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Review

ROLE OF SOIL MULTIFUNCTIONALITY IN FUTURE SUSTAINABLE AGRICULTURAL DEVELOPMENT

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Soils represent a considerable part of the natural resources of Hungary. Consequently, rational land use and proper soil management – to guarantee normal soil functions – are important elements of sustainable (agricultural) development, having special importance both in the national economy and in environment protection. The main soil functions in the biosphere are as follows:

- conditionally renewable natural resource;
- reactor, transformer and integrator of the combined influences of other natural resources (solar radiation, atmosphere, surface and subsurface waters, biological resources), site of "sphere interactions";
- medium for biomass production, primary food-source of the biosphere;
- storage of heat, water, plant nutrients and – in some special cases – wastes;
- high capacity buffer medium, which may prevent or moderate the unfavourable consequences of various environmental stresses;
- natural filter and detoxication system, which may protect the deeper geological formations and the subsurface waters from various pollutants;
- significant gene reservoir, an important element of biodiversity;
- conservator of natural and human heritages.

Society has utilized these functions in different ways (rate, method, efficiency) throughout history, depending on the given natural conditions and socio-economic circumstances. In many cases the character of the particular functions has not been properly taken into consideration during the utilization of soil resources, and misguided management has resulted in their over-exploitation, in the decreasing efficiency of one or more soil functions, and – above a certain limit – in serious environmental deterioration.

The scientifically based planning and implementation of sustainable land use and rational soil management to ensure desirable soil functions, without any undesirable environmental side-effects, require the efficient control of soil processes.

Key words: soil functions, sustainable land use, control of soil processes, environmental stresses, degradation, pollution, soil moisture control

Introduction

Each society wishes to create favourable living conditions for its members. "Life quality criteria" are formulated in different ways by various societies or individuals, depending on the given geographical and socio-economic conditions, living standards, national, ethnical and religious traditions, history, policy, age, sex, educational level, position in the social hierarchy, etc. However, there is full agreement on the need for three elements:

– healthy, good quality food, and food security;
– clean water;
– a pleasant environment.

All three are closely related to rational land use and the sustainable management of land resources (Várallyay, 2002b).

Sustainable development

"Sustainable development" is a global objective which needs to be realized everywhere and in all fields, i.e. every region or country, whether it is advanced or developing, and in each branch of the economy, ranging from settlement policy to agriculture, from health care to industry or infrastructure development (Láng, 1995; Proc. of Seminar on Technologies…., 1985; Várallyay and Németh, 1996; Várallyay, 2000d; Greenland and Szabolcs, 1993).

The term "sustainable development" was not yet mentioned at the UN Conference on the Human Environment (Stockholm, 1972). Twenty years later it became the most fashionable and most frequently used term at the World Summit on the Environment (Rio de Janeiro, 1992), and it was the title of the Rio+10 Conference on Sustainable Development (Johannesburg, 2002).

The two parts of the expression ("sustainable" and "development") could be a potential point of conflict in themselves. They have been interpreted (and translated) in different ways in various countries, depending on their environmental and socio-economic conditions, historical background and even political situation, with more emphasis being laid sometimes on "development" and sometimes on "sustainability". Consequently, the realization of the declared aims and formulated objectives requires global compromises and joint efforts instead of regional or national economic and/or social confrontation.

FAO formulated the following definition in 1988: "Sustainable development is the management and conservation of the natural resource base, and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such sustainable development (in agriculture, forestry and fisheries sectors) conserves land, water, plant and animal genetic resources, is environmentally non-degrading, technically appropriate, economically viable, and socially acceptable." The definition formulated jointly by IUCN, UNEP and WWF tends to emphasize the biological elements: "Sustainable development is improving the quality of human life while living within the carrying capacity of supporting ecosystems" (Várallyay, 1997a,d).

The basic concept was adopted in Hungary according to the country's natural endowments and socio-economic circumstances in the "AGRO-21" Programme (1995).

Sustainable development includes efficient multifunctional agriculture (using environment-friendly, energy- and material-saving technologies and paying special attention to quality) and socially acceptable rural development, simultaneously. The given land resources (geological formations, relief, atmosphere, surface and subsurface water resources, soil biota, vegetation) are used, managed and – hopefully – protected by society according to its requirements, depending on the given socio-economic conditions, modified by the historical background and formulated by decision-makers at various levels (Fig. 1).

