil Map with their FAO/Unesco equivalents**

Map symbols	Names of soils & their literal translation	Synonyms in the FAO/Unesco system	
<u>По<sup>Ж</sup></u>	- Подзолы железистые. <b>Ferric podzols</b>	<u>Pf</u>	Ferric Podzols
<u>По<sup>Ж</sup></u>	- Подзолы железистые. <b>Ferric podzols</b>	<u>Pf</u>	Ferric Podzols
<u>По</u>	- Подзолы железисто-гумусовые, часто торфянистые. <b>Ferric-humic podzols, frequently peaty</b>	<u>Ph</u>	Humic Podzols
<u>По<sup>М</sup></u>	- Подзолы мерзлотные. <b>Podzols with permafrost</b>	<u>Px</u>	Gelic Podzols <sup>2</sup>
<u>По<sup>СТ</sup></u>	- Подзолы субтропические грунтово-глеватые местами с горизонтом плинтита. <b>Subtropical gleyic podzols, locally with plinthite</b>	<u>Pg</u>	Gleyic subtropical podzols, locally with plinthite <sup>+</sup>
<u>Пб</u>	- Побуры. <b>Podburs</b>	<u>Bds</u>	Spodi-Dystric Cambisols <sup>3</sup>
<u>Пб<sup>М</sup></u>	- Побуры сухомерзлотные. <b>Podburs with dry permafrost</b>	<u>Bds</u>	Spody-Dystric Cryic Cambisols <sup>3+</sup>
<u>Тпр</u>	- Тундровые примитивные. <b>Primitive tundra soils</b>	<u>I</u>	Litosols (Leptosols <sup>3</sup> )
<u>Дк</u>	- Дерновые остаточнок-карбонатные. <b>Leached rendzinas</b>	<u>E</u>	Rendzinas
<u>Дк<sup>СТ</sup></u>	- Дерновые остаточнок-карбонатные субтропические. <b>Subtropical leached rendzinas</b>	<u>E</u>	Subtropical Rendzinas
<u>Дк<sup>М</sup></u>	- Перегнойно-мерзлотные карбонатные. <b>Raw-humus cryogenic calcareous soils</b>	<u>Ex</u>	Gelic Rendzinas <sup>+</sup>
<u>Дгл</u>	- Субальпийские и альпийские горнолуговые. <b>Subalpine and alpine meadowmountain soils</b>	<u>U</u>	Rankers, Umbric Leptosols <sup>2</sup>
<u>Ва</u>	- Вулканические пепловые (андосолы). <b>Volcanic ash soils</b>	<u>Tv</u>	Vitric Andosols
<u>Во</u>	- Вулканические пепловые охристые. <b>Volcanic ash ochric soils</b>	<u>To</u>	Ochric Andosols
<u>Ал<sup>Г</sup></u>	- Аллитные гумусные. <b>Humus allitic</b>	<u>Ah</u>	Humic Acrisols
<u>Грл</u>	- Грубогумусные лесные кислые. <b>Raw-humus acid forest soils</b>	<u>Bdo</u>	Orti-Dystric Cambisols <sup>3</sup>
<u>Дт</u>	- Дерново-таежные. <b>Sod-taiga soils</b>	<u>Bh</u>	Humic Cambisols
<u>Б<sup>К</sup></u>	- Буроземы кислые. <b>Acid brown forest soils</b>	<u>Bd</u>	Dystric Cambisols
<u>Б</u>	- Буроземы типичные. <b>Brown forest soils</b>	<u>Be</u>	Eutric Cambisols
<u>Б<sup>СТ</sup></u>	- Буроземы субтропические. <b>Brown forest subtropical soils</b>	<u>Be</u>	Eutric Cambisols
<u>Ж</u>	- Желтоземы и желто-бурые. <b>Zheltizems and yellow-brown soils</b>	<u>Bf</u>	Ferrallitic Cambisols

Appendix I (cont.)

<u>ФЖ</u>	- Желтые ферраллитные часто с горизонтом плинтита. <b>Yellow Ferrallitic, locally with plinthite</b>	<u>Fx</u>	Xantic Ferralsols locally with plinthite <sup>+</sup>
<u>Ф</u>	- Красножелтые ферраллитные местами с горизонтом плинтита. <b>Red-yellow ferrallitic locally with plinthite</b>	<u>Fa</u>	Acric Ferralsols, locally with plinthite <sup>2+</sup>
<u>ФК</u>	- Красноземы и темнокрасные ферраллитные. <b>Red and dark red ferrallitic</b>	<u>N, Fr</u>	Nitosols and Rhodic Ferralsols
<u>ФГ</u>	- ферраллитные гумусные. <b>Humus ferrallitic soils</b>	<u>Fu</u>	Umbric Ferralsols
<u>П</u>	- Подзолистые типичные. <b>Typic podzolic</b>	<u>Dd</u>	Dystric Podzoluvisols
<u>ПГ</u>	- Подзолистые торфянисто-глеевые. <b>Peaty gleyic podzolic</b>	<u>Dg</u>	Gleyic Podzoluvisols
<u>П<sup>Л</sup></u>	- Дерново-подзолистые и почвы лессиве. <b>Sod-podzolic and lessivé soils</b>	<u>La</u>	Albic Luvisols <sup>2</sup>
<u>Б<sup>Л</sup></u>	- Бурные лессивированные. <b>Brown lessivé soils</b>	<u>Bl</u>	Luvic Cambisols <sup>+</sup>
<u>ЖК<sup>0</sup></u>	- Желтоземы и красноземы оподзоленные. <b>Podzolized zheltozems and krasnozems</b>	<u>Lc</u>	Chromic Luvisols
<u>Ф<sup>0</sup></u>	- ферраллитизированные и ферраллитные оподзоленные часто с горизонтом латерита. <b>Ferrallitized and ferrallitic podzolized, frequently with laterite</b>	<u>Flp</u>	Luvi-Plinthic Ferralsols <sup>3+</sup>
<u>ГЭ<sup>М</sup></u>	- Глееэлювиальные мерзлотные. <b>Gley-eluvi-eluvial soils with permafrost</b>	<u>Lga</u>	Albi-Gleyic Gelic Luvisols <sup>2</sup>
<u>ГЭ</u>	- Глееподзолистые часто торфянистые. <b>Gley-podzolic frequently peaty</b>	<u>Dg</u>	Gleyic Podzoluvisols
<u>ГЭ<sup>П</sup></u>	- Глееэлювиальные дерновые (псевдоплен, псевдоподзолистые). <b>Gley-eluvial soddy (pseudogleys, pseudopodzolic)</b>	<u>Lga</u>	Albi-Gleyic Luvisols
<u>ГЭ<sup>СТ</sup></u>	- Глееэлювиальные субтропические, часто с горизонтом латерита. <b>Gley-eluvial subtropical, frequently with laterite</b>	<u>Lga</u>	Albi-Gleyic Luvisols subtropical, with plinthite <sup>3+</sup>
<u>Г<sup>М</sup></u>	- Глеевые тундровые мерзлотные. <b>Tundra gley soils with permafrost</b>	<u>Gx</u>	Cryic Gleysols
<u>ГТ<sup>М</sup></u>	- Глеевые таежные мерзлотные. <b>Tayga gley soils with permafrost</b>	<u>Gx</u>	Cryic Gleysols
<u>Г</u>	- Глеевые тундровые. <b>Tundra gley soils</b>	<u>Gd</u>	Dystric Gleysols
<u>ГТ</u>	- Глеевые таежные. <b>Taiga gley soils</b>	<u>Gd</u>	Dystric Gleysols
<u>ГЛ</u>	- Глеевые лесные и лугово-лесные. <b>Gley forest and meadow-forest soils</b>	<u>Gh</u>	Humic Gleysols
<u>ГЛ<sup>СТ</sup></u>	- Глеевые субтропические часто с горизонтом латерита. <b>Gley subtropical soils frequently with laterite</b>	<u>Gp</u>	Plinthic Gleysols



