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Contents

Environmental protection through sustainable soil management, a holistic approach

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Introduction

Environmental protection aims at protecting and maintaining natural resources, including soils, which play a central role at the cross-roads between the atmosphere, the hydrosphere, the geosphere and the biosphere. Today, nearly all natural resources, including soils, are used by human societies. Therefore, the quesiton arises, how this use can be performed in a sustainable way, aiming at maintaining or even improving ecological, economic, social and cultural conditions for future generations (World Commission on Environment and Development, 1987).

Because of the central role of soils, sustainable soil management is the first step towards sustainable use of natural resources. In this context, the functions of soils for human societies and the environment are of special importance.

The six main functions of soil and land

Soils have at least six different functions for the social and economic development of humankind, which can be distinguished into three more ecological functions and three others directly linked to human activities defined as technical, industrial and socio-economic functions (Blum 1998 a, 1998 b).

The three ecological functions are:

1. production of biomass, ensuring food, fodder, renewable energy and raw materials. These well-known functions are the basis of human and animal life;

2. filtering, buffering and transformation capacity between the atmosphere, the ground water and the plant cover, strongly influencing the water cycle at the air surface as well as the gas exchange between terrestrial and atmospheric systems, and protecting the environment, including human beings, against the contamination of ground water and the food chain. This function becomes increasingly important, because of the many solid, liquid or gaseous, inorganic or organic depositions, on which soils react through mechanical filtration, physical or chemical absorption and precipitation on its inner surfaces, or microbiological and biochemical mineralization and metabolization of organic compounds (Blum 1996). These biological reactions may also contribute to global change through the emission of gases from the soil into the atmosphere, because globally the total pool of organic carbon in soils is three times higher than the total organic carbon in the above-ground biomass and twice as high as the total organic carbon in the atmosphere. Under this aspect, soils are a central link in the biotransformation of organic carbon and continually play a role in releasing CO_2 and

other trace gases into the atmosphere. These gases are very important for processes of global change, which in this case involve large-scale feedback of many localized small-scale processes. As long as these filtering, buffering and transformation capacities can be maintained, there is no danger to the groundwater or to the food chain. However, these capacities of soils are limited and vary according to the specific soil conditions.

3. a biological habitat and gene reserve, with a large variety of organisms. Soils contain more species in number and quantity than all other above-ground biota together. Therefore, soils are a main basis of biodiversity. Human life is extremely dependent on this biodiversity, because we do not know if we will need new genes for maintaining human life from soils in the near or the remote future. Moreover, genes from the soil become increasingly important for many technological, especially biotechnological and bioengineering processes.

In addition to these three ecological functions, soils have three other functions more linked to technical, industrial and socio-economic uses:

4. They are the physical basis for technical, industrial and socio-economic structures and their development, e.g. industrial premises, housing, transport, sports, recreation, dumping of refuse etc. One of the main problems in this context is the exponential increase of urban and peri-urban areas, including transport facilities between them. This is not only true for Europe, but also for other continents, and especially for countries in development in Africa, Latin America and Asia.

5. Soils are a source of raw materials, e.g. clay, sand, gravel and minerals in general, as well as a source of energy and water. Raw materials are the basis for technical, industrial and socio-economic development.

6. Last but not least, soils are important as a geogenic and cultural heritage, forming an essential part of the landscape in which we live, concealing and protecting paleontological and archaeological treasures of high value for the understanding of our own history and that of the earth.

In view of the soil as an absolutely limited resource which cannot be extended or enlarged, the use of these six main functions of soil and land, which is often concomitantly in the same area becomes the key issue of sustainability. Under holistic aspects soil or land use can be defined as the temporarily or spatially simultaneous use of all these functions, although they are not always complementary in a given area.

Sustainability, interaction and competition between soil functions

For understanding the role of soil in a sustainable environment, it is necessary to define all the interactions and competitions which exist between soil functions and their uses.

In this context, three different categories of interaction and competition can be distinguished:

1. exclusive competition between the use of soil for infrastructural development, as a source of raw materials and as a geogenic and cultural heritage on the one hand, and

the use of soil for biomass production, filtering, buffering and transformation activities and as a gene reserve, on the other hand.

This becomes evident by the sealing of soil through urban and industrial development, e.g. the construction of roads, of industrial premises, houses, sporting facilities or when soils are used for the dumping of refuse, all this being known as the process of urbanization and industrialization, thus excluding all other uses of soil and land, see Fig. 1. In this context, the exponential increase of urbanization on a world-wide level is one of the main indicators for irreversible soil losses, which means unsustainability in soil and land use in the long run.

The process of sealing of soils is still very prominent in most of the European countries and leads to severe soil losses.

2. A second category of competition exists through intensive interactions between infrastructural soil and land uses and agriculture and forestry as shown by Fig. 1, the scale of which indicates the intensity of interference, which significantly contributes to the problem of soil contamination and pollution, because all these linear and point sources are loading local soils with contaminants on three different pathways: through atmospheric deposition, on waterways and through terrestrial transport, see Fig. 2.

Figure 2 illustrates the many possible interactions between infrastructural soil and land use on the one hand, and agriculture and forestry on the other hand. This is especially true for densely populated areas in Europe and other regions of the world. In this context, it also seems necessary to point out that soils are the last but one sink for many inorganic and organic depositions, the last one being the bottom of the oceans. In Figure 2, different forms of loads can be distinguished: inorganic and organic depositions from traffic and transport and from urban and industrial activities. Most of these loads, such as severe acidification, pollution by heavy metals and other elements, pollution by xenobiotic organic compounds, deposition of non-soil materials, severe salinization and alcalinization are more or less irreversible, because soils act as a sink (Blum 1998 c). Irreversibility is defined as the non-reversibility by natural forces or technical remediation measures within 100 years, a time span which corresponds to about four human generations.

Only few processes of soil degradation, such as superficial compaction or the contamination by biodegradable organics or by small amounts of heavy metals, can be regarded as reversible by technical measures, or natural remediation, e.g. bioturbation and bio-accumulation processes (Blum 2000 a). Some of the adverse effects of transport, urbanization and industrialization on agricultural and forest soils are exemplified by Blum 1998 c.

3. A third form of competition also exists among the three ecological soil uses themselves, as shown in Fig. 3. Waste and sewage sludge deposition on soil as well as intensive use of fertilizers and pesticides, in addition to the deposition of air pollutants (compare Fig. 2) may have a negative influence on the groundwater and the food chain, surpassing the natural capacity of soils for mechanical filtering, chemical buffering and biochemical transformation. This is specifically true for high input agricultural systems. In this context, it should be remembered that agriculture

and forestry not only produce biomass above the ground, but also influence the quality and quantity of the groundwater production underneath, because each drop of rain falling on the land has to pass the soil before it becomes groundwater.

Such problems are well-known for many parts of the world, where contamination of the groundwater as drinking water though nitrate, pesticides and other chemical compounds from the use of fertilizers, pesticides and the deposition of sewage sludge and waste compost are analyzed. When the groundwater is used as drinking water, the competition between the production of food and fibre on one side and the production of ground water on the other side is a competition between the satisfaction of human basic needs. In many areas of the world, especially in Europe, conventional agricultural production becomes increasingly controlled by quality standards for drinking water. It is easier to transport and sell food and fodder than to do the same with the necessary amount of drinking and household water.

What is the role of soil management in a sustainable environment?

Sustainability in the use of soil seems only possible by a temporal and/or spatial (local or regional) harmonization in the uses of the cited six soil functions, excluding or minimizing irreversible uses, e.g. sealing, excavation, sedimentation, acidification, contamination or pollution, salinization and others. This definition includes the dimensions of space and time.

Summarizing, the role of soil management in a sustainable environment is to provide multiple functions for the well-being of humans. However, the necessary harmonization of the uses of the six soil functions is not a scientific question, but a political one, which means that all people living in a given area or space have to decide which soil functions they may use at a given time and/or a given space (by a top-down or bottom-up approach). Scientists only have the possibility to develop scenarios and to explain which causes and impacts may occur when different options are exercised. Those scenarios can be condensed into indicators, which may help politicians and decision makers as well as people living in a certain area to choose the right options.

The use of indicators for the development of soil and land use policies, the DSR and DPSIR approaches

In the last years, the Organization of Economic Cooperation and Development (OECD) has developed a framework to address agri-environmental linkages and sustainable soil and land use by the Driving Force-State-Response (DSR) Framework (OECD, 1998). In this framework, environmental, economic and social as well as other driving forces are described, aiming at understanding the state of soil and land and giving a basis for responses to soil problems by steering the driving forces (Blum 2000 b).

In this concept, driving forces describe the cause of changes in environmental conditions of soil and land, e.g. as agri-environmental indicators for agricultural land. The state describes the effects on soil use and the responses describe possible actions to be taken, in order to respond to the changes in the environment, in the sense of new soil policies, modifying and controlling the driving forces.

Indicators used in this context should have the following characteristics:

- policy relevance: this means that data should be more demand (issue) than supply (data)-driven and indicate important political features;
- analytical soundness: indicators must be based on science and reveal cause-response relationship in a clear way;
- easy interpretation: indicators should be easily understandable for stakeholders, e.g. farmers, citizens, as well as for decision makers and politicians;
- measurability: indicators should be feasible and cost-effective in data collection, processing and dissemination.

In recent years, within the context of environmental protection efforts by the European Environment Agency (EEA) the DPSIR framework approach was developed, which can be also applied to soil. This framework includes driving forces (D), pressures (P), state (S), impact (I) and responses (R), and is easy to use by politicians and decision makers (EEA 1999). For example, in the agricultural context, a driving force can be the lowering of prices for agricultural commodities on local markets, thus decreasing the income of farmers. The pressure coming out of that is nutrient mining, because the farmer has no money to replace nutrients by fertilizers, which he cannot afford to buy. This leads to soil degradation by nutrient depletion, and in extreme cases also to soil erosion (state), if no anti- erosive measures under slope conditions can be taken due to a lack of funds. The direct impact is a change in soil function, which means a decrease in soil fertility and a decrease in biomass production. An indirect impact can be changes in population size and distribution in rural areas, due to low income. – The responses should not be to remediate the state of the soil or to alleviate the pressure itself, e.g. through furnishing fertilizers to local farmers, but it should be directed towards improving market conditions and maintaining reasonable market prices for agricultural commodities. In this case, the response would be an economic and social response and not a technical one.

Conclusions

In the next century, the role of soil in a sustainable environment will be much more critical than ever before, because we have reached the cross-roads of conflicts between the uses of different functions, with severe environmental problems in many areas. Soil use therefore will occur under quite different ecological, technical and socio-economic conditions than in the centuries before. This is not only due to increasing competition for space, e.g. through the growth of urbanization and industrialization with all its socio-economic and environmental impacts, especially in Europe, but also through increasing and severe competition between biomass production on one side and ground water production on the other side, including problems of biodiversity and global change, e.g. through the extinction of species and through the emission of gases from soils into the atmosphere (Blum 2000 c).

Therefore, a new concept of soil and land management is needed in order to maintain a harmonized use of functions of soils for a sustainable development. Soil physics can play an important role in these endeavours because the spatial arrangement of soil materials is decisive for all physico-chemical and biological soil processes.

This holistic approach to the role of soil in a sustainable environment may be helpful in order to define the specific ecological, socio-economic and technical problems, thus enabling science to develop more comprehensive scenarios for sustainable development in the next century. The use of indicators can help in this endeavour because they can be used in a framework which is understandable for those who have to take initiative in order to solve the problem. These are politicians, decision-makers and administrators. The DSR and the DPSIR approaches seem to be a reasonable tool in order to alleviate soil and land management problems and to create better environmental conditions in the future.