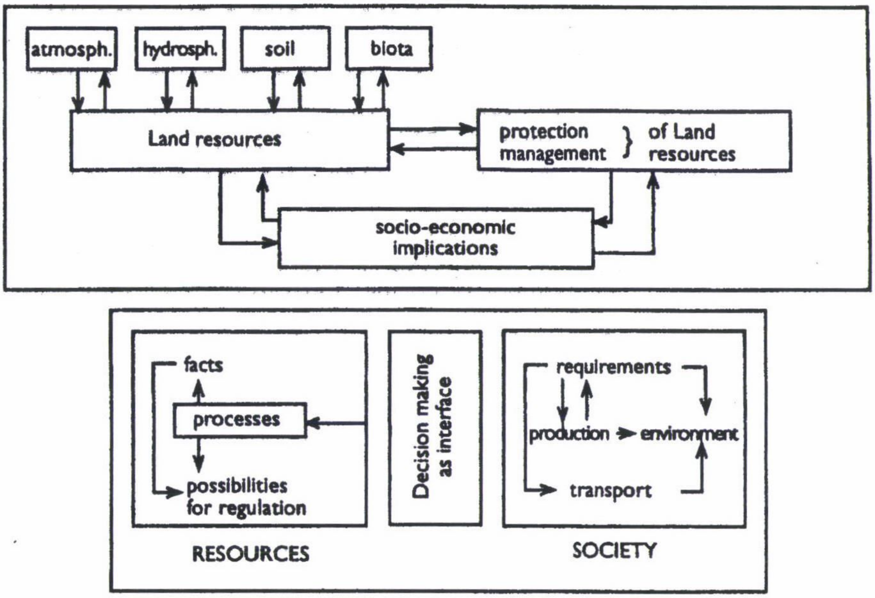

Fig. 1. Relationships between resources and society

Soil resources and soil functions

Land (the soil–water–near the surface atmosphere continuum, with its geology, relief and biota) represents a considerable part of the natural resources of Hungary (Láng et al., 1983; National Atlas of Hungary, 1989; Várallyay et al., 1985; Várallyay, 1998b, 1999, 2000a). Consequently, rational land use and proper soil management – to guarantee normal soil functions – are important elements of sustainable (agricultural) development, having special importance both in the national economy and in environment protection.

In our present world, soil is much more than the most important medium for primary biomass production. Consequently, it has to be managed as a multifunctional natural resource and its other functions have to be taken into consideration in the mechanism for optimizing rational land use. The main soil functions and their role in the biosphere and in the biogeochemical cycles of natural or human-applied elements or compounds can be summarized as follows (Várallyay, 1997c, 1998b):

• Soils are the most significant – conditionally renewable – natural resources. During rational biomass production they do not change irreversibly, their quality does not decrease unavoidably and fundamentally, but their "renewal", based on soil resilience does not happen automatically: soil conservation, the maintenance and increase of soil fertility, requires permanent activities, such as sustainable land use, agronomic measures, remediation and reclamation.

• Soil is a reactor and transformer, integrating the combined influences of other natural resources, such as solar radiation, atmosphere, surface and subsurface waters, deeper geological strata and biological resources. Their biogeochemical cycles develop a "life medium" for microbiological activities, as well as an ecological environment (landsite) for natural vegetation and cultivated crops. The pedosphere forms under the integrated influence of the lithosphere (geology, parent material), the atmosphere (climate, weather), the hydrosphere (surface and subsurface water resources), and the biosphere, but – at the same time – the pedosphere influences and modifies the mass and energy regimes of these spheres, as demonstrated in Figure 2.

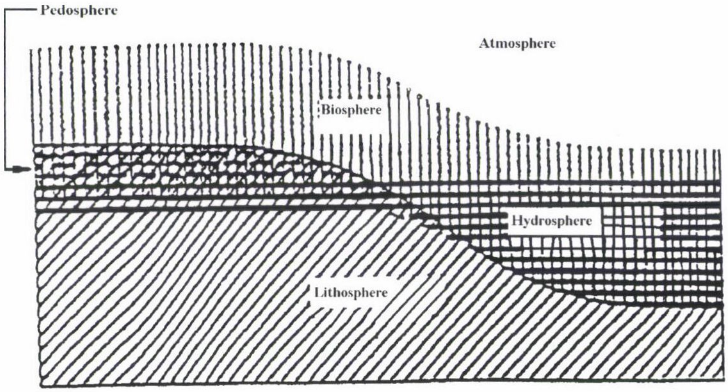

Fig. 2. The pedosphere

• Soil is the most important medium for biomass production (food, fodder, raw material for industry, alternative energy). Soil, as a four-dimensional [spatial (horizontal and vertical) variability and temporal dynamism] three- (or four-) phase, polydisperse system can simultaneously satisfy – to a certain extent – the ecological requirements (air, water and nutrient supply) of living organisms, the natural vegetation and cultivated crops. This special ability is the unique soil property: soil fertility, which varies greatly and has changed considerably depending on natural factors and human activities, such as land use and soil management. The territorial distribution of the most important soil characteristics determining their agro-ecological potential (soil fertility, soil productivity) is summarized in Table 1 (Láng and Csete, 1992; Láng et al., 1983; Várallyay et al., 1985). Soil is the primary food source of the biosphere, the starting point of the food chain.