Appendix I (cont.)

<u>БЛ<sup>СТ</sup></u>	- Лугово-болотные субтропические. <b>Meadow-boggy subtropical soils</b>	<u>Ghd</u>	Humi-Dystric Gleysols <sup>3</sup>
		<u>Gu</u>	Umbric Gleysols <sup>2</sup>
<u>Т<sup>М</sup></u>	- Торфяно-глеевые и торфяные мерзлотные. <b>Peaty gley and peaty soils with permafrost</b>	<u>Ox</u>	Gelic Histosols
<u>Т<sup>В</sup></u>	- Торфяно-глеевые и торфяные верховых болот. <b>Peaty-gley and peaty soils of high moor</b>	<u>Od</u>	Dystric Histosols
<u>Т<sup>Н</sup></u>	- Торфяно-глеевые и торфяные низинных болот. <b>Peaty-gley and peaty soils of low moor</b>	<u>Oe</u>	Eutric Histosols
<u>Т<sup>СТ</sup></u>	- Торфяно-глеевые и торфяные субтропические. <b>Peaty-gley and peaty subtropical soils</b>	<u>Oe</u>	Eutric Histosols subtropical <sup>+</sup>
<u>Ар</u>	- Арктические сухомерзлотные. <b>Arctic soils with dry permafrost</b>	<u>Rx</u>	Cryic Regosols
<u>Пл</u>	- Палевые. <b>Pale soils</b>	<u>Lk</u>	Calcic (Cryic) Luvisols <sup>+</sup>
<u>Пл<sup>3</sup></u>	- Палевые оподзоленные, осолоделые. <b>Pale podzolic, solodized soils</b>	<u>Lx</u>	Cryic Luvisols <sup>+</sup>
<u>Л</u>	- Серые лесные. <b>Grey forest soils</b>	<u>Hi</u>	Luvic Phaeozems
<u>Ч<sup>В</sup></u>	- Черноземы выщелоченные и оподзоленные. <b>Leached and podzolized chernozems</b>	<u>Cl</u>	Luvic Chernozems
<u>А<sup>М</sup></u>	- Аллювиальные мерзлотные. <b>Alluvial with permafrost</b>	<u>Jx</u>	Cryic Fluvisols
<u>М</u>	- Маршевые болотные и солончаковые. <b>Marshy boggy and solonchakous soils</b>	<u>Gt</u>	Thionic and solonchakous Gleysols
<u>А</u>	- Аллювиальные. <b>Alluvial soils</b>	<u>J</u>	Fluvisols
<u>А<sup>СТ</sup></u>	- Аллювиальные субтропические. <b>Alluvial subtropical soils.</b>	<u>J</u>	Fluvisols
<u>Мг</u>	- Мангровые болотные и солончаковые в том числе кислые. <b>Mangrove boggy and solonchakous soils, acid soils included</b>	<u>Gt</u>	Thionic Gleysols <sup>2</sup>
<u>Тк</u>	- Такыры и такыровидные. <b>Takyr and takyr-like soils</b>	<u>Yt</u>	Takiric Yermosols <sup>+</sup>
<u>Лг</u>	- Луговые, местами солончаковатые, солонцеватые и осолоделые. <b>Meadow, including solonchakous, solonetzic, planosolic (solodic)</b>	<u>Gu</u>	Umbric Gleysols, locally solonchakous, solonetzic, planosolic
<u>Снл</u>	- Солонцы луговые часто осолоделые. <b>Meadow including solonchakous, solonetzic, solodic</b>	<u>Sg</u>	Gleyic solonetztes, frequently planosolic
<u>Сн<sup>СТ</sup></u>	- Солонцы субтропические. <b>Subtropical solonetztes</b>	<u>S</u>	Subtropical solonetztes <sup>+</sup>
<u>Лг<sup>СТ</sup></u>	- Луговые субтропические преимущественно слитые, местами осолоделые. <b>Meadow subtropical, locally solodic, mainly vertic</b>	<u>Gmv</u>	Verti-Mollic-Gleysols, locally planosolic <sup>3 +</sup>

Appendix I (continued)