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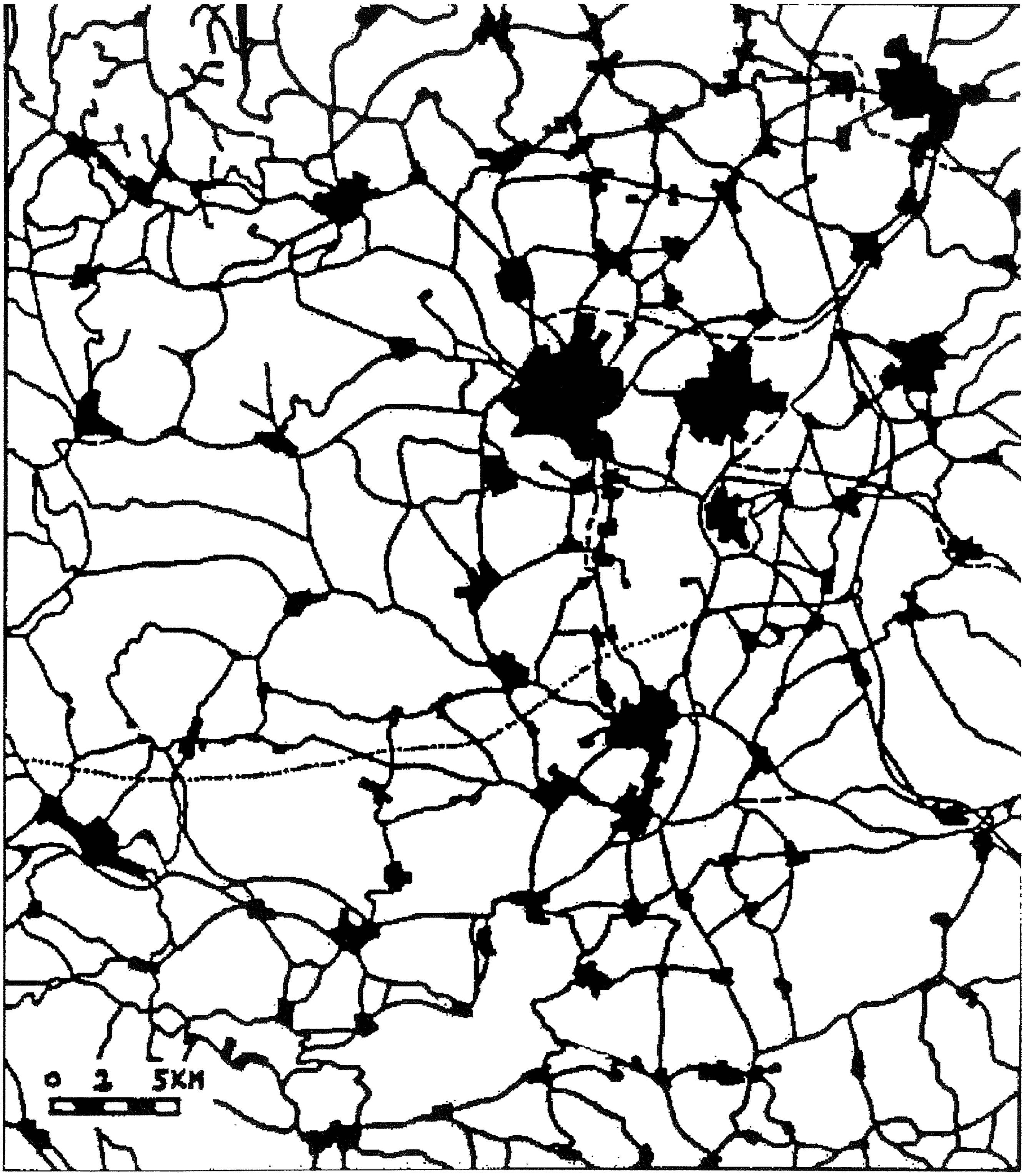
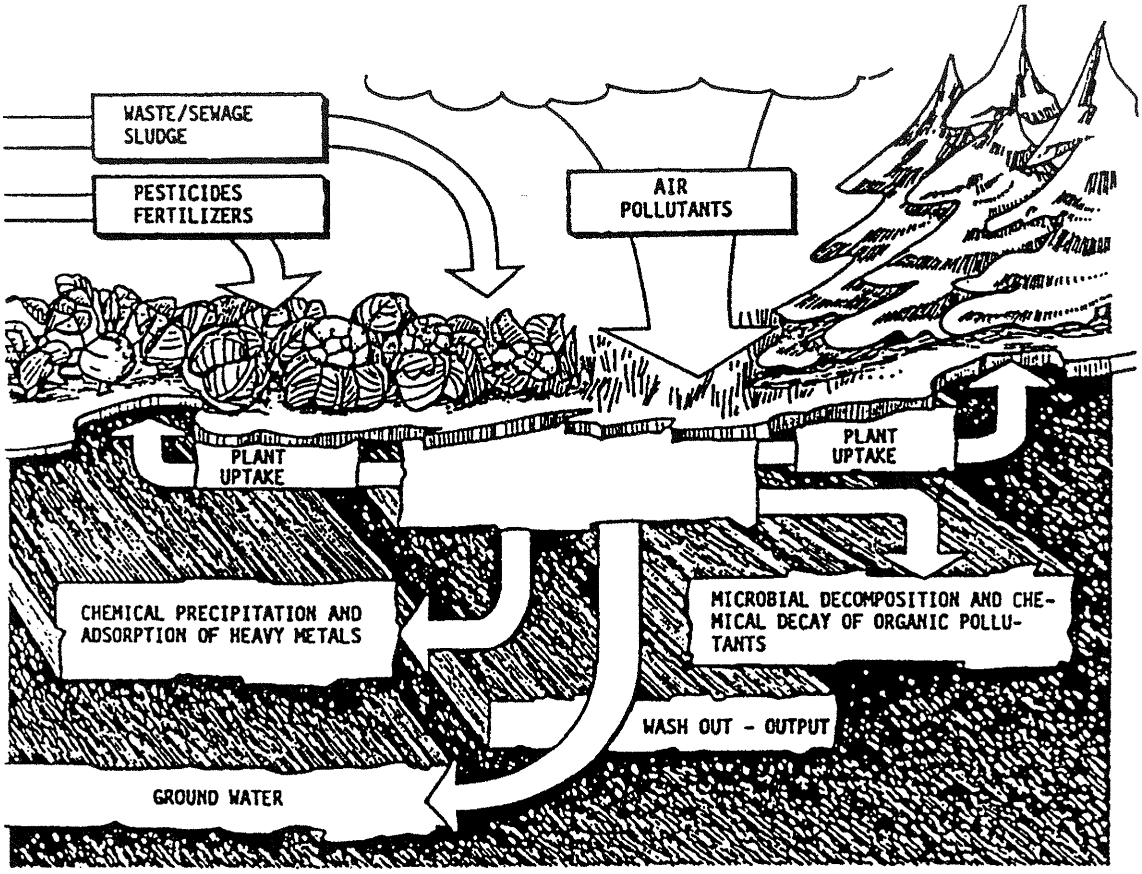


Fig 1 Sealing of soils and landscapes by urban and industrial development (Baar region in south-western Germany)



SOIL CONTAMINATION BY FERTILIZERS, SEWAGE SLUDGE AND PLANT PROTECTION PRODUCTS

Fig 2 Soil contamination and pollution through excessive use of fossil energy and raw materials

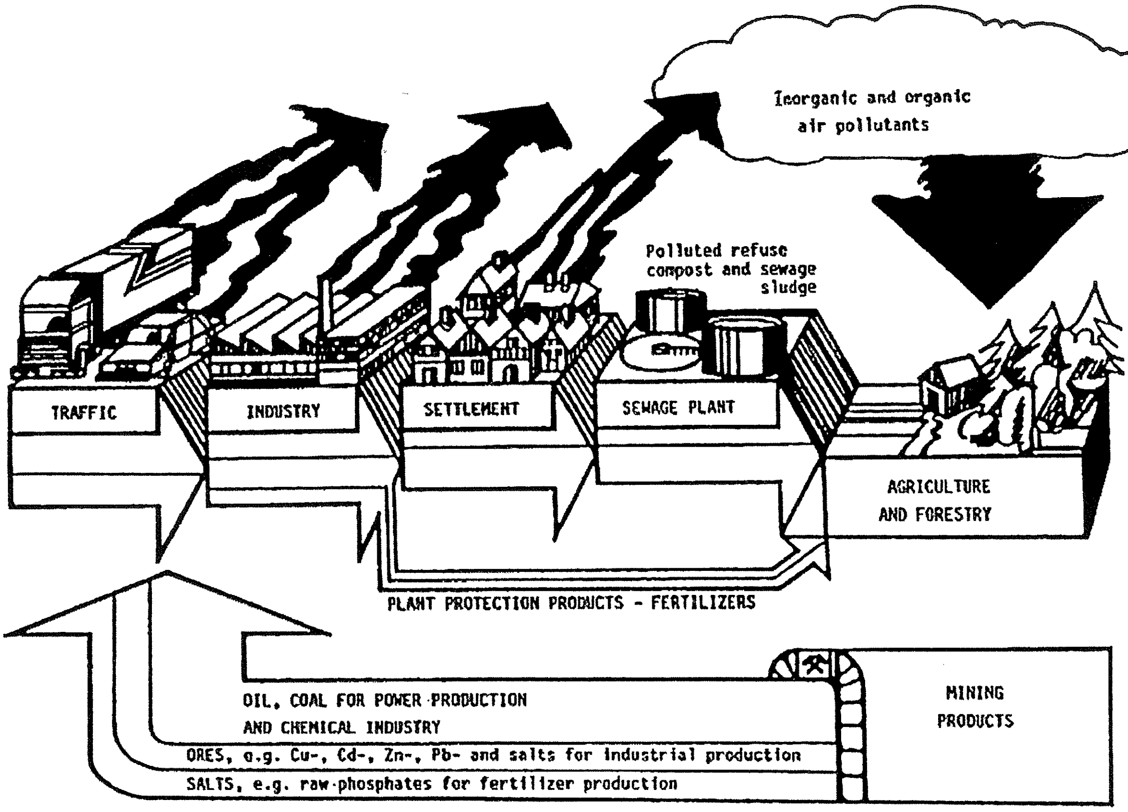


Fig 3 Competition between the production of biomass and groundwater and the maintenance of biodiversity, due to pollutive depositions and the use of fertilizers and plant protection products

Progress and perspectives in soil physics

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Introduction

Soil physics was first defined as the capacity of a soil to provide a medium favorable to the development of the whole biomass, in particular plants. Nowadays, beyond the scope of agricultural production, soil physics includes our environment, i.e. constraints related to land layout as well as the protection of water quality or food health.

Soil physical properties depend on several factors. Intrinsic soil factors should be distinguished from external factors, in particular environmental and climatic factors. Soil is a physical support used for the repeated passage of animals and farm machines, as well as a reservoir and transit area for water and gas. The development of the whole biomass, in particular plants, depends on the soil capacity to allow the transport of gas and water from one place to another. Physical properties control some of the chemical properties and especially ion transfers for plants and chemical reactions. The presence of ions in excess, whether useful or not, can cause toxicity phenomena.

This paper aims to present ideas regarding the physical properties of soils. It does not attempt to be exhaustive. It emphasizes the role of human activity in soil properties. We will show how the study of soil properties and processes is concerned with integrating physics to understand the fundamental soil processes controlling transport, cycling and the bioavailability of elements or molecules. These phenomena are studied on multiple scales ranging from the molecule to the field, and up to the regional scale.

Definition

Soil Physics addresses topics related to soil physical properties and processes, and mass and energy transport in soils. Its main goal is to determine the mechanisms of temporal and spatial variability of these properties. This implies developing models for integrating the basic processes as well as describing soil systems, from individual constituents up to soil organization on a regional scale.

The specific areas of interest include the fate and transport of heat, gas, solutes and solid particles in soils and the environment, the role of stresses on soil properties on various space and time scales, and the control of biological activity and its relation with soil functioning.

Spatial distribution and context

The diversity of rocks on which soils develop, the type of climate and the vegetation are keys to understanding soil distribution on the landscape scale. Nowadays, the results of the studies performed in soil surveys are integrated into databases. Soil maps as well as thematic maps are now the graphical representation of the knowledge of soils and of their properties in a given territory at a given time and on a given scale. On a catchment scale, the diversity and pattern of soil distribution can be understood rather well. Depending on the climate, different types of soils, for instance from the top of the hill to the valley, can be differentiated. In general, their drainage is a function of their position in the topography, of their amount of fine fraction, but also of other factors, for instance the more or less stoniness of the soil.

In traditional agriculture, for example up to the middle of the 20th century in Europe, the land use pattern clearly reveals the main factors that have determined land development in the past. The soils which were too hard to cultivate or with an excess of water were used as pastures or kept as forests. Generally, the soils with few physical and chemical constraints (low slope, sufficient water reserve, easy tillage, or chemical content) were used for crops. The small size of plots restricted the possible transfer of particles by runoff over short distances. Even after 2000 years of cultivation, the agricultural system based on mixed crop-livestock farming with low inputs has been rather well adapted to environmental constraints in a given region at a given time.