• Soil is a major natural store of heat, water, plant nutrients and other elements, including wastes and (potentially) harmful elements or chemical compounds. The stored water and plant nutrients ensure the continuous moisture and nutrient supply of plants – according to their uptake dynamics – for shorter or longer periods without any additional supply (rain, irrigation, nutrient application). This soil function is the basis of rational moisture regime control and plant nutrition (Várallyay et al., 1985, 1992; Várallyay, 1994a, 1997c, 2002a).

• Soils represent a high capacity buffer medium for the biosphere, which, within certain limits, may moderate the various stresses caused by environmental factors (climatic droughts or excessively humid conditions, frost, etc.) and/or human activities (high input, fully-mechanized and chemically controlled crop production; liquid manure from large-scale livestock farms; wastes and waste waters originating from industry, transport, urban and rural development, etc.). Buffer systems have strict limits and boundary conditions. Sometimes this is forgotten by the "users", which leads to serious environmental problems. To prevent and avoid unfavourable side-effects, the tolerance limits must be identified, quantified, precisely determined and clearly formulated. This can only be done on the basis of comprehensive sensitivity (susceptibility, vulnerability) studies and impact analyses. Intensive international, regional and national studies have been carried out to determine these tolerance limits and target conditions. In Hungary comprehensive studies have identified and sometimes quantified the susceptibility of soils to wind and water erosion, acidification, salinization/alkalization/sodification, physical soil degradation (compaction, structure destruction, surface sealing) and chemical pollution. As an example, a simplified map of the susceptibility of soils to acidification is shown in Figure 3 (Várallyay et al., 1993; Várallyay, 2000b, d).

• Soil is an efficient "natural filter" and detoxication system that may prevent the deeper horizons and the subsurface waters from becoming contaminated by various pollutants deposited on the soil surface or put into the soil. A good example of such an assessment is the map of the nitrate leaching hazard, presented in Figure 4, according to Németh and his research team.

• Soil is a significant gene reservoir for the biosphere and thus an important element in biodiversity. A considerable proportion of living organisms live in or on the soil or are closely related to (sometimes depending on) the soil. This function has particular significance in the stabilization and conservation of biodiversity.

• Soil is the conservator of natural and human heritages.

These functions are all equally important, but society has used them in different ways (rate, method, efficiency) throughout history, depending on the given natural conditions and socio-economic circumstances. In many cases the character (territorial and temporal variabilities, changeability–stability–controllability, boundary conditions, limitations) of a certain function was not (properly or adequately) taken into consideration during the utilization of soil resources. In such cases the misguided management resulted in over-exploitation, decreasing the efficiency of one or more soil functions, and – above a certain limit – causing serious environmental deterioration (Várallyay, 1997c, 2002b).

Table 1
Territorial distribution of the various factors determining the agro-ecological potential in Hungary (in hectares)

Soil factors determining the agro-ecological potential	Total	%
PARENT MATERIAL		
1. Glacial and alluvial deposits	3 433 430	37.7
2. Loess, loess-like deposits	4 373 920	48.0
3. Tertiary and older deposits	681 440	7.5
4. Volcanic clayey tuffs ("Nyirok")	151 660	1.7
5. Limestone, dolomite	238 950	2.6
6. Sandstone	11 430	0.1
7. Shale, phyllite	38 530	0.3
8. Granite, porphyrite	9 740	0.1
9. Andesite, riolite, basalt	179 350	2.0
SOIL REACTION AND CARBONATE STATUS		
1. Strongly acidic soils	1 228 930	13.5
2. Slightly acidic soils	3 848 550	42.2
3. Calcareous soils (effervescence with dilute acid from the surface)	3 496 090	38.4
4. Salt-affected soils, calcareous from the surface	385 260	4.2
5. Salt-affected soils, non-calcareous from the surface	153 620	1.7
SOIL TEXTURE		
1. Sand	1 437 230	15.8
2. Sandy loam	875 460	9.6
3. Loam	3 932 320	43.2
4. Clay loam	1 692 630	18.6
5. Clay	632 840	6.9
6. Organic soils (peat, partly decomposed peat)	117 560	1.3
7. Coarse fragments (gravel, non- or partly weathered rocks, etc.)	421 410	4.6
SOIL WATER MANAGEMENT PROPERTIES		
1. Soils with very high infiltration rate (IR), permeability (P) and hydraulic conductivity (HC), low field capacity (FC) and very poor water retention (WR)	957 420	10.5
2. Soils with high IR, P and HC, medium FC and poor WR	1 009 910	11.1
3. Soils with good IR, P and HC, good FC and good WR	2 264 230	24.9
4. Soils with moderate IR, P and HC, high FC and good WR	1 735 640	19.1
5. Soils with moderate IR, poor P and HC, high FC and high WR	571 080	6.2
6. Soils with unfavourable water management, low IR, very low P and HC and high WR	1 349 750	14.9
7. Soils with extremely unfavourable water management, very low IR, extremely low P and HC, and very high WR	329 210	3.6
8. Soils with good IR, P and HC, and very high FC	117 560	1.3
9. Soils with extreme moisture regime due to shallow depth	774 650	8.4
ORGANIC MATTER CONTENT (t/ha)		
1. 0–50	481 750	5.3
2. 50–100	1 915 130	21.0
3. 100–200	2 586 270	28.5
4. 200–300	1 923 590	21.1
5. 300–400	1 887 270	20.7
6. 400–	305 440	3.4
DEPTH OF THE SOIL (limited by solid or slightly fragmented rocks, gravel, cemented layers, pans, peat, loose sand, groundwater, etc.)		
1. 0–20 cm	25 780	0.3
2. 20–40 cm	445 260	4.9
3. 40–70 cm	480 310	5.3
4. 70–100 cm	370 630	4.0
5. 100– cm	7 787 470	85.5