<u>Лс</u>	- Лугово-степные, субальпийские и альпийские местами мерзлотные. <b>Meadow-steppe subalpine and alpine, locally cryogenic</b>	<u>Im</u>	<b>Mollic Leptosols locally cryogenic<sup>2</sup></b>
<u>Сд</u>	- Солоди (планосоли). <b>Solods (Planosols)</b>	<u>W</u>	<b>Planosols</b>
<u>Сд<sup>СТ</sup></u>	- Солоди (планосоли) субтропические. <b>Subtropical solods (Planosols)</b>	<u>W</u>	<b>Planosols</b>
<u>Ц<sup>T</sup></u>	- Черноземы типичные. <b>Typical chernozems</b>	<u>Ch</u>	<b>Haplic Chernozems</b>
<u>Ц<sup>ОЮ</sup></u>	- Черноземы обыкновенные и южные. <b>Ordinary and southern chernozems</b>	<u>Ck</u>	<b>Calcic Chernozems</b>
<u>Ц<sup>МЦ</sup></u>	- Черноземы глубокие мнцеллярно-карбонатные. <b>Deep Chernozems with mycelium carbonates</b>	<u>Ck</u>	<b>Deep Calcic Chernozems<sup>2+</sup></b>
<u>К</u>	- Темно-каштановые и каштановые. <b>Dark chestnut and chestnut soils</b>	<u>Kh</u>	<b>Haplic Kastanozem</b>
<u>К<sup>СН</sup></u>	- Темно-каштановые и каштановые часто солонцеватые. <b>Dark chestnut and chestnut soils frequently solonetzic</b>	<u>Kl</u>	<b>Luvic (solonetzic) Kastanozems<sup>+</sup></b>
<u>Кч</u>	- Коричневые сухих лесов и кустарников. <b>Cinnamonic soils of xerophyllous forests and shrubs</b>	<u>Bc</u>	<b>Chromic Cambisols</b>
<u>Ц<sup>СТ</sup></u>	- Черноземы субтропические (Черноземы смолницы, terra negro). <b>Subtropical Chernozems (Smolnitza)</b>	<u>Chv</u>	<b>Vertic Chernozem = Veg Grumi-Eutric Vertisols</b>
<u>Цп</u>	- Черноземовидные почвы прерий, местами глееватые и осолоделые	<u>Hh</u>	<b>Haplic Phaeozems, locally gleyic and sodic<sup>+</sup></b>
<u>Цпк</u>	- Черноземовидные и красновато-черные почвы прерий, местами глееватые и осолоделые	<u>Hh + Hhc</u>	<b>Haplic Phaeozems and Chromi-haplic Phaeozems, locally gleyic and solodic<sup>+</sup></b>
<u>Тр</u>	- Терра росса	<u>E</u>	<b>Terra Rossa</b>
<u>Кр</u>	- Красные и красно-коричневые	<u>Nr, No</u>	<b>Rhodic and Haplic Nitosols<sup>2</sup></b>
<u>КБ</u>	- Краснобурные и бурные	<u>Bc</u>	<b>Chromic Cambisols<sup>2</sup></b>
<u>КБ<sup>Ф</sup></u>	- Краснобурные остаточо-ферралитные	<u>Bcf</u>	<b>Ferrallic chromic Cambisols<sup>3+</sup></b>
<u>Пф</u>	- Песчаные ферраллитизированные	<u>Qf</u>	<b>Ferrallic Arenosols</b>
<u>Лг<sup>М</sup></u>	- Луговые мерзлотные солонцеватые и осолоделые	<u>Gmx</u>	<b>Mollic gelic Gleysols<sup>3</sup></b>
<u>Сд<sup>М</sup></u>	- Солоди и осолоделые солонцы мерзлотные	<u>Wis</u>	<b>Si Solodic gelic Planosols and gelic Solonetztes</b>
<u>Цс</u>	- Темноцветные слитые. <b>Dark vertic soils</b>	<u>Vp</u>	<b>Pellic Vertisols</b>
<u>СС</u>	- Серые, часто солонцеватые осолоделые и глеевые	<u>Vk</u>	<b>Calcic Vertisols, frequently solonetzic, planosolic, gleyic<sup>3+</sup></b>
<u>Ск<sup>М</sup></u>	- солончаки мерзлотные. <b>Solonchaks with permafrost</b>	<u>Zi</u>	<b>Gelic Solonchaks</b>

Appendix I (continued)

<u>Ск</u>	- солончаки. <b>Solonchaks</b>	<u>Z</u>	Solonchaks
<u>Ск<sup>СТ</sup></u>	- солончаки субтропические. <b>Subtropical Solonchaks</b>	<u>Z</u>	Solonchaks
<u>Ар<sup>П</sup></u>	- Арктические пустынные. <b>Arctic desert</b>	<u>Rx</u>	Gelic Regosols
<u>В<sup>П</sup></u>	- Высокогорные пустынные. <b>Arctic desert</b>	<u>Ie</u>	Eutric Leptosols <sup>2</sup>
<u>КсБ</u>	- Светлокаштановые и бурые пустынно-степные. <b>Light chestnut and brown desert-steppe soils</b>	<u>Xh</u>	Haplic Xerosols
<u>СБ</u>	- Серо-бурые пустынные. <b>Grey-brown desert soils</b>	<u>Yl</u>	Luvic Yermosols
<u>С</u>	- Сероземы. <b>Serozems</b>	<u>Xk</u>	Calcic Xerosols
<u>Скч</u>	- Серокоричневые. <b>Grey cinnamonic</b>	<u>Bk</u>	Calcic Cambisols
<u>Кб</u>	- Красноовато-бурные. <b>Reddish-brown</b>	<u>Bcc</u>	Calcari-Chromic Cambisols <sup>2</sup>
<u>Кб<sup>ЛТ</sup></u>	- Красноовато-бурные остаточного-латеритные. <b>Reddish-brown residually lateritic</b>	<u>Bcc(p)</u>	Calcari-Chromic Cambisols with plinthite
<u>Ппр</u>	- Пустынные примитивные. <b>Desert primitive soils</b>	<u>Rc</u>	Calcaric Regosols = Yi Leptic Yermosols <sup>+</sup>
<u>КсБ<sup>СН</sup></u>	- Светлокаштановые и бурые пустынно-степные солонцеватые. <b>Light-chestnut and brown desert-steppe solonetzic</b>	<u>Xk</u>	Calcic solonetzic Xerosols <sup>+</sup>
<u>Сн</u>	- Солонцы. <b>Solonetzcs</b>	<u>S</u>	Solonetzcs
<u>СБ<sup>Г</sup></u>	- Серо-бурные гипсоносные и солончаковатые. <b>Grey-brown gypsic and solonchakous soils</b>	<u>Y</u>	Gypsic luvic Yermosols
<u>Скч<sup>СН</sup></u>	- Серо-коричневые солонцеватые и гипсоносные. <b>Grey-cinnamonic solonetzic and gypsic</b>	<u>Bks</u>	Calcic Cambisols, solonetzic and gypsic <sup>+</sup>
<u>Пп</u>	- Песчаные пустынные. <b>Sandy desert soils</b>	<u>Qc</u>	Calcic Arenosols <sup>2</sup>
<u>Ппж</u>	- Песчаные пустынные ожелезненные. <b>Sandy desert ferruginated soils</b>	<u>Qcf</u>	Ferry-calcaric Arenosols <sup>3</sup>
<u>Пк</u>	- Пустынные каменистые. <b>Desert stony soils</b>	<u>Rc</u>	Calcaric Regosols
<u>Пк<sup>Г</sup></u>	- Пустынные каменистые гипсоносные. <b>Desert stony gypsic soils</b>	<u>Rcy</u>	Gypsi-calcaric Regosols <sup>3</sup>

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1. Soil symbols and names of soils: first and second levels of the basic system (1979); + with additions, not always in terms of FAO legend.
  2. Names of soils according to the revised FAO/Unesco legend (1977)
  3. Third level of the revised legend (1985).

Appendix II Map on potential danger of soil pollution by toxic micro-elements

Groupings of soils with similar response to contamination by toxic micro-elements.