Throughout history, land-use has evolved permanently. To summarize, we can say that fertilization techniques and development operations have removed some constraints while introducing other new ones. In recent times, many farms and regions throughout the world have become specialized. In many regions, the evolution of pasture, crop and forest areas, the various livestock farming types and the structure of farms over the last few years have evolved considerably during the last 50 years. For instance, the tractor, which replaced draught animals, led to an increase in the diary herd. Many natural pastures were ploughed and replaced by an alternation of crops and temporary pastures. Grain and for instance fodder maize for ensilage was also introduced after the sixties in the northern part of Europe, up to about 55°-north latitude. In low lands, new areas where only forests had grown previously were used for crops. Eliminating constraints resulting from fertilization has also enabled the development of intensive farming. The soils devoted to pastures are now cultivated and those at the bottom of valleys (low lands) have been drained. In order to increase the field pattern, hedges and banks have been removed at the periphery of the plots. By contrast, in marginal areas, i.e. at high altitudes with steep slopes, the reforestation of abandoned land has entirely changed the landscape. In France, the transformation of agriculture and rural emigration led to a global increase in the surface areas covered by forests from the 19th century (from 10 to 25%).

It should be noted that this sort of specialization and intensification of agriculture has led to an increase in the cereal surface areas with new crops, such as maize, protein-rich peas, soy beans, sunflowers, etc. Changes in the landscape are related to agricultural practices and are mainly due to mechanization and land reorganization. In particular, land consolidation induces an increase in plot size and removes numerous linear elements which have participated in landscape structuring. With the use of herbicides, the plant cover under orchard and vineyard conditions has disappeared, thus modifying the activity of fauna, the fate of organic matter and in turn the soil environment. The introduction of new machinery, especially for seedbed preparation, has also been a factor of soil evolution (decrease in organic matter content, sensitivity to crusting and runoff, mechanical compaction, etc.). The effect of such changes on soil properties and the environment are still poorly understood, especially because it takes several years to become really visible. Since the soil properties may be affected, the consequences for water quality, food security and ecosystem biodiversity are generally advanced.

In many areas of the World, available productive land is running out. The remaining land is of marginal quality for agricultural development and most of these marginal land areas are grasslands and forests. In mountainous regions, for instance in Southern Europe, the Middle East, North Africa, as well as in China, erosion rates are very high and land degradation is also the result of agriculture occurring over a number of centuries. Consequently, soil landslides, siltation of reservoirs, and lowland flooding occur in many areas.

As reported in the literature, the environmental status of soils in the world can be greatly affected by different processes such as soil structure degradation and compaction, erosion, water logging and flooding. Acidification, salinization and alkalinization are also major constraints that cover a large spectrum of processes, mechanisms and factors, most of them directly or indirectly human-induced.

Importance of soil constituents and history

Soil physical properties are closely related to its structure i.e. the spatial arrangement of mineral and organic constituents are organized. Water, solutes and gas circulate or are stored and living organisms develop in the different types of voids resulting from this organization. On a microscopic scale, the soil properties depend on the organization of elementary particles. On a more macroscopic scale, several levels of organization can be observed, from millimetric aggregates resulting from the assembly of elementary particles to decimetric or even metric structures.

Soil structure partly results from the conditions of soil formation and evolution in the long term. In cultivated soils, the direct or indirect action of man, with agricultural practices such as tillage, seedbeds, the passage of machines, or the action of plants and fauna, may allow the structure to evolve. With time, this evolution can lead to degradation or regeneration. The stability of the structure, which is subject to various damaging agents, such as rain, wind and compaction by machines and animals, is a major issue in soil physical properties.

Clayey soils are usually the most stable while loamy soils are far less stable. The presence of binding agents and cement between soil particles, such as organic matter, oxides, and the implementation of adapted agricultural practices (soil tillage, plant canopy) make it possible to increase the stability of the structure or to limit its sensitivity to degradation. Soil chemical properties also have an influence on structural stability.

Analyzing soil physical properties assumes knowledge of not only the particle size of the constituents but also their mutual arrangement, both of which determine soil structure. Each level of soil organization has a particular function and especially for living organisms. The nature of constituents in relation with the chemical environment is of primary importance in interpreting soil-particle and soil-water interactions. Even if no volume change appears macroscopically, the soil system can reorganize itself on a microscopic scale. For instance, shrinkage curves combined with X-ray scattering measurements show that volume variation is related to a change in particle distance and orientation. It is clear that, for clay minerals and associated compounds, the water retention curve cannot be directly deduced from the capillary equation. Soil fabric and properties also depend on soil stress history i.e. various factors such as drying and wetting cycles, mechanical compaction, parent material burial, as well as salinity (osmotic pressure) and low temperature (freezing). As a consequence, after a single desiccation, the water retention curves and porosity of aggregates or cores measured in the laboratory can be completely different to those of the physical properties in the field. This means that physical measurements should preferably be taken on undisturbed samples, i.e. undried conditions but also with non-fragmented samples (without grinding). Thus, modeling soil physical properties in the laboratory as well as in the field should assume that the soil is a structured and non-rigid material, with stress dependent properties.

A medium sensitive to chemical properties

Some of the physical properties are determined by the evolution of the soil. Its chemical reserve depends on the type of material the soil has developed. It also depends on the age of the soil as well as outputs from plants. Plants take up the elements necessary for their vital functions, i.e. primary nitrogen, phosphorus and potassium as well as calcium, iron, sulfur, magnesium and trace elements. The soil is an open system, which tends to lose some of its chemical elements. Generally, plant uptake is much greater than the supply originating from rock weathering in the absence of fertilization.

During genesis, different features can be observed. For instance, in temperate climate, with drainage, carbonates are dissolved first, and afterwards calcium desaturation and acidification take place. Migrations of the fine fractions, both vertically (translocation) and laterally (runoff), are generally favored by this mechanism. Particle transfers can explain the loamy nature of many soils, for instance alfisols (sols lessivés). It is generally observed that slightly acid conditions favor soil structure instability and in turn sensitivity to soil particle loss and movement in the environment. This phenomenon can be accelerated due to agricultural intensification, i.e. plant uptake, fertilization and aeration, as well as acid rain deposits. It justifies carefully monitoring the chemical status to control soil structure stability and particle mobility in the environment.

Soil properties are partly due to the fact that, for clay minerals and associated compounds, the surface areas are sufficiently extensive for surface interactions between particles to be dominant in soil structure properties. Electric charge density partly and specific sites determines the more or less hydrophobic nature (water repellency) of the soil. It also determines cation selectivity and in turn cohesive forces between soil constituents. The cation selectivity (Na, K), the nature of the clays and their layer charge (permanent substitutions, pH-dependent charges) have a strong influence on soil particle interaction, and thus on soil structure and behavior. Soil Physics should also integrate the fundamental cause and effects of redox potential, on transient physical properties. Such a concept means that the nature and surface properties of soil constituents are a key factor in understanding soil behavior. Although the nature, shape and surface properties of soil particles are relatively well defined, little is known about how these units are arranged from a microscopic to a macroscopic scale. Cracks, failure planes as well as pores originating from roots and fauna also determine, on a more macroscopic scale, transfer properties. Modeling transfer properties of non-rigid and stress-dependent materials is probably one of the main challenges of this decade faced by soil physics.

Highly acidic conditions are found in many parts of the world. With climatic drainage, acidification takes place and leads to low contents in exchangeable earth alkaline cations and high aluminum contents. Restoring soil chemical fertility is crucial in acidified soils but liming may affect soil physical properties, and especially sensitivity to compaction and erosion. For instance, the aggregate stability of oxisols with similar texture and mineralogy can be related to additional factors in relation to variable surface charges of the minerals and organic components as a function of pH. Schafer et al. (1992) have stated that significant knowledge gaps exist in the description and modeling of soil physical properties in relation to biological activity and to the conservation of soil and water resources. Models describing changes in physical properties due to the chemical environment, especially for acidic conditions, have yet to be developed.

An essential role in the water cycle

Water has to pass through the soil to supply ground water tables. The water that is really available for plants depends on the energy with which it is retained. The amount of water retained depends on the size of the water reservoir, i.e. the porosity and the depth of the soil. The extension of the root system of plants determined by the climate (rainfall, temperature, and plant transpiration) is also a major factor that should be taken into account when studying the availability of water for plant development. When the rain reaches the soil surface, some of it is intercepted by plants and may be directly evaporated into the atmosphere. In extreme cases, in conifer forests for example, there are cases where less than 65 % of rainfall reaches the soil. Interception is usually lower in crops (<10%). The proportion of water that reaches the soil can either percolate if soil permeability is high enough, or on the contrary run off over the surface. The distribution between percolation and runoff depends both on the soil structure and the type of rainfall. It is a phenomenon which evolves with time and, in the case of several tens mm/hour over a few minutes or tens of minutes, runoff is almost inevitable. With drizzle (less than a few mm per hour) the percolation rate is high enough, except in the presence of highly developed crusts.

In temperate climate areas, a soil usually becomes recharged in water in autumn and winter i.e. when the proportion of water evaporated at the soil surface or evapotranspirated by plants is lowest in comparison to a given rainfall height. In many areas of the world with long rain-deficient periods, field capacity is not attained. Plant transpiration participates in mobilizing the water reserve. It is generally accepted that the soil can dry up until the plant reaches wilting point, which corresponds to the maximal suction a plant can exert on the soil. Drought dynamics depend on the development of the root system and soil structure.

Soil physicists develop mathematical functions in order to provide a continuous expression of the water retention curve. Recent theories based on different concepts: percolation, fractal dimensions, fragmentation, neural networks, give more flexibility to the models. However, although the wilting point is often estimated at – 1.5 MPa water potential, it is well known that this limit can be exceeded in forests because some trees, for instance in dry areas, are well adapted to high water stress (up to - 4.0 MPa). By contrast, in horticulture, the irrigation management range corresponds to very low stresses (up to about -10 kPa).

Nowadays, the apparent bulk density of a soil, which gives a good estimate of its porosity, is considered to be a good factor for estimating water holding capacity. It is used for developing (pedotransfer) functions, in particular for predicting water retention properties and deriving hydraulic conductivity. In pedotransfer functions, the cation exchange capacity, which can be correlated to the surface area, generally gives a good estimate of the water content at wilting point, unlike particle size distribution which often appears to be a poor estimating factor.

On the catchment scale, the soils have a major influence on hydrology through the storage and transmission of water. The pathways of water movement through the soil and the ability of the soil to act as a chemical or biological buffer constitute one of the main fields of soil physics research. Process-based models intend to overcome site specificity and maximize transferability of soil information across locations and to new situations. Depending on the scale, these models require variables that are not easy to measure and are not readily developed from existing data. A large field of research concerns new methods, the definition and ways to obtain data, their frequency and incidence, but also the validation of models before adoption.

A fragile environment at the surface

As seen before, mechanization or deforestation, land use and field patterns have changed much over the last 50 years. With respect to erosion problems, it is necessary to consider the elementary watershed, which can be defined as an isolated territory from a hydraulic point of view and which leads to a single outlet. Briefly, runoff occurs when infiltration at the soil surface is lower than rain intensity. Under temperate climate conditions, soils mainly composed of loam present the highest erosion risks due to their sensitivity to soil capping, which increases as the organic matter level decreases. The degradation of the soil surface is more rapid when agricultural practices reduce the size of soil aggregates and the soil is bare. Seedbeds often constitute potential trickling surfaces. The slope, the geometry and nature of the flow network when the water runs off in the watershed also play a role.

In the case of intense rainfall, the surface can be degraded when it is not completely closed. Under the impact of drops, soil particles can be suspended. Runoff can wash away the finest particles: this is referred to as sheet erosion. In Europe it is admitted that, in most fragile loamy type soils, with low organic matter contents (< ~ 1.5 %), a cumulated rainfall of 60 to 100 mm is enough for a fragmented seedbed to reach the ultimate stage of degradation. At this stage, a sedimentary crust is formed, soil infiltrability becomes very low and the smallest rain event can cause runoff. If the soil is covered by plants, runoff water is only slightly loaded. Water speed can be high in the lines where runoff concentrates and create furrows and ravines which are specifically localized in the landscape.

Studying erosion and runoff processes involves the amount of water, the slope, the length of the water trajectory as well as the soil state at the beginning of the rain event. The initial state depends on the previous successive rain events leading to the evolution of the surface soil structure. In general, understanding the phenomena requires taking into account the succession of rain events during the growth cycle. With regard to soil quality, erosion means the disappearance of arable land and in particular the fine fractions which play a major role in soil quality (clays and organic matter).