Fig. 3. Map of the susceptibility of Hungarian soils to acidification. 1. Strongly acidic soils (13.5%). 2. Highly susceptible soils due to their low buffering capacity (slightly acidic soils with light texture and low organic matter content) (14%). 3. Susceptible soils due to their medium buffering capacity (slightly acidic soils with medium texture and organic matter content) (5.0%)..4. Moderately susceptible soils due to their high buffering capacity (slightly acidic soils with heavy texture and/or high organic matter content) (23.2%). 5. Slightly susceptible soils (salt-affected) (5.9%). 6. Non-susceptible soils (calcareous from the surface) (38.4%)

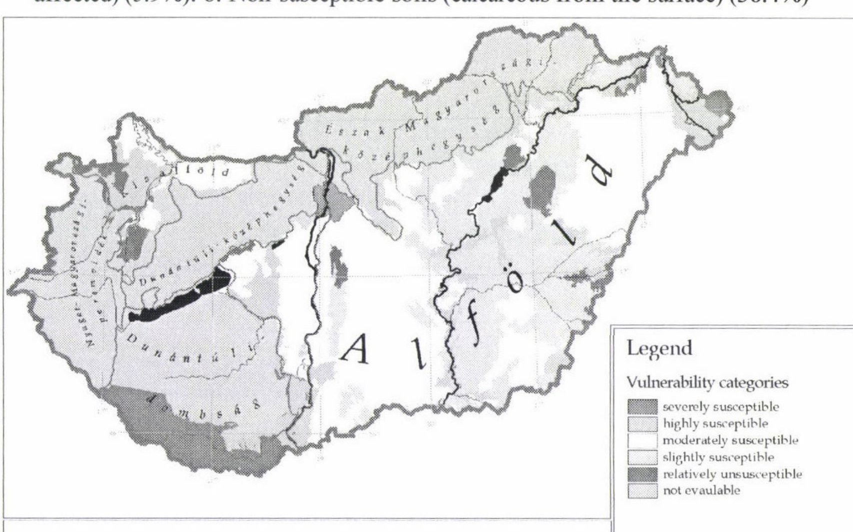

Fig. 4. Vulnerability of soils to N-leaching in Hungary

Soil processes and their control

The multifunctionality of the soil is determined by the combined influences of soil properties, which are the results of soil processes (mass and energy regimes, abiotic and biotic transport and transformation, and their interactions) under the combined influences of soil-forming factors. Any soil-related human activity influences the soil through these processes. Consequently, the control of soil processes is a great challenge and the main task of soil science and soil management is sustainable development (Várallyay, 1994b, 1997b, 2000b, c).

The conceptual model of a rational strategy for the control of soil processes is illustrated in Figure 5.

In spite of the fact that Hungarian natural conditions are relatively favourable for rainfed biomass production, more than half the soils are subject to various ecological constraints (Szabolcs and Várallyay, 1978; Várallyay, 1993b, 1999) (Fig. 6) and unfavourable soil processes:

• Soil degradation processes. The main soil degradation processes are: soil erosion by water or wind; soil acidification; salinization and/or alkalization; physical degradation (structure destruction, compaction); extreme moisture regime: drought sensitivity and waterlogging hazard; biological degradation; unfavourable changes in the plant nutrient regime; decrease in natural buffering capacity, soil (and water) pollution (Szabó et al., 1998; Várallyay, 1989a, 1998b, 2000b).