Redox and water regimes of the soils	Oxidative, percolative	Oxidative-reductive periodically stagnant	Reductive stagnant	Oxidative periodically non-percolative	Oxidative-reductive alternating	Oxidative non-percolative	Oxidative-reductive exudative	Strongly oxidative non-percolative, exudative	Strongly reductive hydrogen sulphide stagnant
Classes of water migration	H <sup>+</sup> - HCO <sub>3</sub>	H <sup>+</sup> - Cl <sup>-</sup> - Fe <sup>2+</sup>	H <sup>+</sup> - Cl <sup>-</sup> - Fe <sup>2+</sup>	H <sup>+</sup> - Ca <sup>2+</sup> - HCO <sub>3</sub>	H <sup>+</sup> - Ca <sup>2+</sup> - Na <sup>+</sup> - Fe <sup>2+</sup>	Ca <sup>2+</sup> - HCO <sub>3</sub> , Ca <sup>2+</sup> - Na <sup>+</sup> - HCO <sub>3</sub>	Na <sup>+</sup> - HCO <sub>3</sub> <sup>-</sup> - Cl <sup>-</sup> - SO <sub>4</sub> <sup>2-</sup>	Ca <sup>2+</sup> - Na <sup>+</sup> - HCO <sub>3</sub> <sup>-</sup> - SO <sub>4</sub> <sup>2-</sup>	Na <sup>+</sup> - Cl <sup>-</sup> - H <sub>2</sub> S
Mobility of micro-elements	1) Mo 2) Se, Co, Ni, Cr 3) Hg, Cd, Cu, Zn, Pb, As, V	1) Se, As, Mo, V 2) Hg, Cd, Cu, Zn, Pb, Ni, Cr, Co 3) -	1) Pb 2) Hg, Cd, Cu, Co, Zn, Ni, Cr, V 3) Se, As	1) Pb, Mo 2) Se, Hg, Cd, Cu, Zn, Co, Ni, Cr 3) -	1) Pb, Co 2) Hg, Cd, Cu, Zn, Ni, Cr 3) Se, Mo, As	1) Pb, Cd, Cu, Zn, Co 2) Se, Mo, V, As 3) Hg, Ni	1) Pb, Cd 2) Co, Ni, Cr 3) Hg, Se, Mo, Cu, Zn, As, V	1) Se, Hg, Cu, Pb, Zn, Co, Cu, Ni 2) Mo, As, V 3) -	
<b>RISK1</b>									
Very High	1*	3	4	5	6	7			
High	8, 15	9, 16	10, 17	11, 18	12	13		14, 19	
Moderate		20						22, 23	

\* Risk that poorly mobile and moderately mobile micro-elements will accumulate in the upper horizons.

\*\* Indices on prognostic map (see Table 12 for the names of the corresponding soil families and Fig.2 for their geographic occurrence)

\*\* Mobility of micro-elements: 1) poorly mobile, 2) moderately mobile, 3) easily mobile micro-elements under the specified conditions

Appendix II (continued)

Combinations of soil geochemical barriers

Soil-geochemical barriers									
Combinations of acid/alkaline and oxidative/reducing barriers									
Combination of sorptive barriers	A-O	A-G	A-S	N-O-E <sub>1</sub>	N-O-E <sub>2</sub>	N-G-E <sub>1</sub>	Al-O-E <sub>3</sub>	Al-S-E <sub>3</sub>	
C <sub>3</sub> -M <sub>1</sub>		2							
C <sub>3</sub> -M <sub>2</sub>		17							
C <sub>3</sub> -M <sub>3</sub>	1					3			
C <sub>2</sub> -M <sub>1</sub>	8								
C <sub>2</sub> -M <sub>2</sub>	15		11		13				
C <sub>1</sub> -M <sub>1</sub>	9,20	10				12			
C <sub>1</sub> -M <sub>2</sub>	16	21			18		19		
C <sub>1</sub> -M <sub>3</sub>					4		23		
M <sub>1</sub>							22		
M <sub>2</sub>							6		
M <sub>3</sub>			7				14		5

Indices of soil-geochemical barriers

- A = acid
- N = neutral and weakly alkaline
- Al = alkaline and strongly alkaline
- O = oxidative
- G = gley reductive
- S = hydrogen sulphide reductive
- E = evaporative
- (E<sub>1</sub> = seasonally weakly evaporative; E<sub>2</sub> = seasonally strongly evaporative; E<sub>3</sub> = intensively evaporative)
- C = organic and organo-mineral sorptive and chemosorptive
- (C<sub>1</sub> = low capacity; C<sub>2</sub> = medium capacity; C<sub>3</sub> = high capacity)
- M = mineral sorptive and chemo-sorptive
- (M<sub>1</sub> = low capacity; M<sub>2</sub> = medium capacity; M<sub>3</sub> = high capacity)