Emphasis is currently laid on the consequences of erosion at the environmental level: flooding, silting of rain sampling networks, submersion of roads, etc. The part of the soil washed away is the most superficial and generally the finest. It thus contains mineral nutrients and associated chemicals controlling plant pests and diseases (herbicides and pesticides). Most of these chemicals, except nitrates, are fixed on solid particles, thus contributing to the pollution of rivers and shores. Erosion and its consequences are thus not limited to agricultural systems.

Conclusions

For the agro-environmental management of soils

While fertilization has made it possible to solve problems resulting from increasing discrepancy between the soil chemical capacity and the requirements of a cultivated plant, removing physical constraints has made it possible to reach high intensification levels in farming. Nowadays, the current agricultural systems are located in transformed landscapes. Farming intensification has modified the terrestrial water cycle. Although not well known, erosion and its consequences at the environmental scale, especially spate and water pollution, have been detected. Other effects have been studied less, but their long term consequences deserve attention. The changes in physical properties of soils in the long term following severe desiccation, and the use of heavy and powerful machines, should be mentioned. Ground water recharge and quality will probably raise major problems in the future, because soil water reserves are under increasing demand, which affects the global water resources from a qualitative as well as quantitative point of view.

New degradation concerns and the impact of soil evolution on global change have emerged over the last years. Land degradation contributes to global warming due to atmospheric enrichment with greenhouse gases. Among the possible strategies for enhancing carbon sequestration in soils, different approaches can be proposed. Their aim is to increase the enrichment of soil carbon content and increase the turn-over time of carbon in soil. One of the possible ways is to reduce soil aeration and to improve the management of soil residues, but also to use-fertilizers more efficiently and increase net primary products.

Identifying some soil scale priorities

Within the structure of the International Union of Soil Science, Division 2 "Soil properties and processes" is concerned with integrating physics, chemistry, biology and mineralogy. In Soil Physics, processes and phenomena are studied on multiple scales ranging from the molecule to the field, and up to the regional scale.

On the horizon scale, i.e. from crystal structure to soil fabric, it appears that little is known about the combined effect of stress (matric and osmotic potential, redox potential) and confining pressure (mechanical pressure) on soil structure and rheological properties. The influence of surface properties (variable electric charge density, hydrophobic or hydrophilic nature) on soil structure and transfer properties deserves more attention. The role of specific microbial and clay-organic associations with their consequences on physical, chemical and mechanical properties, for instance due to carbon sequestration, is already a central question for research. However, close collaboration with chemists, biologists and agronomists is required.

It is necessary to reflect carefully on the soil data to be used in data bases, especially to carry out a diagnosis on soil physical properties and quality. An important topic concerns the conditions of validation, according to the type of soil, the surrounding environment, and in particular in terms of climatic conditions and soil management.

At the soil profile scale, one of the most important tasks seems to be to correlate preferential flow to soil structure and behavior for modeling transport. It is assumed that soil is a non-rigid and structured material. On this scale, it is important to introduce biological activity more accurately in models, in relation to the fate and transport of heat, gas, solutes and solid particles. An important aspect should concern the development of techniques for measuring mass and energy in the soil profile. The use and development of new theories and concepts of spatial and temporal evolution on this scale should be considered a priority.

At the watershed scale up to the regional scale, the last IUSS congress in Montpellier showed that few results considering soil water dynamics on this scale were reported. It appears necessary to integrate new concepts and techniques to bridge the gap between phenomena from the scale of the soil profile to those on the scale of the watershed (soil cover).

One of the main challenges is also to transfer results from laboratory studies or model simulations to the soil, which is considered to be a continuum medium, temporally dynamic, heterogeneous and spatially anisotropic.

Scientific research in Soil Physics has a central role in contributing to improving our understanding of soil evolution and controlling the extent and impact of human activity at all levels. It must produce reliable information to understand soil formation mechanisms and processes, and to make the most informed decisions on land use and management. Significant gaps remain in our understanding of soil physical properties and processes, and much remains to be clarified.

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- O.M a doesn't have permanent charge
- structure better in ↑pH soil,
- W. retention curves in function of nature of clay at the same clay content

Sustainable land use: the role of Agricultural Engineering

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Abstract

There is an increasing awareness that the world's resources are not boundless. There is now a concern about husbanding and protecting the environmental resources upon which life depends. Among the basic resources is the soil. The sustainable use of the soil is, nowadays, a problem of paramount importance for all social and economic sectors and regions. Imbalances between availability and demand, resource degradation, intersectoral competitions call for new issues in soil conservation, use and management.

Sustainable use of the soil is a form of land management which retains the natural fertility of the soil and allows for the production of food and fiber supplies and renewable natural resources on a long-term basis. It implies that the natural environment should be treated and managed in such a way that the cycles and energy fluxes among the soil, bodies of water and atmosphere are considered, preserved or restored. To this respect, the term "sustainable land use" is more comprehensive than the term "sustainable soil use". Land, commonly, stands for a section of the earth's surface, with all the physical, chemical and biological features that influence the use of the resource. It refers to soil, spatial variability of landscape, climate, hydrology, vegetation and fauna, and also includes improvements in land management, such a drainage schemes, terraces and other agrobiological and mechanical measures. The term "land use" encompasses not only land use for agricultural and forestry purposes, but also use of the land for settlements, industrial sites, roads and other human activities. Land use, in this meaning, can be termed sustainable only if is achieved such a spatial distribution or configuration of the different uses, as to guarantee biodiversity and preserve the eco-balance of the whole system. Rational land use planning is fundamental to this process. There is an increasingly urgent need to match land types and land uses in the most functional way, as to maximize sustainable production and satisfy the manifold needs of society, while at the same time, preserving the environment. Land use projects, nowadays, are caught up between two seemingly contradictory dimensions: ecological conservation and economic viability. Both the dimensions are interchangeably related to sustainability, viewed as a frame in which the exploitation of the resources, the direction of investments, the orientation of technological development, along with institutional changes are all in harmony and enhance both current and future potential, to fulfill the growing human needs and aspirations. Meeting these challenges calls for specific advances in our ability to manage and protect the natural resources. The design of environmentally friendly technologies and networking with other concerned partners and sectors are crucial aspects of the process.

With reference to the aforestated issues, the paper describes the main physical, social and economic features of land use planning projects, along with their environmental impacts and constraints to sustainable development. The importance and role of institutional strengthening, sound financial and managerial frameworks, availability of human resources involved, research thrust, technology transfer and networking improvement are also analyzed.

Key-words: Land use planning, sustainable development, networking system, Agricultural Engineering.

Foreword

The world's population is expected to grow from 6 billion today to at least 8 billion in the year 2025. It is, therefore, clear that achieving food security and improving the quality of life, while preserving the environment, will continue to pose major challenges to scientists, decision-makers and technicians in the years to come. The main activity of agriculture is the production of food, so increasing agricultural development in a sustainable manner will be crucial in responding to these challenges.

In the past, demand for growth in food has been met by expanding agricultural land. Nowadays, the availability of new land is limited; moreover, the more or less uncontrolled growth in agricultural production, during the past few decades, in industrial as well as developing countries, has pushed agricultural production to and, in many cases, over the edge of sustainability. This means that the traditional ways to increase production are facing a new challenge: to find a new balance between agricultural development and the conservation of the natural resources.

Agricultural engineering has been applying scientific principles for the optimal use and management of natural resources for centuries, and its role is increasing with the dawn of the new millennium. There are, at least, two reasons for this growing significance. First, it is well understood that the wise use of land resources will play a role of paramount importance in the provision of food for future generations. Second, the demand for different land uses is increasing tremendously, especially in the developed world. The land demands for cropping, grazing, forestry, wildlife, infrastructure, outdoor recreation, landscape and industrial and urban development are greater that the land resources available. To this end, rational land use planning will help to find a balance among these different demands and assure agricultural production, while conserving the natural environment.

With reference to the afore-mentioned issues, the paper, firstly, describes the main physical, social and economic features of the land use planning process, along with its environmental impacts and constraints to sustainable development. Finally, the importance and role of institutional strengthening, sound financial and managerial frameworks, availability of human resources involved, research thrust, technology transfer and networking improvement are analyzed.

The Concept of Sustainable Land Use

To meet future challenges of food security, further development of agriculture is necessary. This development has to guarantee both the growth in agricultural output and the conservation of natural resources. The conservation of the natural resources is important because of the dependence of agriculture on these resources. This means that the natural environment should be treated and managed in such a way that food production is secured now and in the future. So, food security is not only a matter of quantity, but also of continuity. Agriculture, thus, is forced to find a balance between development and conservation. In this process the responsible use of natural resources plays a role of paramount importance. Among the basic natural resources, upon which life depends, is the soil.

The responsible use of the soil can be described in terms of sustainability or sustainable development. Sustainability has been defined in many different ways and there is no single, universally accepted definition. According to the Brundtland Commission "sustainable development is a process of change in which the exploitation of resources, the direction of investments, the orientation of technological development and institutional changes are all in harmony and enhance both current and future potential, to meet human needs and aspiration".

This process implies long-term perspective for planning and integrated policies for implementation. FAO has formulated its own definition of sustainability, specifically in the context of agriculture, forestry and fisheries: "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 the present and future generations. Such sustainable development conserves land, water, plant and animal genetic resources, is environmentally non-degrading, technically appropriate, economically viable and socially acceptable".

Scarcity of suitable soil is a major constraint for further agricultural development in many countries of the world. Therefore, as the demand for soil continues to increase, it is imperative that this limited resource be used efficiently for agricultural and other uses.

Sustainable use of the soil is a form of land management which retains the natural fertility of the soil and allows for the production of high quality of foodstuffs and renewable natural resources on a long-term basis. This means that the natural environment should be treated and managed in such a way, as to preserve or restore the cycles and energy fluxes among soil, bodies of water and atmosphere.

The term "sustainable land use" is more comprehensive that the term "sustainable soil use". Land, commonly, stands for a section of the earth's surface, with all the physical, chemical and biological features that influence the use of the resource. It refers to soil, spatial variability of landscape, climate, hydrology, vegetation and fauna, and also includes improvements in land management, such as drainage schemes, terraces and other agrobiological and mechanical measures.The term "land use" encompasses not only land use for agricultural and forestry purposes, but also land uses for settlements, industrial sites, roads and so on. Land use, in this sense, can be termed sustainable if, and only if, is achieved such a spatial distribution or configuration of the different uses, as to guarantee biodiversity and preserve the eco-balance of the whole system. In other words, land use that limits the interactions among soil, water and atmosphere and degrades the habitat standards vital to biological diversity of flora and fauna cannot be defined sustainable. In this respect, the term "sustainable land use" combines technology, policies and activities aimed at integrating socio-economic principles with environmental concerns. The term bears more dimensions or meanings:

- Sustainable use in the meaning of husbandry. In this sense, it is related to concepts such as continuity, durability and equity in the exploitation of natural resources over long periods of time. The dimension refers to methods by which land is managed – crop rotation procedures, tillage systems and so on – all striving to preserve or restore the quality and fertility of the soil. This meaning is strongly related to the long-term physical and economic sustainability.
- Sustainable use in term of interdependence. This meaning is related to the spatial dimension of sustainability. It involves such aspects as fragmentation and relations among different land uses. On this facet of sustainability are, nowadays, focusing many land use planning studies, due to the fact that there is still a great lack of knowledge and uncertainty.
- Sustainable use in terms of ethical obligations to future generations. This refers to the losses and depletions of natural resources in combination with the expected increase in population. Land is not a simple commodity that can be stored and replaced, destroyed and remade, or even recycled in exactly the same way as manufactured goods. It is a complex and biological system, built up over long periods of time. The land could have lost its suitability for cropping or other uses by means of natural or anthropogenic causes. To restore its capacity for beneficial use, while protecting the environment, methods of

reclamation have to be tailored to the specific problems at hand. In this field much needs to be done to ensure the future of mankind.

Any assessment of sustainability would be incomplete if it did not address all the dimensions previously described.

Clearly, there are conflicts among these goals. More equity may mean less efficiency. In the short term it may not be possible to meet the needs or demands of even the present generations, let alone the future ones, if these needs or demands are greater than what the environment can afford. Furthermore, degrading the natural resources will reduce their capacity to meet future needs, whatever those needs will be. So, demand management and degradation prevention play a basic role in the process of sustainable use and development of land. Decision – makers have to consider and agree upon a trade-off among different goals but, if the ecosystem as a whole is to survive, the use of natural assets must be compensated by the development of human or physical assets of equal or greater worth. In this regard, good and reliable information is essential, that is, information on the people's needs, land resources and on the economic, social and environmental consequences of alternative decisions. To this end, the task of the land-use planners is to ensure that decisions are made on the basis of consensus, to avoid disagreements on the ways and directions the natural resources should be exploited. Wise land use planning will help to reduce the trade-off costs and resolve conflicts by involving the community in the decision process.