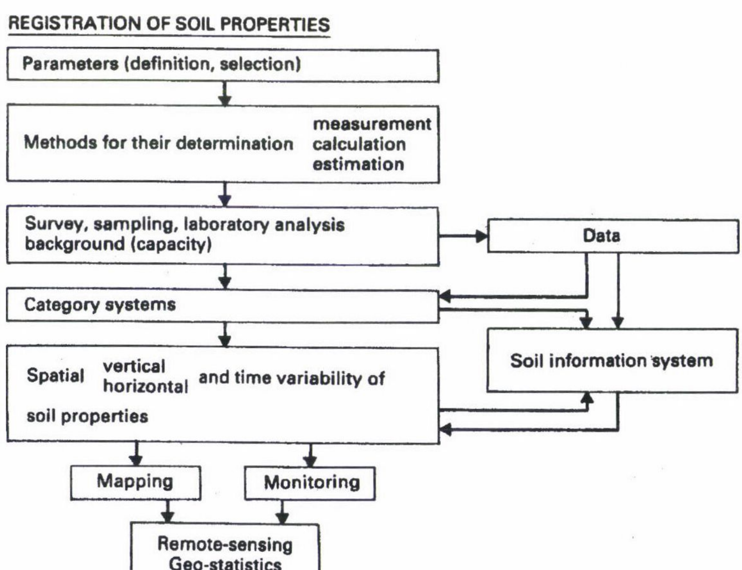

Fig. 5. Control of soil processes

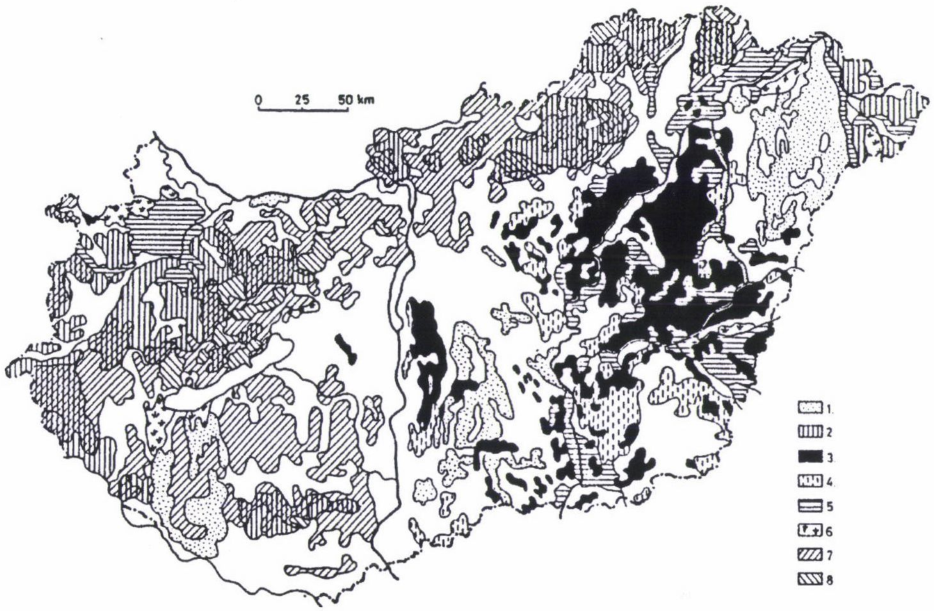

Fig. 6. Map of the limiting factors of soil fertility in Hungary (original scale: 1:500,000). 1. Extremely coarse texture. 2. Acidity. 3. Salinity and/or alkalinity. 4. Salinity and/or alkalinity in the deeper layers. 5. Extremely heavy texture. 6. Waterlogging. 7. Erosion. 8. Shallow depth

• Extreme moisture regime. The annual precipitation (especially on the Hungarian plains) shows extremely high spatial and temporal variability – even on a micro-scale. Non-uniform rainfall distribution, the heterogeneous microrelief of the "flat" Hungarian Plain, and the unfavourable hydrophysical properties of soils are the main reasons for the extreme moisture regime: the simultaneous hazard of waterlogging or over-moistening and drought sensitivity on large areas, sometimes in the same places within a short period. Based on a detailed assessment of the physical and hydrophysical properties of soils (texture, structure; water retention curves: total and field capacity, wilting percentage, available moisture range; infiltration rate; saturated and unsaturated hydraulic conductivity) and on the factorial analysis of field water balance and soil moisture regime the general conclusion was drawn that 43% of Hungarian soils can be characterized by unfavourable, 26% by moderate and 31% by good moisture regime. Their extent is illustrated in Figure 7 for the whole country, and in Figure 8 for the administrative regions of Hungary, indicating the main reasons for the differences (Várallyay, 1989b, 1997b, 2001).

• Nutrient stresses. The deficiency or accumulation and/or toxicity of one or more elements in the biogeochemical cycle are strongly increasing environmental threats, mainly due to the non-scientifically based, inadequately controlled, sometimes over-chemized social development, including biomass production and waste management (Kádár, 1991; Várallyay, 1994a, 2002a; Várallyay and Németh, 1996; Várallyay et al., 1992).