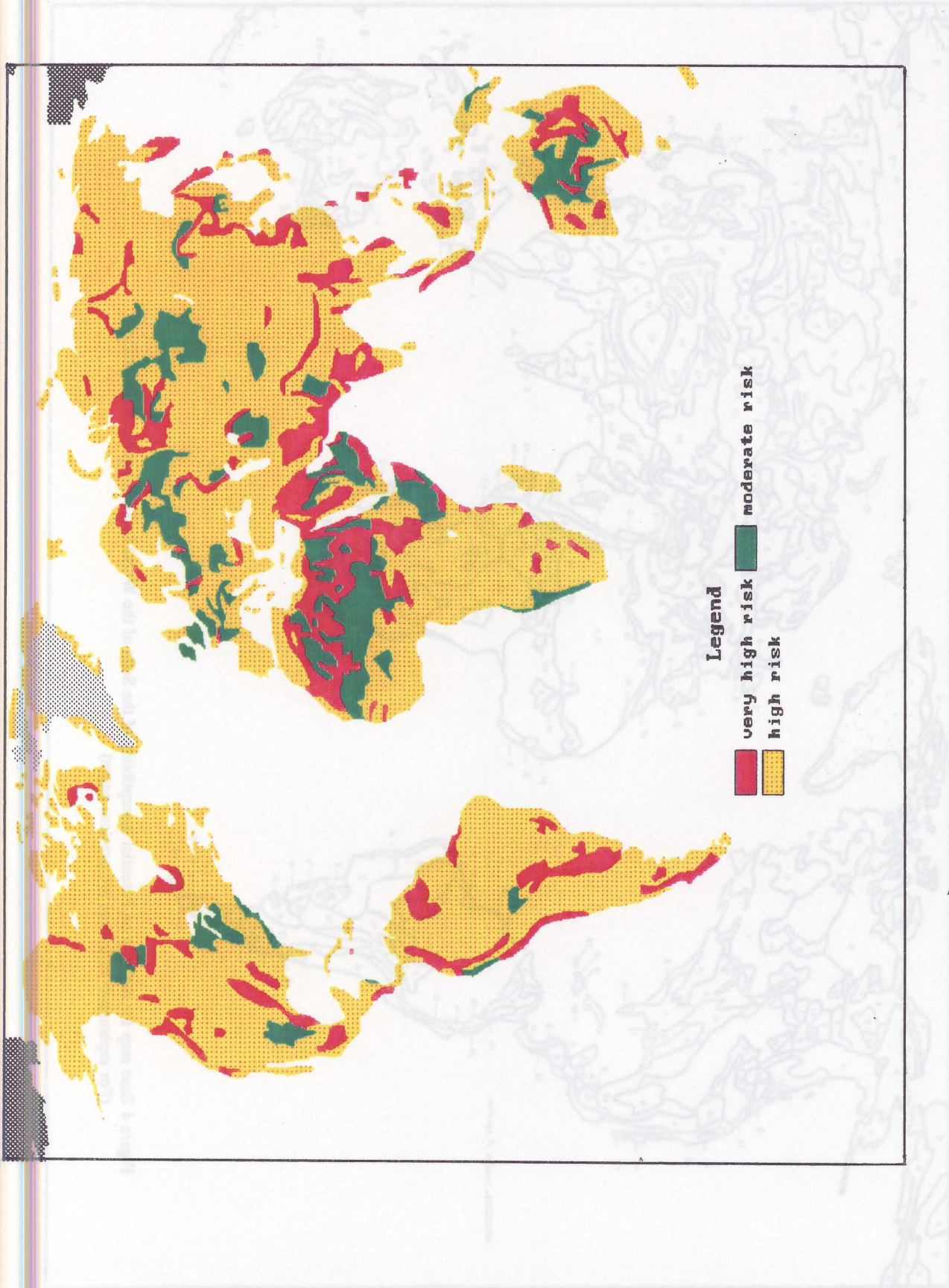


Figure 1 Potential susceptibility of the soils of the world to pollution by toxic elements (Polyconic projection; approximate equatorial scale, 1 cm = 1400 km; glaciers = light grey; not-classified = dark grey)

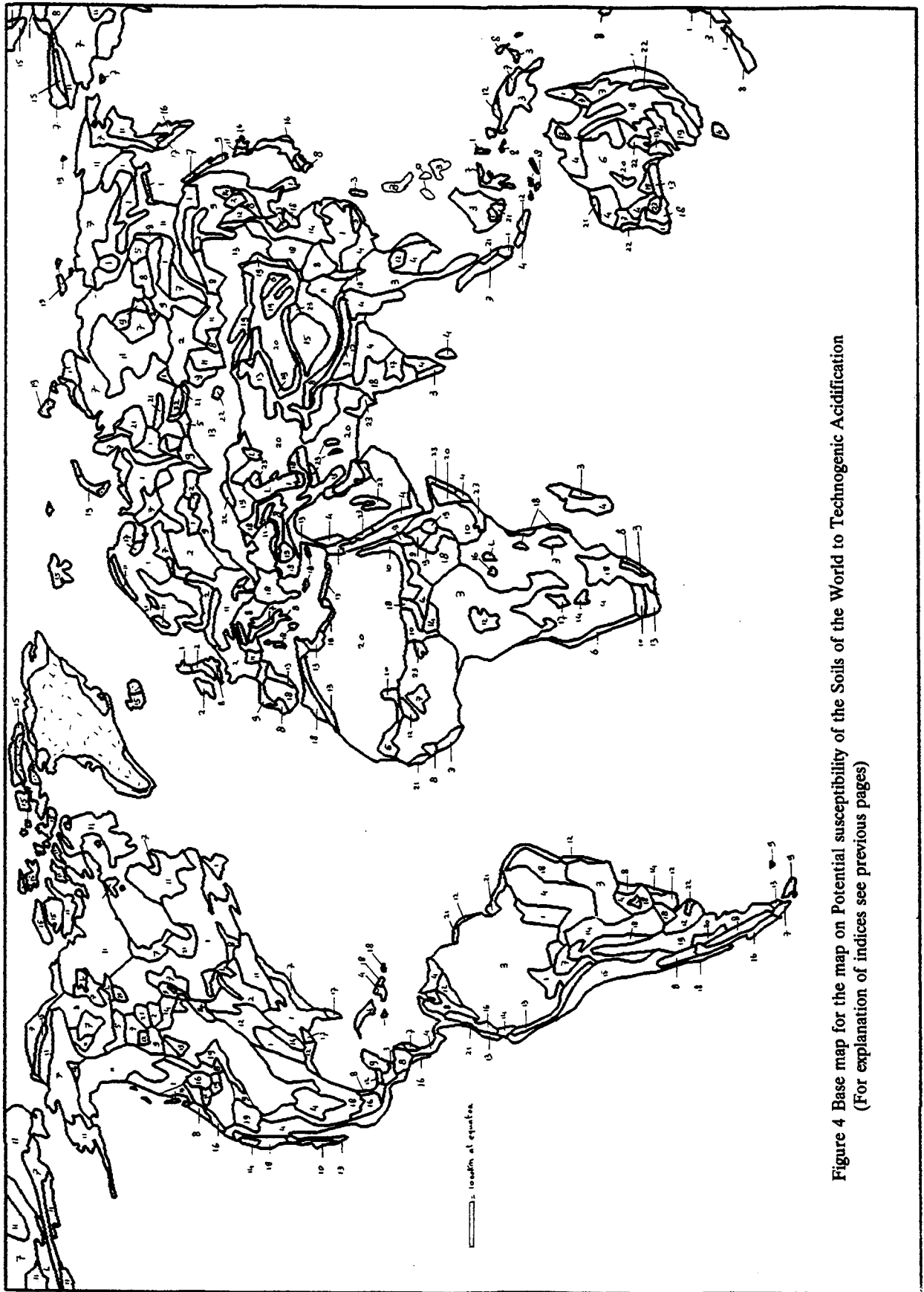


Figure 4 Base map for the map on Potential susceptibility of the Soils of the World to Technogenic Acidification  
 (For explanation of indices see previous pages)