Land Use Planning: A Tool to Achieve Sustainability

Land use planning is the systematic assessment of land and water potential, alternatives for land use and economic and social conditions in order to select and adopt the best land use options. Its purpose is to select and put into practice those land uses that will best meet the needs of the people while safeguarding resources for the future. The driving force in planning is the need for change, the need for improved management or the need for a quite different pattern of land use dictated by changing circumstances. In the process all kinds of land use are involved: agriculture, forestry, wildlife conservation, urban and industrial expansions, tourism and amenities. Planning also provides guidance in case of conflicts among manifold alternatives, by indicating which areas are most valuable for any particular land use. Land use planning can be viewed as an iterative and continuous process, whose aim is to make the best use of land resources by:

- assessing present and future needs and evaluating the land's availability to meet them;
- identifying and resolving conflicts among competing uses and needs;
- devising alternative options and choosing those that best fit identified targets;
- learning from experience.

At every stage, as better information is available, the process may have to be changed to take account of it.

Goals are important in the planning process. They define what is meant by the best use of the land and they have to be specified at the outset of every planning project.Goals, normally, are divided into objects and targets.

Objectives are the general aims within the planning process. They allow the judging of different solutions of a concrete problem in the planning area, and lead to suitable propositions and projects for the use of the land.The targets are the most detailed aims of land use planning. They lead to the design of actual measures that have to be taken and carried out in an area to solve the problems at hand.

The objectives and targets identify the best use of the land. If two different forms of land use bring forth exactly the same profit (economically and socially), the objectives will determine which of the two land uses should be implemented, while the targets will indicate which procedures should be followed.

The goals, as a whole, may be grouped under three main headings: efficiency, equity and acceptability and sustainability.

- Efficiency refers to the economic viability of the land use plan.

  The plan should yield more than it costs. So one goal of planning development is to make efficient and productive use of the land. In general terms, for any particular land use, certain areas are better suited than others. Efficiency is achieved by matching different land uses with the areas that will yield the greatest benefit at the least cost. However, it is not always clear which land use is the most profitable one; this depends on the point of view. The point of view of individuals, for instance, focuses on the greatest return on capital and labour invested or on the greatest benefit from the area available. Government's point of view is more complex: it may include improving the foreign exchange situation by producing for export or for import substitution.
- Equity and acceptability represent the social features of land use planning.

  The plan must be accepted by the local population, otherwise the proposed changes will not take place. Equity refers to the levelling of the living standards of the residents. People living in the planning area are expected to gain from the land use plan, even if they do not own the land. Living standards may include levels of income, food security and housing. Planning to achieve these standards then involves the allocation of land for specific uses as well as the allocation of financial and other resources.
- Sustainability, as stated before, refers to a development in land use planning that meets the needs of the present while conserving resources for future generations.

  This requires a combination of production and conservation: the production of the goods needed by the people now, combined with the conservation of the natural resources on which the production depends. So, land use to be sustainable, has to be planned for the community as a whole, because the conservation of soil, water and other land resources is often beyond the means of individual land users.

  Other goals of the planning process could be:

- Livability After the land use plan is implemented, the area should still be a suitable place to live for the inhabitants;
- Flexibility The plan should be flexible and leave options for using the land in different ways, if needed, in the future;
- Public involvement Every group or individual with an interest in the plan should be allowed to participate in the process, to keep their land use from disappearing through the plan, or to be offered a new land use, as part of the plan.

On the whole, the land use planning, to be sustainable, should develop into an interdisciplinary, holistic approach that gives attention to all functions of the land and actively involves all land users through a participatory process of negotiation platforms, be it at national or local levels. The aim of the process is to create the conditions to achieve an environmentally sound, socially desirable and economically appropriate form of land use.

Research and Development

International and national research, nowadays, needs to be focused more effectively than in the past on problems of land use planning and management. This is the only way to provide land users and planners with suitable and tested technologies for targeted measures to increase agricultural production while protecting the natural resources. The lack of research, application of research findings and access to new and advanced technology in this field is

seen as one of the main reasons for the problems that plague the sector: poor land use efficiency, environmental degradation, high costs and lack of responsiveness to beneficiaries.
Successful research thrust on sustainable land use planning should include the following actions:

- Data base improvement;
- Adaptive research;
- Institutional strengthening;
- Socio-economic analysis;
- Environmental protection and conservation;
- Technology transfer and infrastructure.
- Data base improvement.

  Availability of reliable hydro-climatic and other associated natural resource data is an essential prerequisite for sustainable land use planning development. As long as adequate and reliable data are not available, planning, design and management of land use programmes will continue to remain guesswork, use of other natural resources haphazard and wasteful, and the development process unsustainable. Many land use projects were conceived and designed on a medium – to long-term basis, on the assumption that future climatic conditions will not be different from the past ones. This will not be so in the years to come, due to the global warming and greenhouse effect. Therefore, land use planning designers and managers should begin a systematic re-examination of engineering design criteria, operating rules, contingency plans and land allocation policies. Demand management and adaptation are essential components for increasing project flexibility to meet uncertainties of climate change. On the whole, land use planning programmes can only be soundly formulated on the basis of adequate data on soil and its production capacity, potentially available water resources, performance of existing land use projects and other related factors.
- Adaptive research.

  A wide variety of techniques or methods are use in land use planning. They are taken from the natural sciences (climatology, hydrology, soil science, ecology), from technology (agriculture, forestry, irrigation and drainage engineering) and from the social science (economics, sociology). Research for land use planning requires enhanced field investigations and a large variety of tools such as: Information Management, System Analysis, Decision Support Systems, Multicriteria Analysis, Geographic Information Systems, Remote Sensing, Computer Image Analysis, Sensors, Modeling Technique, Neural Network Technology, Land Evaluation. All these tools have to be considered under a broad and integrated approach related to food and other agricultural commodity production, rational land use planning, water saving, resource conservation, environmental impacts and socio-economic effects. Current research thrust needs to be reoriented by recognizing the complex role of the land resources in agricultural development, and by following a broad-based holistic approach. To this end, adaptive research programmes must be directed to investigate the actual and real problems associated with the planning, design implementation and management of land use projects. It is important that the resulting methodology be technically feasible, environmentally and economically viable and socially acceptable.
- Institutional strengthening.

  The importance of a functional and coherent institutional framework aiming to promote, at both national and international levels, sustainable land use planning development, has been fully recognized at present. The solution may not always require the creation of new and enlarged institutions and establishment of larger governmental services. An important criterion in reorganizing and/or establishing new institutions should be the ability of such institutions to address successfully the multi-dimensional problems that are generally faced by the land users at both local and national levels. Such institutions should be capable of undertaking, regulating, stimulating and facilitating the roles and the tasks carried out by the land users. These institutional frameworks need to be strengthened or restructured to meet more efficiently the land users' requirements and to promote sustainable land use planning development. Principal institutions should have effective linkages with all other related frameworks, so as to optimize the use of physical, financial and human resources involved.

The necessary actions are the following:

- review, strengthen and restructure, is required, existing institutions in order to enhance their capacity in land use planning activities;
- review, assess and revise, if needed, existing legislation on land management within the broader framework of legislation for the development, use and conservation of land resources.

- Human resource development.

  Successful technology and research thrust on land use planning depends on the number, orientation and quality of human resources (decision makers, professionals and research related people) involved. They orient appropriate knowledge and skill to solution of priority issues and emphasize the adaptation of available techniques to solve local problems. These knowledge and skill will include the ability to:

- identify local hurdles and constraints;
- formulate research strategies;
- design suitable technologies for testing, monitoring and evaluating;
- assess the technical, economic, social and institutional aspects regarding the application and adaptation of modern and advanced technology.

Moreover, this body of human resources will help national and international institutions, improve educational contents and training in land and other natural resources related topics, as well as scientific organizations identify subjects to be further analyzed and investigated.

The necessary actions can be summarized as follows:

- assess training needs for land use planning and management;
- increase formal and informal training related activities;
- develop practical training courses for improving the ability of extension services to disseminate technologies and strengthen land users' capabilities;
- enhance the capabilities of decision makers, administrators and officers at all levels, involved in land use planning programmes.

- Social economic analysis.

  Social and economic analyses are important features of the land use planning process. A land use project, like many other projects, can be implemented only if the total benefits exceed the total costs. Therefore, sustainable land use planning should meet two basis considerations, namely economic viability and social acceptability. Comparisons of social with economic analysis can highlight the need for policy changes. A particular land use may be degrading and thus destroying other land resources. If the economic analysis shows the use to be advantageous from a land user's point of view, it is likely to continue, whether the process is environmentally sound or not. Economic analysis should take account of damage to land resources and the consequent lowering of their productivity.

  A great many land use planning projects in the past have failed due to the inadequate attention given to social and economic aspects in their design and implementation. Application of appropriate socio-economic analysis in all phases of the planning process is urgently required in the development of land use projects. In this regard it is recommended that:

- effort should be made to incorporate economic and social analyses in land use planning methodologies;
- governments, relevant international and national institutions and decision – makers should ensure that socio-economic analyses are adequatly applied in the formulation and selection of land use planning projects for implementation.
- Environmental protection.

Sustainable land use planning has to find a balance between agricultural development and conservation of natural resources. Thus, development and environment are two aspects of the same process. Much agricultural land is deteriorating due to inappropriate soil and water management. Soil erosion, nutrient depletion, salinization and waterlogging all reduce productivity and jeopardize long-term sustainability. Wise management of the environment requires ability to forecast, monitor, measure and analyze environmental trends and assess the potentials of the land resources at different levels, ranging from the farm to the watershed. Adopting suitable environmental impact assessments will enable decision makers, professionals and institutions to plan land use without irreversible environmental damage and allow sustainable natural resource use. Environmental impact assessments should be followed by monitoring and appropriate actions in order to maximize positive impacts of development and minimize environmental hazards. In this regard, environmental protection and conservation of natural resources must be made an integral part of development. The necessary actions have to:

- carry out objective environmental impact assessments in order to ensure the sustainability and environmental acceptability of land use projects and programmes;
- establish environmental monitoring, evaluation and feedback systems on a long term basis;
- expand, improve and coordinate international assistance to improve the capabilities of less developed countries to assess, manage and protect their environment and natural resources.
- Technology transfer and infrastructure.

The success of a land use planning project is strongly influenced by the availability of technology and whether or not appropriate choices have been made to suit the local conditions. So, a framework for information transfer which includes storing, disseminating, receiving feedback and updating information is urgently needed to support sustainable land use activities. As in all economic activities, agricultural development, particularly involving the land use sector, has infrastructural requirements to ensure its success. Farmers and other land users must have appropriate funds, food supplies must be delivered in time and in adequate quantities, and proper marketing facilities and pricing structures must be assured. In addition to physical infrastructure, services such as education and health are also necessary. The necessary actions have to:

- establish effective methods to facilitate the transfer of new and tested techniques and practices;
- encourage and provide required facilities for transfer of knowledge and experiences among developed and developing countries;
- enhance the development of a more effective production environment.

The Role of the Network of Agricultural Engineering

The previously described actions and activities emphasize the fostering of national and international institutions on land use planning and agricultural development. Collaboration with and among these frameworks is imperative if the proposed initiatives are to be integrated into on going projects and plans. To this end, the establishment of an effective networking system can greatly facilitate such collaboration and integration. This enterprise will require an interdisciplinary, multisectoral approach, using system engineering methodology to recognize the necessary links and interrelationships. The nodes of the network will be organizations, institutions and agencies, as well as professional, academic, commercial and industrial bodies. The aim is to create a permanent, world-wide structure able to:

- speed up to process of collection, selection and exchange of information, avoiding duplication and overlap;
- build up synergies among its partners;
- interact with other frameworks;
- seek financial support to foster local activities deemed to be worthy;
- provide an international forum for debating land use planning issues and finding sound, socio-economically and environmentally sustainable solutions.

Within this frame, the world-wide network of the International Commission of Agricultural Engineering (CIGR) plays an important role. CIGR is an international, non governmental, not profit organization regrouping, as a networking system, regional and national societies, as well as private and public companies and individuals all over the world. CIGR aims at improving the cooperation among agricultural engineers and strives towards the establishment of national and international frameworks impinging upon the wide ranger of disciplines encompassed by Agricultural Engineering.