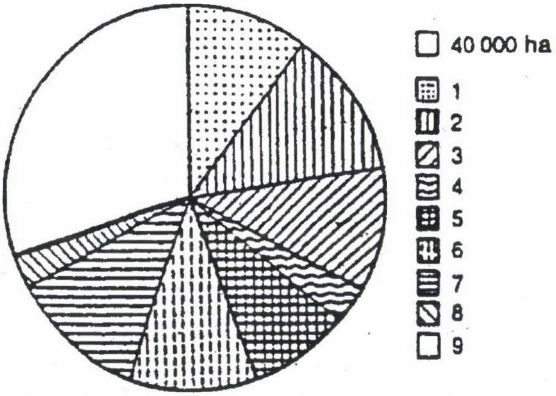

Fig. 7. Distribution of soils according to their hydrophysical properties in Hungary.
1–5 = Soils with unfavourable hydrophysical properties: 1: due to very coarse texture; 2: due to very heavy texture; 3: due to strong salinity–alkalinity; 4: due to waterlogging; 5: due to shallow depth; 6–8 = Soils with moderately unfavourable hydrophysical properties: 6: due to coarse texture; 7: due to heavy texture or clay accumulation in the B horizon; 8: due to moderate salinity/alkalinity in the deeper layers; 9 = Soils with good hydrophysical properties

• Environmental pollution. The accumulation or mobilization of various, potentially harmful (or even toxic) elements (or compounds) in the "life media" of various organisms, in air, in water, in soil; or in the biomass of various organisms within the soil–water–plants–animals–human beings "food chain" (Kádár, 1991; Várallyay, 1993a, 1996, 1998a, b).

The scientifically based planning and implementation of sustainable land use and rational soil management require adequate soil information: exact, reliable, "detectable" (preferably measurable) and accurate, quantitative territorial data on well-defined soil and land properties, including the characterization of their spatial (vertical, horizontal) and temporal variabilities and pedotransfer functions; on the soil processes and biogeochemical cycles, including their determining and influencing factors and their mechanisms, and on the actual and/or potential impacts of human activities.

In Hungary a large amount of information is available on the ecological conditions, including soils, as a result of long-term observations, and various soil surveys, analytical and mapping activities conducted at the national (1:500,000), regional (1:100,000), farm (1:10,000–1:25,000) and field levels (1:5,000–1:10,000) over the past 60 years (Fésűs et al., 2000; Várallyay, 1993a, 1994c). Recently a considerable part of these data have been organized into computer-based GIS databases giving opportunities for the prevention, elimination or reduction of environmental stresses and their unfavourable consequences (Szabó et al., 1998; Várallyay, 1994c).

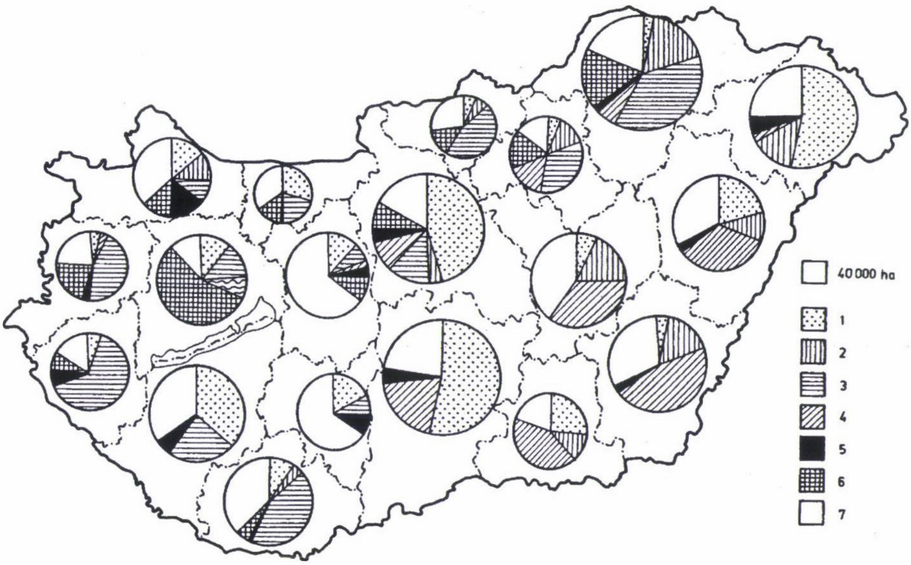

Fig. 8. Distribution of soils according to their hydrophysical properties in the counties (administrative districts) of Hungary. 1–6: Soils with unfavourable hydrophysical properties: 1: due to coarse texture; 2. due to heavy texture; 3: due to clay accumulation in the B horizon; 4: due to salinity/alkalinity; 5: due to waterlogging; 6: due to shallow depth. 7 = Soils with good hydrophysical properties

Main elements of rational land use and soil management for sustainable, multifunctional agriculture