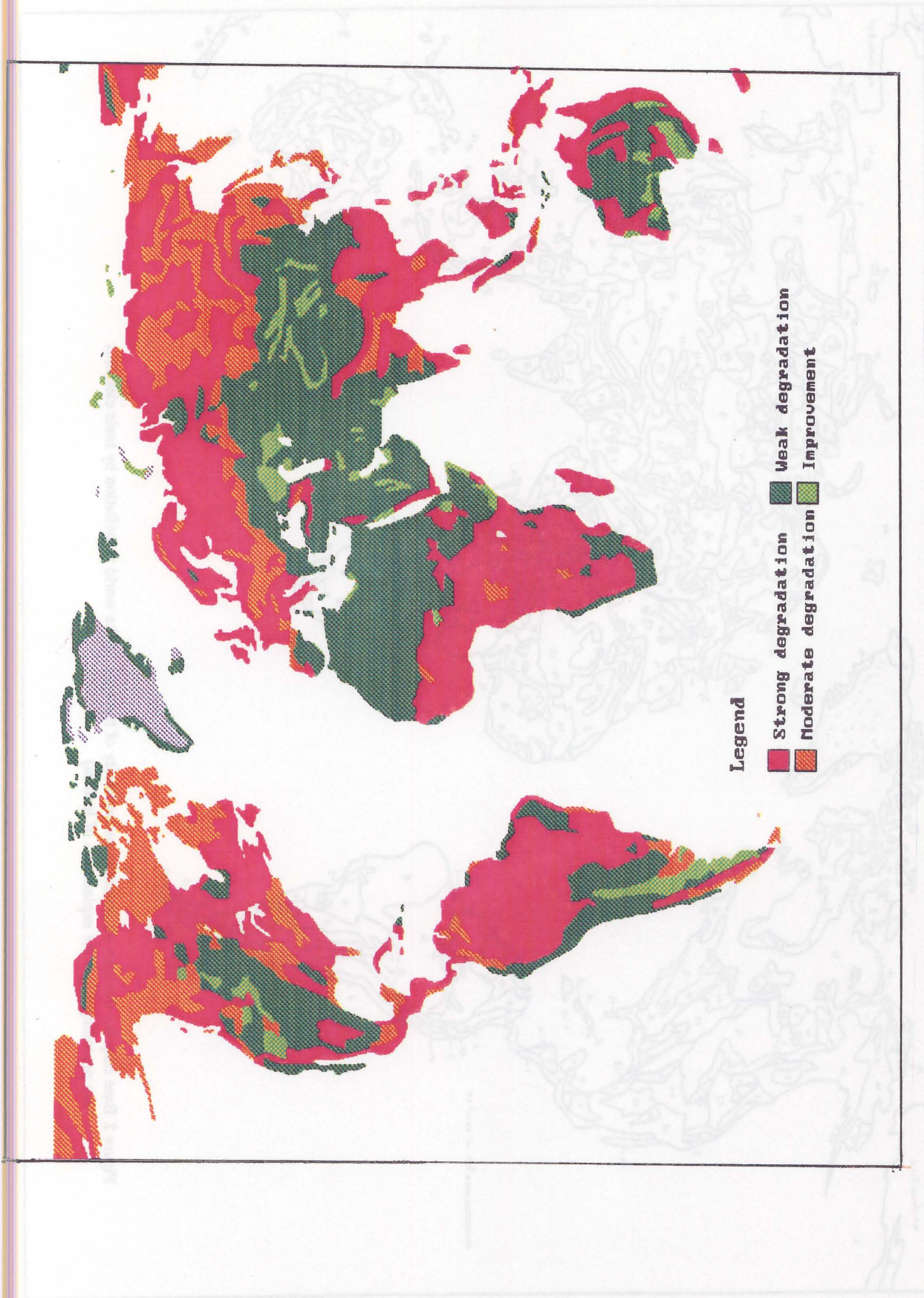


Figure 3 Potential susceptibility of the soils of the world to technogenic acidification (Polyconic projection; approximate equatorial scale, 1 cm = 1400 km; glaciers = light grey; not-classified = dark grey)



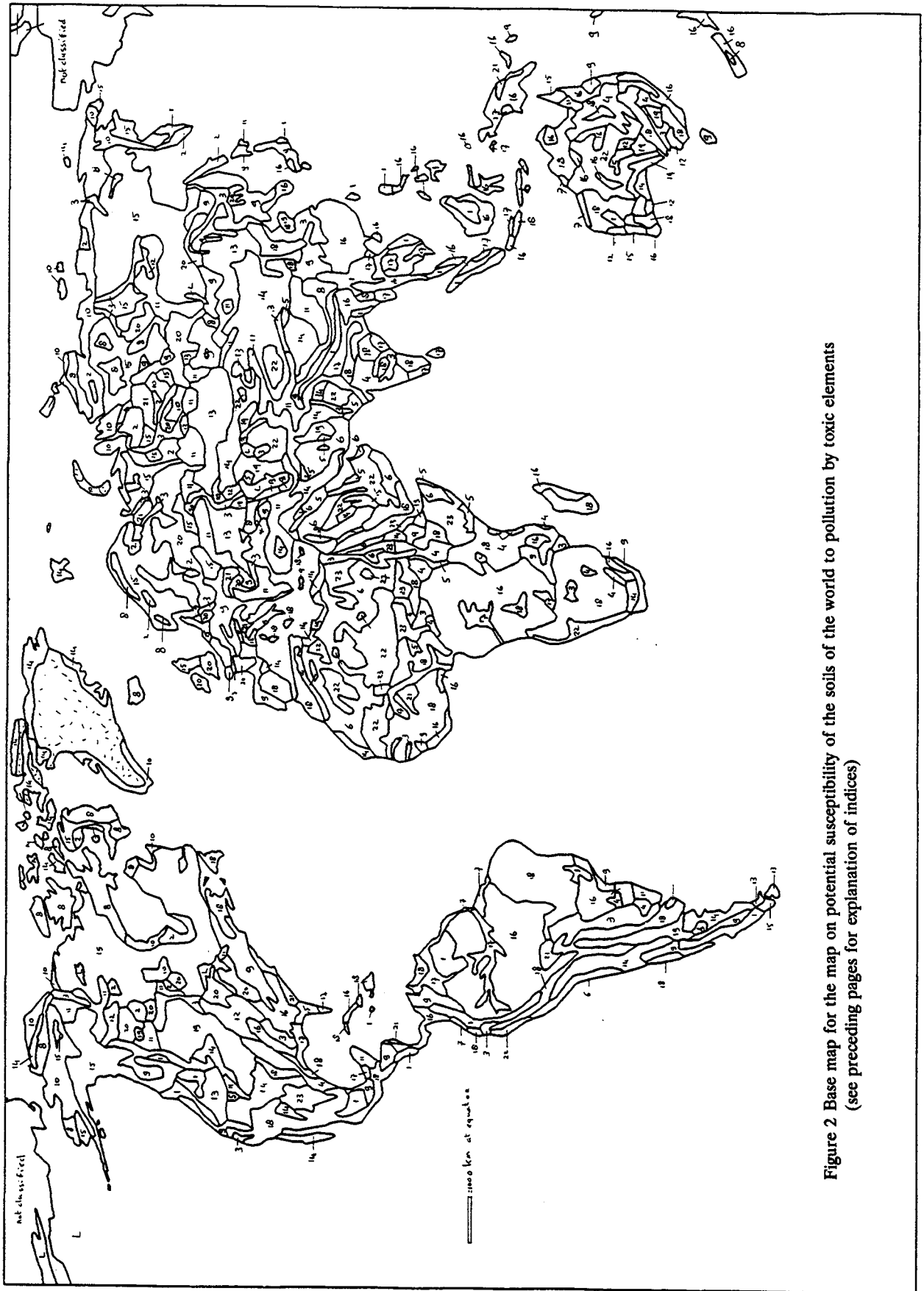


Figure 2 Base map for the map on potential susceptibility of the soils of the world to pollution by toxic elements (see preceding pages for explanation of indices)