Within CIGR, the european (EurAgEng) and the american (ASAE) societies represent the most important nodes of the network. CIGR, EurAgEng and ASAE contain a number of technical bodies active in specific broad subject areas. The CIGR Section on Land and Water Use, the EurAgEng Field of Interest on Soil and Water and the ASAE Soil and Water Division are the official structures that promote and manage, on behalf of their societies and by means of scientific and technical meetings, guidelines and handbooks, the exchange of knowledge and experience dealing with the use and management of natural resources. Cooperation with other national and international organizations focusing on the afore-mentioned issues like the International Union of Soil Science (IUSS), the Food and Agriculture Organization (FAO), the International Commission on Irrigation and Drainage (ICID), and the European Soil Bureau, are solicited and welcome.

Concluding Remarks

- Sustainable land use planning is a process that aims to integrate ecological with socio-economic, and political with ethical principles in the management of land, for productive and other functions, to achieve intra – and inter – generational equity.
- For formulating and implementing policies and strategies for land use planning it is essential to collect, process and disseminate timely and reliable information and utilize modern land assessment and evaluation technologies, to create sound scientific knowledge for proper decision support.
- The establishment of an effective networking system, such as the world-wide Agricultural Engineering network, can greatly improve, enhance and speed up the process of collection, selection and exchange of information avoiding duplication and overlap.
- No detailed layout for sustainable land use planning can be drawn up for a region as a whole. A regional strategy can, at best, give a general idea of what needs to be achieved at the country level. Each country, then, will have to tailor its sustainable development strategy in view of its particular problems, constraints and comparative advantages.

- Regional strategies must set priorities and identify relevant projects, assess the environmental impacts of policies, investigate mechanisms to mobilize resources, enhance and encourage the participation of all concerned parties.
- The promotion and implementation of land use planning projects will not come free of cost. Major emphasis should, therefore, be paid on developing new sources of funds to supplement the national budgetary allocations. Chief among these approaches are measures that seek to mobilize local funds, in particular under the "user pays" principle.
- The challenging, but widely acceptable concept of sustainable land use planning calls for new approaches on development and, therefore, on land use and management. To this respect, new perspectives are required to manage the land and its associate resources. This is not only a question of allocating and controlling the use of the land, but of combining the knowledge of pressure influencing the resources themselves, with the relations among users and human and social objectives, the technologies available to improve and enhance the land use planning process, the maintenance of biodiversity and natural equilibrium.
- The lessons learned demostrate that it is necessary to make a decisive break from past policies to embrace a new holistic approach in land use planning and management, that is comprehensive, participatory and environmentally sustainable.
- There is an urgent need for adequately trained professionals who can work in the multisectorial environment of integrated natural resource management.
- Finally, to achieve a sustainable land use planning development, objectives and goals, policies and regulations should be grounded in local realities, traditions and natural resource management strategies. The environmental and socio-economic impact of such policies and regulations should be assessed before they are implemented.

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Assessing the vulnerability of soils to degradation

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Abstact

With soil degradation in Europe high on the political agenda, there is a real opportunity for the soil science community to influence the way soils are used in Europe and how they might best be protected in the future. This paper lists the most important aspects of soil degradation in Europe and emphasises the importance of adopting a spatial approach. Three examples of soil degradation are examined: soil erosion risk assessment in Italy, the susceptibility of subsoils in Europe to compaction and the impoverishment of organic matter in southern Europe. The European Soil Database is identified as the best source of spatial data available at the present time for studying the extent of the degradation and it is clear that soil physical properties provide the key to explaining many of the processes. Computer-based models that employ soil physical properties together with spatial data, for predicting soil degradation, need better data than currently exist. Whilst these data are being collected, researchers must resort to pedotransfer functions and pedotransfer rules for estimating risks and vulnerabilities. The DPSIR framework is proposed as a simple methodology for transferring the results of research work to the policy making process. However, implementing this will require a multidisciplinary approach.

Introduction

Soil degradation is now high on the political agenda and the soil science community is being asked for advice by the policy making process. This new opportunity to influence the way soils are used in Europe, and how they might best be protected, must not be missed. The European Commission is currently framing an official communication on soil that should evolve into a Soil Protection Strategy. This paper offers a view on assessing the vulnerability of soils to degradation in Europe today that can contribute to this important new EC initiative. The paper emphasises the spatial aspects of soil degradation and highlights the importance of finding a simplified framework suitable for providing much needed technical input to the policy making process.

Soil degradation

According to the Tutzing Project, *Sustaining Soils for Life,* soil degradation means the damage to and the destruction of soils, and of soil functions, in the form of:

- Erosion by wind and water, salinisation, acidification, contamination and various pollutions;
- Damage to life in soils and other forms of damage to the soil conditions;
- Compression, surface sealing, excavation and other negative effects from human activities.

The Tutzing Project goes on to recognise that there is considerable discrepancy between the rapid progression of soil degradation and the extremely slow process of soil formation. Furthermore, there is a variety of measures to achieve a sustainable use of soil and to all its vital functions. These functions depend on the different types of soil, the climatic conditions, and the forms of land cultivation. Despite single counter-measures and some positive examples of sustainable soil management, accelerated soil degradation continues almost unabated.

Many soil degradation processes reflect the result of highly extreme events as well gradual long-term trends. Both these processes can lead to irreversible changes. The main aspects of soil degradation, of concern in Europe today, are:

- Soil erosion, by water and wind
- Organic matter impoverishment
- Compaction of surface and subsoils
- Structural deterioration
- Salinization (and sodication)
- Desertification
- Contamination and pollution
- Acidification

Desertification is included here though in reality it combines a number of degradation processes including water erosion and sedimentation, salinization and sodication. Soil sealing, meaning the covering of the land with impermeable materials, is not dealt with directly here because soil physical properties have less influence on the consumption of land for other purposes such as urbanisation. However, soil sealing *de facto* it is dealt with through the compaction of subsoils.

During the last decade, the European Commission has produced a number of Directives aimed at protecting the European environment. Some of these, such as the EC Nitrate Directive (91/676/EEC) and the Directive (86/278/EEC) on the 'Use of Sewage Sludge in Agriculture', refer to specific aspects of soil. In the case of the Nitrate Directive for drinking water, the focus is on the filtering capability of soil.

However, the Directorate-General Environment has begun the preparation of a 'soil communication' with the 'ultimate goal of raising the political profile of soil at EU level so that practical soil protection receives as much attention as that devoted to air and water'. This initiative recognises that there is an overwhelming need to secure, through a necessarily broad range of instruments, the sustainable use of soil as a core element of sustainable development. These are refreshing words in a modern world where, in both rich and poor countries, there are too many examples of soils that have been modified and seriously damaged though misuse. It is clear that this new initiative can benefit greatly from the expertise of the soil science community.

Assessing vulnerability of soils to degradation

Vulnerability is a liability to injury or damage and, in the context of soil degradation, it is important in assessing or estimating the risk of damage occurring in the future. A *risk* is the chance of a *bad consequence* or *loss*. Another definition of *risk* is the *chance that some undesirable event may occur*. *Risk assessment* involves the identification of the *risk*, and the measurement of the exposure to that risk. The response to risk assessment may be to initiate categorisation of the risk and/or to introduce measures to manage the risk. In some cases, the risk may simply be accepted. In other cases, the priority will be to adopt a mitigation strategy.

Now the concept of risk and the assessment of the vulnerability of ecosystems to damage are being increasingly adopted for environmental protection.

The vulnerability and/or risk addressed in this paper, is the average vulnerability or risk that is likely to occur over a number of years based on a combination of soil factors and climate. Quantifying this kind of risk is of value for long-term planning, at the European scale, using the best spatial and point data available.

Since the modern world is strongly driven by economics, the new challenge to soil scientists is to translate the measurements and predictions of soil degradation into factors that policy makers can understand and use. This is not to say that ecological and moral considerations should be subordinated but a simple framework for expressing the effects and implications of soil degradation offers the best chance for the adoption of more sustainable land management practices and the implementation of the necessary mitigation strategies.

What is the problem? Where does it exist? Is it getting worse? What should be done to stop it and how much will this cost? These are the questions now being put to the soil science community and a methodology for representing spatially the various aspects of soil degradation is needed to provide answers.

The European Soil Database

The European Soil Bureau (ESB), based at the Joint Research Centre, Ispra (Italy) has been sponsoring the collection of soil information throughout Europe for more than ten years (Montanarella and Jones, 1999). This has culminated in the compilation of the first version of a European Soil Database containing spatial data at 1:1,000,000 scale, harmonised for the whole continent according to a standard international classification (FAO-UNESCO, 1974; FAO-UNESCO-ISRIC, 1990), together with analytical data for standard profiles (Madsen and Jones 1995). The process of data collection is still going on and in future this offers the promise of much needed soil physical data becoming available. In the short term however, spatial assessments of soil degradation must rely on simplistic methods using pedotransfer rules (Daroussin and King, 1997; van Ranst *et al.*, 1995) and standardised data.

The European Soil Database therefore provides a starting point for delineating various aspects of soil degradation at a European level. The structure of this is outlined in general terms in Heineke *et al.* (1998) and for simplicity, it is sufficient to say here that the Soil Map of Europe comprises polygons that represent soil map units (SMU) to which attribute data can be attached. Then with the application of simple models, the soil physical data can be interpreted for use in a wider context.

Results and discussion

Three examples of how soil physical data can be used, for assessing the risk of soil erosion in Italy, the susceptibility of subsoils in Europe to compaction and the impoverishment of organic matter in southern Europe, are described below.

Soil Erosion risk assessment in Italy

Soil erosion by water is a widespread problem throughout Europe. In an attempt to identify areas in Italy that are susceptible to soil erosion, a project was initiated to assess erosion risk at national level using standardized, harmonized data sets. The risk of erosion by water was assessed using the Universal Soil Loss Equation (USLE). It is emphasised here that USLE is appropriate for predicting rill and inter-rill erosion only.

Rainfall erosivity was estimated using an approximate relationship with annual rainfall. Soil erodibility was estimated using information on soil texture and parent material stored in the Soil Geographical Database of Europe. The USLE slope- and slope length factor was estimated using a 250-m resolution elevation model. Yearly timeseries of NOAA AVHRR images were used to obtain monthly estimates of vegetation cover.

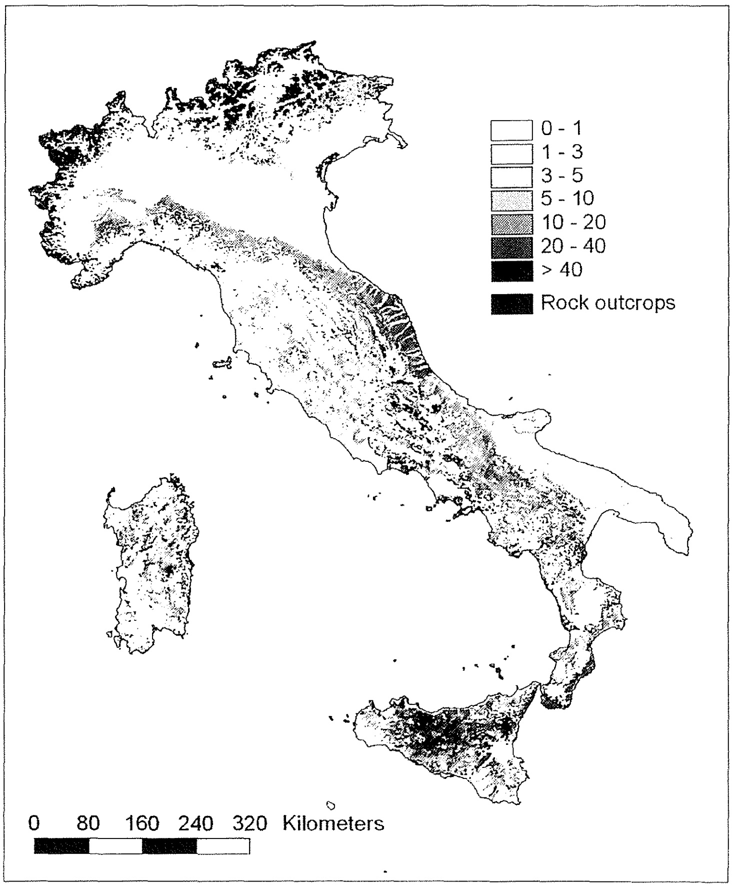

Figure 1 Estimated actual soil loss (t ha^{-1} y^{-1}).