Efficient, economically viable, socially acceptable and environmentally sound sustainable land management includes the following main elements (Várallyay, 1994b, 1997a; Várallyay and Németh, 1996):

1. Territorial coordination of the agroecological conditions (land-site characteristics) and the agro-ecological requirements of cultivated crops, taking into consideration both production and environmental aspects on short-, mid- and long-term scales:
   - rational land use and optimization of cropping patterns under the given (and hardly controllable) natural conditions;
   - selection of proper crops (crop rotations) and cultivars for the given natural circumstances (selection and breeding of varieties or genotypes tolerant of certain ecological constraints, such as frost, soil acidity, salinity/alkalinity, drought, moisture surplus, extreme soil texture, soil compaction, etc.);
   - improvement of (soil) ecological conditions according to crop requirements (amelioration of land, reclamation/improvement of soil, soil conservation, irrigation and drainage, proper agronomic measures).

2. Rationalization of the structure of agricultural fields (under the new ownership structure):

- optimization of field size according to the given physiographic conditions: development of more homogeneous fields for uniform agrotechnical measures, taking into consideration a rational level of biodiversity;
- development of proper infrastructure: rational territorial arrangement of fields, roads, canals, buildings, forest shelter belts, etc., taking into consideration landscape preservation requirements, as well.

3. Reduction (minimalization) of production wastes: plant residues; animal excrements, such as organic manure and liquid manure; wastes from yield and food processing, with their most efficient recycling without any harmful environmental side-effects.

4. Control (prevention, elimination or at least moderation) of undesirable soil degradation processes. Priority must be given to efficient preventive measures. For successful prevention satisfactory prognosis is necessary. This can be rationally based on a comprehensive
- sensitivity analysis: evaluating the susceptibility of soils to various soil degradation processes;
- impact analysis: evaluation and forecast of the potential "positive" and "negative" impacts of various human activities.

5. Improvement of the efficiency of agricultural water management and soil moisture control. The greatly variable climate and weather conditions, the relief (undulating surface and the heterogeneous microrelief of the "flat" Hungarian Plain), and the unfavourable hydrophysical properties of some soils necessitate special "two-way" soil moisture control. Because both irrigation and drainage have serious ecological and economic limitations every effort should be made
- to increase water storage within the soil in plant-available form without any unfavourable environmental consequences: to help infiltration into the soil; to increase the water storage capacity; to reduce the immobile and not plant-available moisture content;
- to reduce evaporation, surface runoff and filtration losses of water (atmospheric precipitation and irrigation water);
- to improve the vertical and horizontal drainage conditions of the soil profile or the given area (prevention of over-saturation and waterlogging).

Most of these measures are – at the same time – an integral part of environment protection (Table 2).

6. Precision plant nutrient management:
- rational use of fertilizers based on crop requirements (dynamics of their nutrient uptake), soil conditions and agroclimate;
- efficient recycling of crop residues and production wastes (including organic manure);
- utilization of other wastes with utilizable plant nutrient content and without potentially harmful chemical compounds.

7. Soil pollution control. The main elements of efficient soil pollution control – based on a comprehensive assessment of the quantity, status and regime of pollutants in the soil–water–plant–near the surface atmosphere continuum and in the food-chain (Fig. 9), and on the evaluation of their ecological impacts and environmental hazards – are as follows:

- emission/imission reduction (preventing or reducing the quantity of pollutants deposited on or transported to the soil surface or into the soil);
- prevention of the mobilization of potentially harmful chemical compounds or elements which are already present in the soil but in – temporarily – immobile form;
- decrease in the susceptibility/vulnerability of soil to various pollutants (through an increase in the buffering capacity of soils), making it tolerant of a higher critical load of pollutants and consequently reducing the "exceedance risk" and the unfavourable ecological consequences.

The conceptual model of such a system is shown in Figure 10.

Table 2

Elements and methods of soil moisture control with their environmental impacts (EI)

Elements	Methods	EI*
Reducing		
surface runoff	Increase in the duration of infiltration (moderation of slopes; terracing contour ploughing; establishment of permanent and dense vegetation cover; tillage; improvement of infiltration; soil conservation farming system)	1,1a,5a,8
evaporation	Helping infiltration (tillage, deep loosening); Prevention of runoff and seepage, water accumulation	2,4
feeding of ground-water by filtration losses	Increase in the water storage capacity of soil; moderation of cracking (soil reclamation); surface and subsurface water regulation	5b,7
rise of the water table	Minimalization of filtration losses (↑); groundwater regulation (horizontal drainage)	2,3,5b,5c
Increasing		
infiltration	Minimalization of surface runoff (tillage practices, deep loosening) (↑)	1,4,5a,7
water storage in soil in available form	Increase in the water retention of soil; adequate cropping pattern (crop selection)	4,5b,7
Irrigation	Irrigation; groundwater table regulation	4,5c,7, 9,10
Surface } drainage	surface } moisture control (drainage)	1,2,3,5c,6,7, 11
Subsurface	subsurface	