Appendix III Map on the potential susceptibility of the soils of the world to technogenic acidification

A - Groupings of the soils of the world according to their buffering capacity and susceptibility to acidification

Soil buffering capacity, ( $\Delta$ pH)	Acidity or alkalinity of initial soils			
	Acid non-calcareous	Acid non-calcareous	Calcareous in B horizon	Calcareous throughout the solum
very low, $\Delta$ pH > 3.5	1*	2	-	-
low, $\Delta$ pH: 3.5-2.5	3	4	5	6
rather low, $\Delta$ pH: 2.5-1.5	7	8	9	10
moderate and above moderate, $\Delta$ pH: 1.5-1.0	11	12	13	14
high, $\Delta$ pH < 1.0	16	17	18	19
very high, $\Delta$ pH is stable	21	-	-	22
				23

B - Trends of soil changes due to technogenic acidification:  
 strong degradation: 1, 2, 3, 4, 7 & 8  
 moderate degradation: 5, 9, 11, 12, 16 & 17  
 weak degradation: 6, 10, 13, 14, 15, 18, 20 & 21  
 improvement: 19, 22 & 23

\* No. 1-23 are the prognostic soil families as shown in Figure 4.

## Appendix IV Characterization of the soils of the world according and their general response to acidification

### Description<sup>3</sup>:

1. Soils which are strongly acid (pH < 4.7) and acid (pH: 4.7 - 5.7) throughout their solum. Upon acidification their pH decreases and the hydrolytic acidity increases so that exchangeable bases are lost (unsaturated). The mobility of fulvates and hydroxides of iron, aluminium and manganese will increase. Hydrogen sulphide may be formed under poorly drained conditions.
  - 1.1. Very low buffering capacity. Very acid, mostly coarse-textured (sandy, coarse-silty-sandy) soils with a low humus content and a low or very low exchange capacity. Strongly unsaturated. Low contents of iron and aluminium hydroxides and aluminosilicates in the upper horizons. This group includes well and moderately drained podzols ( $\Pi^M$ ,  $\Pi^O$ ,  $\Pi^O^X$ ), podzolized zheltzems and krasnozems ( $XK^O$ ), as well as podzolized, fersiallitic and ferrallitic soils ( $\Phi^O$ ).
  - 1.2. Low buffering capacity. Acid and strongly acid, mainly loamy soils with a low humus content and very low cation exchange capacity, highly unsaturated, with a low or very low content of aluminosilicates (except kaolinite minerals) and a high content of mainly crystalline hydroxides of iron, manganese and sometimes aluminium. This group includes well-drained zheltzems and yellow-brown soils ( $X$ ), yellow ferrallitic soils ( $\Phi X$ ), red-yellow ferrallitic soils ( $\Phi$ ), and humus ferrallitic soils ( $\Phi^T$ ).
  - 1.3. Rather low buffering capacity. Acid soils of varying texture, poor in humus, unsaturated, with a low to medium exchange capacity, iron and aluminium hydroxides in the upper horizons and moderate contents of aluminosilicates. The following soils belong to this group: dystric eluvial-gley soils ( $\Gamma^M$ ,  $\Gamma^O$ ,  $\Gamma^O^H$ ), peaty-podzolic-gley soils ( $\Pi^T$ ), podzolic soils ( $\Pi$ ), dystric-gley tundra soils ( $\Gamma^M$ ,  $\Gamma$ ), and taiga soils ( $\Gamma^M$ ,  $\Gamma^T$ ).
  - 1.4. Medium and rather high buffering capacity. Strongly acid and acid soils, frequently stony, highly permeable, with a medium humus content and exchange capacity, low amounts of non-crystalline iron and aluminium oxides as well as considerable contents of poorly weathered aluminosilicates. The well drained, subalpine and alpine meadow soils ( $Z^H$ ), primitive mountain-tundra soils ( $\Gamma_{HP}$ ), raw-humus acid forest soils ( $\Gamma_{pH}$ ), podburs ( $\Pi^M$ ,  $\Pi^B$ ), and acid brown forest soils ( $B^K$ ) belong to this category.
  - 1.5. High buffering capacity. Strongly acid and acid soils which are highly permeable, very rich in humus, have a very high cation exchange capacity, are unsaturated, and contain large amounts of amorphous and poorly crystalline oxides of iron and aluminium, silica-allophanes, as well as considerable reserve of easily weatherable minerals. This group includes the well drained, ochric volcanic ash soils ( $B^O$ ), andosols ( $B^a$ ) and humus allitic soils ( $A_{\Pi}^T$ ).
  - 1.6. Very high buffering capacity. Very acid organic soils with a very high exchange capacity, unsaturated, with varying contents of amorphous iron and manganese hydroxides. This group includes the poorly to imperfectly drained, gleyed-peat and peat soils ( $\Gamma^M$ ,  $\Gamma^B$ ,  $\Gamma^{CT}$ ), as well as the acid soils of mangroves and marshes ( $M$ ,  $M^T$ ).
2. Soils with weakly acid A horizons (pH: 5.5 - 6.5) and neutral B horizons (pH: 6.5 - 7.5)
  - 2.1. Very low buffering capacity. Weakly acid soils, mainly loamy, with a medium humus content, rather unsaturated with a low content of iron and aluminium hydroxides as well as weatherable aluminosilicates. The soils of this group predominantly are moderately well to well drained and include sod-podzolic soils ( $\Pi^A$ ), brown lessive soils ( $B_{\Pi}$ ), and forest and meadow-forest gley soils ( $\Gamma_{\Pi}$ ,  $\Gamma_{\Pi X}$ ).
  - 2.2. Low buffering capacity. Weakly acid, mainly loamy soils with a low humus content and very low exchange capacity, moderately unsaturated, with high amounts of iron and locally aluminium hydroxides mainly crystallized and low amounts of easily weatherable aluminosilicates. Mainly moderately well drained, dark red ferrallitic soils ( $\Phi^K$ ), red and red-cinnamonic soils ( $K_{p}$ ), red residual ferrallitic soils ( $K_{p}^{\Phi}$ ), red-brown soils ( $K_B$ ) and red-brown residual ferrallitic soils.
  - 2.3. Rather low buffering capacity. Weakly acid, mainly loamy soils with a moderate humus content, moderately and weakly unsaturated, with rather low contents of iron hydroxides and considerable amounts of weakly weathered aluminosilicates. Predominantly well drained, brown forest soils ( $B$ ,  $B^{CT}$ ), sod-taiga soils ( $Z_T$ ), pale soils ( $\Pi_T$ ) and dry-arctic cryogenic soils ( $A_p$ ).