Although it is clear that the approach followed has many deficiencies, valuable information on soil erosion risk is obtained. The main purpose of the analysis is to identify areas that, in the long term, are likely to be vulnerable to rill- and interrill erosion. Then, a more detailed assessment may be performed for these areas using more detailed data and more sophisticated erosion models or field surveys.

Within all its limitations, the erosion risk map of Italy (Figure 1) may simply represent the best information that can be obtained with the currently available data. In this respect, it can aid the formulation of soil protection measures in Italy.

Subsoil compaction in Europe

Compaction can occur at the surface or below in subsurface soil horizons. Knowledge concerning the vulnerability of subsoils to compaction in Europe is now an increasingly important requirement within agriculture and for planning environmental protection measures. The worst effects of surface compaction can be rectified relatively easily by cultivation and hence it is perceived to be a less serious problem in the medium to long-term.

On the contrary, once subsoil compaction occurs, it can be extremely difficult and expensive to alleviate. The risk of subsoil compaction increases with the growth in farm size, increased mechanisation and equipment size, and the drive for greater productivity. Research into the causes and effects of compaction in topsoils and subsoils in Europe has demonstrated the detrimental effects on the farming system but it is now clear that these effects go far beyond agricultural concerns of a decrease in yield and increase in management costs.

The overall deterioration in soil structure that may result from compaction can also:

1. increase lateral seepage of excess water over and through the soil, accelerating the potential pollution of surface waters by organic wastes (slurry and sludge), pesticides, herbicides and other applied agrochemicals;
2. decrease the volume of the soil system available to act as a buffer and a filter for pollutants;
3. increase the risk of soil erosion and associated phosphorus losses on sloping land through the concentration of excess water above compacted layers;
4. accelerate effective runoff from and within catchments.
5. increase green house gas production and nitrogen losses through denitrification under wetter conditions.

Under a FAIR Programme, Jones *et al.* (2001) have made a preliminary attempt to assess the susceptibility of subsoils in Europe to compaction. Applying this approach to European Soil Database, a preliminary map (Figure 2) has been produced, showing the susceptibility of subsoils to compaction. This is only the first stage in assessing the vulnerability of subsoils in Europe to compaction since it does not take into account land use or the interaction of climate (for climate data available in Europe see: Vossen and Meyer-Roux, 1995). However, it provides a useful starting point for policy making by revealing that, given certain conditions, almost one third of the subsoils in Europe are highly or very highly susceptible to compaction.

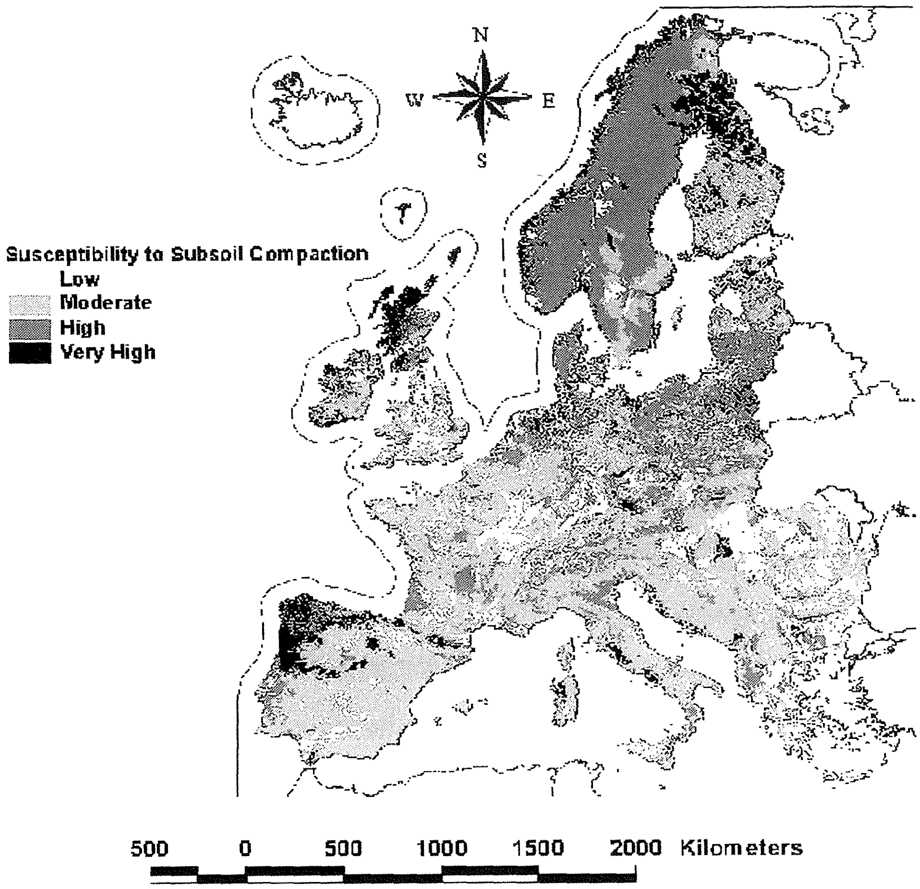

Figure 2 Susceptibility to subsoil compaction

[This assessment does not take into account land use or the interaction of climate]

Organic matter impoverishment in southern Europe

Soil organic matter is extremely important in all soil processes. It is essentially derived from residual plant and animal material, synthesised by microbes and decomposed under the influence of temperature, moisture and ambient soil conditions. In essentially warm and dry areas like Southern Europe, depletion of organic matter can be rapid because the processes of decomposition are accelerated at high temperatures. The annual rate of loss of organic matter can vary greatly, depending on cultivation practices, the type of plant/crop cover, drainage status of the soil and weather conditions.

There are two groups of factors that influence inherent organic matter content: natural factors (climate, soil parent material, land cover and/or vegetation and topography), and human-induced factors (land use, management and degradation). Heterogeneity is the rule for the organic matter content of mineral soils. Within belts of uniform moisture conditions and comparable vegetation, the average total organic matter and nitrogen can increase from two to three times for each 10^0 C fall in mean temperature. In general, under comparable conditions, the nitrogen and organic matter increase as the effective moisture becomes greater.
Cultivation can have a significant effect on the organic matter content of the soil. Experiments conducted in the USA and UK show a decline of up to 30% in organic matter content of soils that have been cropped over a long period. A rapid estimation of the current status of soil structure and fertility in the Mediterranean indicates that there are some distinctly negative

trends. Preliminary estimates, based on the European Soil Database, indicate that 74% of the land in Southern Europe is covered by soils containing less that 2% organic carbon (less than 3.4% organic matter) in the topsoil (0-30cm). The decline in organic matter contents of many soils in Southern Europe, as a result of intensive cultivation, has now become a major process of land degradation. Addressing the issue of soil quality in general, and that of organic matter content in particular, is therefore of high priority for planning the sustainable use of land resources.

A framework for policy support

The DPSIR framework defined by OECD (1993) is proposed as a simple model for presenting the various aspects of soil degradation in a form that can be interpreted by policy makers.

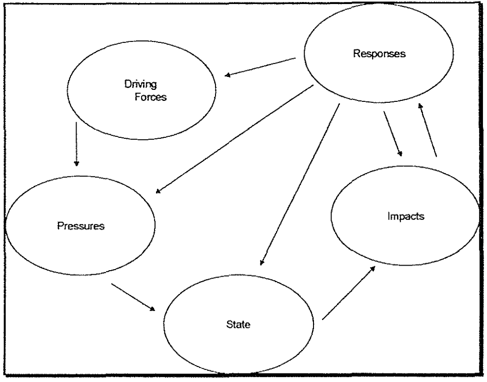

Figure 3 The DPSIR Framework

Discussion and conclusions

The relevance of the type of modelling described above, applied through a soil map at 1:1,000,000 scale, may be questioned. It is more appropriate at scales of 1:50,000 or larger, where real crop performance in specific fields, or where detailed management interventions, are being evaluated. It is clear that the basic data to run such models at scales less than 1:1,000,000 will be lacking for some parts of Europe for many years to come. In the absence of these data, however, the approach described in this paper offers the best chance of achieving results that are satisfactory enough for broad scale policy making in the immediate future.

It is clear that soil physical properties provide the key to tackling many aspects of soil degradation. Such properties underlie many of the soil degradations listed above and yet reliable point data on these properties are very scarce, particularly in southern Europe. Good spatial data are also needed. Computer-based models for predicting soil degradation need better data than currently exist, e.g. the European Soil Database, the FAO Soil Database. In the meantime, we have to resort to pedotransfer functions and pedotransfer rules for estimating risks and vulnerabilities and these rules and functions are not statistically sound.
This deficiency needs to be addressed by scientists and policy makers alike if soil protection measures in future are to be based on a firm foundation. Furthermore, soil scientists must increasingly work with scientists from other disciplines, for example biologists, geologists, chemists, mathematicians, statisticians, ecologists, social scientists and economists to address the problem of soil degradation. It is a complex problem requiring a multidisciplinary approach.
Therefore as soil scientists, we need to make many more measurements to validate the models and we need acceptance by the general public and policy makers alike that society as a whole

has been abusing the soil environment to such an extent that amelioration will cost money! The richer countries must help the poorer countries in this endeavour.

Acknowledgement

The considerable contribution made by the network of centres of excellence in soil science, that have supplied national soil data for the compilation of the European Soil Database, is gratefully acknowledged. The encouragement and ceaseless efforts of Luca Montanarella, secretary of the European Soil Bureau, and the support of the European Commission have been crucial to the successful conclusion of this work.

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Water retention: 3 points
- hydr. conductivity
- Shear strength
- Plasticity

Soil and Terrain Databases and their applications with special reference to physical soil degradation and soil vulnerability to pollution in Central and Eastern Europe

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Abstract

A historical overview is given of the development of global soil information systems since the first call for a world soil map by the ISSS congress in 1960 and the need to update this paper map to produce a digital global soil and terrain database (SOTER) by the IUSS congress of 2002. Although the finalization date may have been overoptimistic, the progress made to date is significant and related developments in particular the links made of this SOTER database in regional studies with land degradation assessments in south-east Asia and in central and eastern Europe are discussed.

he latter study used the soil and terrain units inventoried in SOTER as the basic units in which land degradation is assessed, using an expanded methodology involving the description of the type, extent, severity and effect on crop yields of the land degradation taken place. All data collected by national soil institutes are easily accessible and retrievable in a GIS environment.

Finally this study was complemented with a theoretical model assessing soil vulnerability to pollution. The available soil profile information in SOTER format was then linked as inputs to the model yielding results for about nine different potentially polluting heavy metals, examples of which are illustrated here.

It is concluded that the global SOTER exercise needs additional resources if it is to be finalized soonest to serve as a basis for applied studies and models. The soil degradation studies in Central and Eastern Europe indicated widespread physical deterioration but with a relatively low impact on agricultural production. The soil vulnerability maps to eleven metal ions produced can be used together with actual deposition maps to indicate areas at greatest risk.

Key Words: SOTER, soil degradation, pollution.

Introduction

The objective of the paper is to illustrate two practical applications of soil information against a historical background of the development of methodologies to store global soil and terrain data. One application deals with the inventory of soil degradation data, another with the vulnerability of soils to pollution.

1. Development of the Soil Map of the World and the Global SOTER database

At the global level the 1:5 million scale FAO-UNESCO Soil Map of the World (FAO, 1971-1981) is still, 20 years after his finalization, the only world-wide, consistent, harmonized soil inventory that is readily available in digital format and comes with a set of estimated soil properties for each mapping unit.

The project started in 1961 and was completed over a span of twenty years. The first draft of the Soil Map of the World was presented to the Ninth Congress of the ISSS, in Adelaide, Australia, in 1968. The first sheets, those covering South America, were issued in 1971.The last and final map sheet for Europe appeared in 1981.

With the rapidly advancing computer technology and the expansion of geographical information systems during the 1980's, the Soil Map of the World was first digitized by ESRI (1984) in vector format and contained a number of different layers of land resource-related information (vegetation, geology), often incomplete and not fully elaborated. In 1984 a first rasterized version of the soil map was prepared by Zöbler using the ESRI map as a base and using 1° x 1° grid cells. Only the dominant FAO soil unit in each cell was indicated. This digital product gained popularity because of its simplicity and ease of use, particularly in the United States.

In 1993, FAO and the International Soil Reference and Information Centre (ISRIC) jointly produced a raster map with a 30' x 30' cell size in the interest of the WISE (World Inventory of Soil Emissions) project (Batjes *et al.*, 1995). This database contains the distribution of up to ten different soil units and their percentages in each grid cell.