* Reference numbers: see below

Favourable environmental effects

Prevention, elimination, limitation or moderation of: water erosion (1); sedimentation (1a)
secondary salinization, alkalization (2)
peat formation, waterlogging, overmoistening (3)
drought sensitivity, cracking (4)
plant nutrient losses by:
surface runoff (→ surface waters eutrophication) (5a)
leaching (→ subsurface waters) (5b); immobilization (5c)
formation of phytotoxic compounds (6)
"biological degradation" (7)
flood hazard (8)

Unfavourable environmental effects

overmoistening, waterlogging, peat and swamp formation, secondary salinization/alkalization (9)
leaching of plant nutrients (10)
drought sensitivity (11)

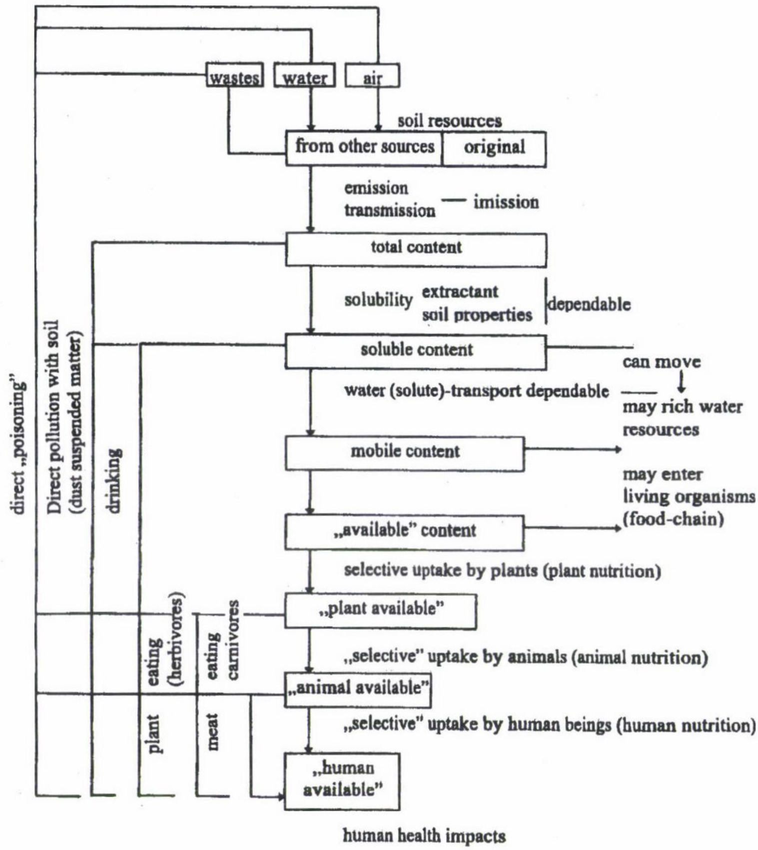

Fig. 9. Sources and pathways of soil pollution

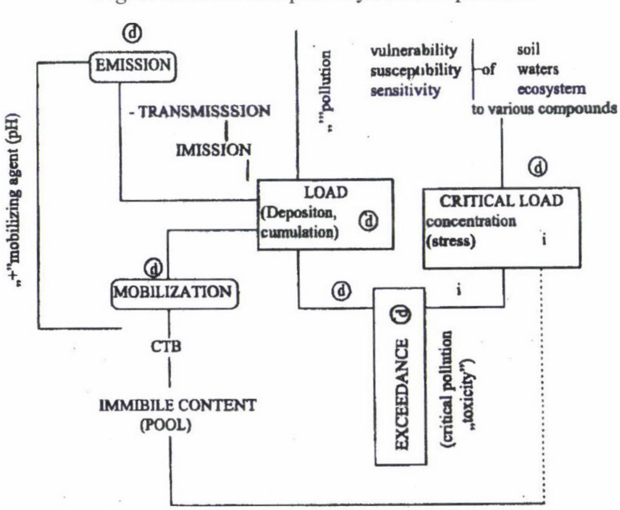

Fig. 10. Strategy for pollution control (i: increase; d: decrease)

Conclusions

Agricultural production is economy driven. In contrast, the maintenance of soil multifunctionality, the quality of surface and subsurface water resources and the protection of the natural environment are not (fully) economy-dependent elements of sustainable development, but imperative tasks of human society. All actions which aim at or assist soil multifunctionality are important elements in sustainable multifunctional agricultural development. These are tasks jointly facing the state, decision makers at various levels, land owners, land users, and – to a certain extent – each member of society. The joint efforts of all will be required to harmonize agricultural production and environment protection to give an improvement in the quality of life.

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