<sup>3</sup> The "groupings" described in this Appendix and the indices (No. 1-23) used in Appendix III were not correlated in the translation.

- 2.4. Moderate and rather high buffering capacity. Weakly acid and neutral, mainly loamy soils which have a considerable humus content, a high exchange capacity, and are weakly unsaturated and rich in slightly weathered aluminosilicates, with moderate contents of iron hydroxides. Mainly moderately well and weakly drained, chernozem-like prairie soils ( $\text{U}\pi$ ), reddish-black prairie soils ( $\text{U}\pi^{\text{K}}$ ), gley forest soils and meadow-forest soils ( $\text{T}\text{J}$ ,  $\text{T}\text{J}^{\text{CT}}$ ).
- 2.5. High buffering capacity. Weakly acid and neutral organic soils with a very high exchange capacity, medium to weakly unsaturated, locally with a high content of amorphous and crystalline iron and manganese hydroxides. This group consists mainly of poorly drained, gley-peat soils and shallow-peaty soils of low moor ( $\text{T}^{\text{H}}$ ,  $\text{T}^{\text{CT}}$ ).
3. Soils with calcareous B horizons as well as weakly acid or neutral A horizons and weakly alkaline B horizons. Upon acidification the pH and base saturation decrease, and the mobility of calcium- and iron-humates increases.
- 3.1. Very low buffering capacity. Neutral sandy soils, with a very low to low humus content and an extremely low exchange capacity. Mainly well drained, desert sandy soils ( $\text{II}\pi$ ) and ferruginated sandy soils ( $\text{II}\kappa$ ).
- 3.2. Low buffering capacity. Mostly loamy soils with a weakly acid A horizon, a low humus content and low exchange capacity, slightly unsaturated. Low contents of iron hydroxides in the upper eluvial horizons and a rather low aluminosilicate content. The well to moderately well drained, pale podzolized and solodic soils ( $\text{IIJ}^{\text{Э}}$ ), and solods ( $\text{C}\lambda$ ,  $\text{C}\lambda^{\text{CT}}$ ) belong to this group.
- 3.3. Rather low buffering capacity. Soils with weakly acid A horizons and alkaline B horizons. Calcareous, mostly loamy and heavy loamy, with a moderate humus content and exchange capacity, saturated or very slightly unsaturated. This group mainly consists of well drained, sod-calcareous soils or rendzinas ( $\text{Z}\kappa^{\text{M}}$ ,  $\text{Z}\kappa$ ,  $\text{Z}\kappa^{\text{CT}}$ ), grey forest soils ( $\text{II}$ ), and leached chernozems ( $\text{U}\text{B}$ ).
- 3.4. Medium and rather high buffering capacity. These soils are neutral in the A horizon and weakly alkaline in the B horizon, predominantly loamy, have a low to medium humus content, well saturated with cation bases and a high exchange capacity. The category is mainly represented by well drained, typical chernozems ( $\text{U}^{\text{T}}$ ), southern chernozems ( $\text{U}^{\text{Ю}}$ ), chestnut soils ( $\text{K}$ ), cinnamonic soils ( $\text{K}_{\text{y}}$ ) and mountain-meadow-steppe soils ( $\text{IIc}$ ).
- 3.5. High buffering capacity. Neutral and weakly acid soils, heavy loamy and clayey, with moderate and low humus content, high and very high exchange capacity, saturated. Mainly moderately and well drained, chernozem-smontizas ( $\text{U}^{\text{CT}}$ ), black vertisols ( $\text{Uc}$ ), grey soils ( $\text{CC}$ ), and terra rossas ( $\text{Tp}$ ).
4. Soils with a weakly alkaline A horizon (pH: 7.5-8.0) and a strongly alkaline (pH: 8.5-9.5) B horizon. Upon acidification the pH of the soils will decrease.
- 4.3. Rather low buffering capacity. Weakly alkaline, loamy sandy or sandy loamy soils with a low humus content and low exchange capacity, well saturated with bases. This group consists mainly of well drained, reddish-brown soils ( $\text{Kб}$ ), and red-brown residual lateritic soils ( $\text{Kб}^{\text{IT}}$ ).
- 4.4. Medium and high buffering capacity. Weakly alkaline, mostly loamy soils with a high humus content, saturated, locally with solonetzic properties. Mainly, moderately well drained meadow soils ( $\text{IIr}^{\text{M}}$ ,  $\text{IIr}$ ,  $\text{IIr}^{\text{CT}}$ ).
- 4.5. High buffering capacity. Alkaline and strongly alkaline, mostly loamy soils, with a low humus content and high exchange capacity, exchangeable sodium present. Predominantly, well drained chestnut solonetzic soils ( $\text{K}^{\text{CH}}$ ), light chestnut and brown semi-desert soils ( $\text{Kcб}$ ), including members with solonetzic properties ( $\text{Kcб}^{\text{CH}}$ ), grey-cinnamon solonetztes ( $\text{CK}_{\text{y}}^{\text{CH}}$ ), and reddish-brown solonetztes ( $\text{Kб}^{\text{C}}$ ).
- 4.6. Very high buffering capacity. Strongly alkaline, predominantly loamy and heavy loamy soils with low humus content and medium exchange capacity, containing exchangeable sodium. The well and moderately drained solonetztes ( $\text{C}_{\text{H}}$ ,  $\text{C}_{\text{HII}}$ ,  $\text{C}_{\text{H}}^{\text{CT}}$ ) are the dominant soils of this group.
5. Soils which are calcareous throughout and alkaline or strongly alkaline (pH: 8.0-9.5). The calcium carbonate content decreases upon acidification. The sodium carbonate and bicarbonate content as well as the alkalinity decrease in sodic solonchaks.
- 5.5. High buffering capacity. Calcareous and strongly calcareous soils of varying texture with a low humus content and low exchange capacity. The well to excessively drained arctic-desert soils ( $\text{Ap}$ ), high-mountain desert soils ( $\text{B}\pi$ ), serozems ( $\text{C}$ ), primitive desert soils ( $\text{II}\pi\text{p}$ ), stony desert soils ( $\text{IIk}$ ), and stony-gypsic desert soils ( $\text{IIr}$ ) belong to this group.

5.6. Very high buffering capacity. Calcareous, saline, and locally sodic, weakly drained soils that often have reducing water regimes. The category includes solonchaks ( $C_K^M$ ,  $C_K$ ,  $C_K^{CT}$ ) and takyrs ( $T_K$ ).

The alluvial soils ( $A^M$ ,  $A$ ,  $A^{CT}$ ) cannot be mapped individually at the considered scale of 1:80 M; they are therefore treated as inclusions and, as such, have been "allocated" to the adjacent mapping units.

ISBN 90-6672-045-X