In 1996, FAO produced its own raster version which had the finest resolution with a 5' x 5' cell size (9 km x 9 km at the equator) and contained a full database corresponding with the information in the paper map in terms of composition of the soil units, topsoil texture, slope class and soil phase in each of the more than 5000 mapping units. In addition vector and raster maps, the CD-ROM contains a large number of databases and digital maps of statistically derived soil properties (pH, OC, C/N, soil moisture storage capacity, soil depth, etc.).The CD-ROM also contains interpretation by country on the extent of specific problem soils, the fertility capability classification results by country and corresponding maps. For more information http://www.fao.org/WAICENT/FAOINFO/AGRICULT/AGL/lwdms.htm

An overview of the publication stages of the paper Soil Map and its digitized version is given in Table 1.

Table 1. Important Dates in the Development of the Soil Map of the World

1960	ISSS recommends the preparation of the soil maps of continents
1961	FAO and UNESCO start the Soil Map of the World project.
1971	Publication of the first sheet of the paper map (South America)
1981	Publication of the last sheet of the paper map (Europe)
1984	ESRI digitizes the map and other information in vector format
1989	Zöbler produces a 1° x 1° raster version
1991	FAO produces an Arc/Info vector map including country boundaries
1993	ISRIC produces a 30' x 30' raster version under the WISE project.
1995	FAO produces a CD ROM raster (5'x5') and vector map with derived soil properties.
1998	FAO-UNESCO re-issues the digital version with derived soil properties, including corrections.

The development of the SOTER (SO=SOil, TER= TERrain) program started in 1986 with the aim to provide the framework for an orderly arrangement of natural resource data in such a way that these data can be readily accessed, combined and analysed. Fundamental in the SOTER approach is the mapping of areas with a distinctive, often repetitive pattern of landform, morphology, slope, parent material and soils at 1:1 million scale (SOTER units). Each SOTER unit is linked through a geographic information system with a computerized database containing, ideally , all available attributes on topography, landform and terrain, and soils. In this way, each type of information or each combination of attributes can be displayed spatially as a separate layer or overlay or in tabular form.

The SOTER methodology was developed by the International Soil Reference and Information Centre (ISRIC) in close co-operation with the Land Resources Research Centre of Canada, FAO and ISSS. After initial testing the methodology was endorsed by the ISSS Working Group on World Soils and Terrain Digital Database (DM) and, in 1993, the Procedures Manual for Global and National Soils and Terrain Digital Databases was jointly published by UNEP, ISSS, FAO and ISRIC, thus obtaining international recognition. The Procedures Manual is available in English, French and Spanish (UNEP/ISRIC/FAO/ISSS, 1995).

The SOTER concept was originally developed for application at country (national) scale and national SOTER maps have been prepared, with ISRIC's assistance, for Uruguay (1:1 M), Kenya (1:1 M), Hungary (1:500 000), Jordan and Syria (1:500 000). More information is available from ISRIC's SOTER website at http://www.isric.nl/SOTER.htm ; in particular the Kenya data are downloadable at http://www.isric.nl/SOTER/KenSOTER.zip

The original idea of SOTER was to develop this system world-wide at an equivalent scale of 1:1 M in order to replace the paper Soil Map of the World (Sombroek, 1984). However, it soon became obvious that the resources were lacking to tackle and complete this huge task in a reasonable timeframe. However, this still remains the long-term objective pursued on a country-by-country basis.

In the early 1990s, FAO recognized that a rapid update of the Soil Map of the World would be a feasible option if the original map scale of 1:5 M were retained, and started, together with UNEP, to fund national updates at 1:5 M scale of soil maps in Latin America and Northern

Asia. At the same time, FAO tested the physiographic SOTER approach in Asia (Van Lynden, 1994), Africa (Eschweiler, 1993), Latin America (Wen, 1993), and the CIS and Baltic States and Mongolia (Stolbovoy, 1996).

These parallel programmes of ISRIC, UNEP and FAO merged together in mid-1995, when at a meeting in Rome the three major partners agreed to join all resources and work towards a common world SOTER approach covering the globe at 1:5 M scale by the 17th IUSS Congress of 2002 to be held in Thailand. Since then, other international organizations have shown support and collaborated to develop SOTER databases for specific regions. This is for instance the case for Northern and Central Eurasia where the International Institute for Applied System Analysis (IIASA) joined FAO and the national institutes involved, and for the European Soils Bureau (ESB) in the countries of the European Union. The ongoing and planned activities are summarized in Table 2. It should be noted that although the information is collected according to the same SOTER methodology, the specific level of information in each region results in a variable scale of the end products presented. The soils and terrain database for north-eastern Africa, for instance, contains information at equivalent scales between 1:1 million and 1:2 million, but the soil profile information is not fully georeferenced. For north and central Eurasia, profile information contained in the CD ROM is very limited. Fully comprehensive SOTER information is available for South and Central America and the Caribbean (1:5 million scale) and includes more than eighteen hundred georeferenced soil profiles. Data are downloadable from http://www.isric.nl/SOTER/LACData.zip and viewable using a viewer program at http://www.isric.nl/SOTER/Viewer102b.exe) . For Central and Eastern Europe (1:2.5 million scale). This SOTER database contains more than 600 georeferenced soil profiles.(http://www.fao.org/catalog/book_review/giii/x8322-e.htm).

It is obvious from Table 2 that, although significant progress has been made over the last six years, more resources are urgently needed if the global SOTER database is to cover the whole world in the near future and serve as a basis for applied studies.

Table 2. Operational Plan for a World SOTER: 1995-2002

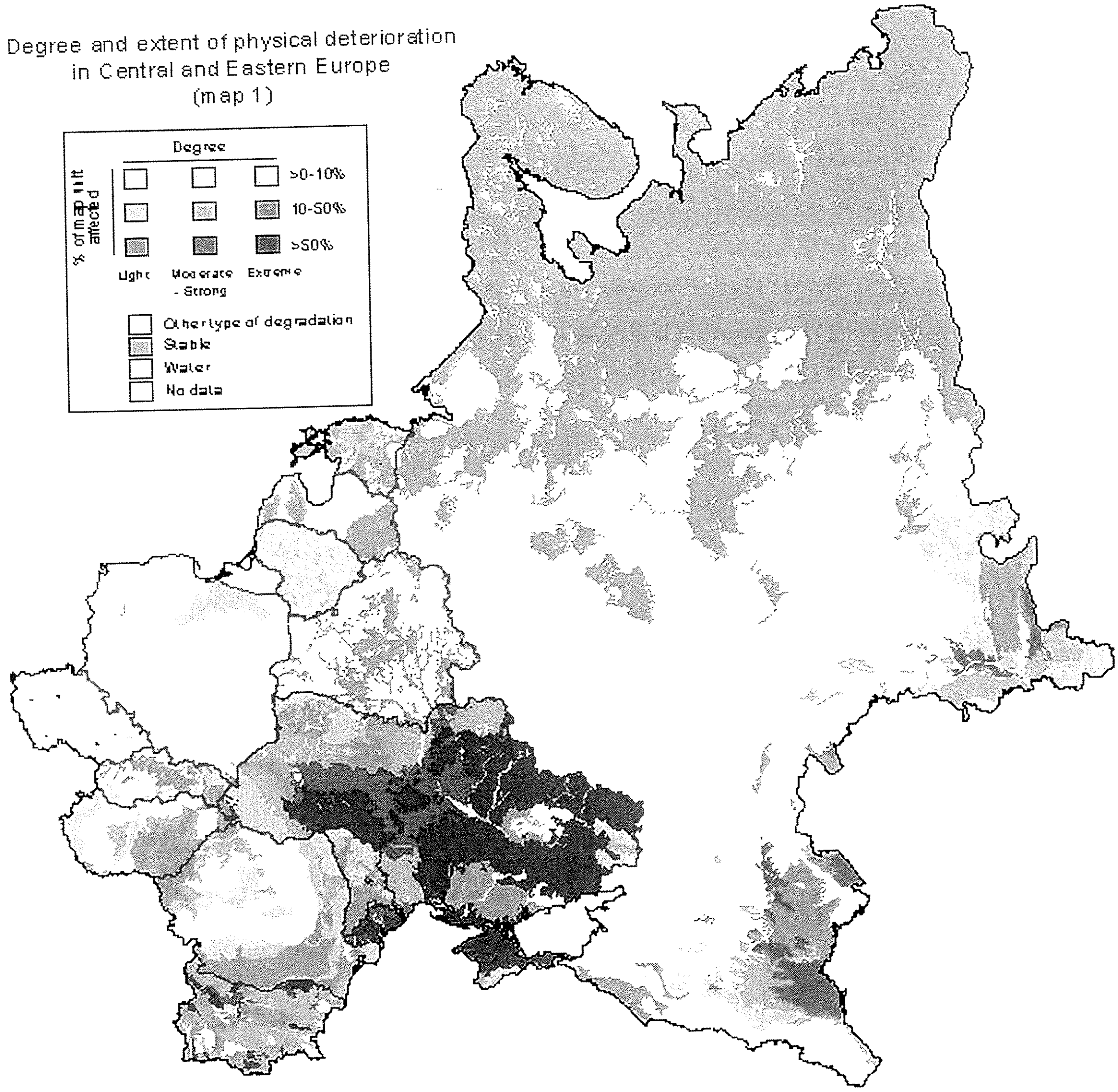
Region	Status	Main Agencies Involved	Published Date
Latin America and the Caribbean	Published	ISRIC, UNEP, FAO, CIAT, national soil institutes	1998
North-eastern Africa	Published	FAO-IGAD	1998
South and Central Africa	Ongoing	FAO-ISRIC-national inst.	2001
North and Central Eurasia	Published	IIASA, Dokuchaev Institute, Academia Sinica, FAO,	1999
Eastern Europe	Published	FAO-ISRIC-Dutch Government-national inst.	2000
Western Europe	Ongoing	ESB-FAO-national inst.	2002
West Africa	Proposal submitted	Awaits funding (ISRIC, IITA)	
Southeast Asia	Proposal discussed	Awaits funding	
USA and Canada	Own Effort	NRCS	Own effort
Australia	Own Effort	CSIRO	Own effort

The SOTER framework has been used to map soil degradation status at regional and national scale carried out in Southeast Asia (the ASSOD project) and in Central and Eastern Europe (The SOVEUR project). In the latter programme special attention was paid to the vulnerability of soils to pollution. These two applications are further discussed in the following sections.

2.Soil degradation and Physical Soil Deterioration in Central and Eastern Europe

In 1997 a project on Mapping of Soil and Terrain Vulnerability in Central and Eastern Europe (SOVEUR) was implemented by FAO and the International Soil Reference and Information Centre (ISRIC) within the framework of the FAO/Netherlands Government Cooperative Programme (GCP/RER/007/NET) One objective of the SOVEUR project was to produce a geographical overview of the current status of soil degradation in this region, with emphasis on soil pollution.

Like previous assessments of soil degradation at a global (GLASOD; Oldeman et al., 1991) and regional scale (ASSOD; van Lynden and Oldeman 1997), this assessment is based on experts' estimates. As such it gives an overall impression of the status of soil degradation in the region. For problem areas thus identified more detailed studies can be carried out to determine the course of action. The major indicators considered for the seriousness of the problem, the spatial distribution (extent), the intensity of the degradation process (degree), the effect - mainly on productivity -(impact) as well as the past recent trend (rate). An example of the outputs is illustrated in the map that follows.



Though SOVEUR had a specific emphasis on the assessment of status of - and vulnerability to – pollution, the outcome of the degradation assessment was that physical deterioration, compaction in particular – is the dominant degradation type in terms of spatial distribution (see Table 3), followed by sheet erosion by water.

Table 3: Extent and Degree of degradation in Central and Eastern Europe

Type	Degree	Light	Moderate	Strong	Extreme	Total	
Pc	Compaction	25.10	36.35	0.72	0.01	62.18	M.ha
Wt	Water erosion (topsoil)	7.81	17.34	19.00	0.00	44.15	M.ha
Cn	Fertility decline	8.16	21.06	1.83	0.00	31.05	M.ha
Pk	Crusting	9.89	17.18	0.47	0.00	27.54	M.ha
Pd	Aridification	1.80	13.47	8.81	0.00	24.07	M.ha
Cpa	Acidification	3.88	18.86	1.46	0.00	24.20	M.ha
Et	Wind erosion (topsoil)	3.36	6.59	7.61	0.18	17.73	M.ha
Cpp	Pesticide pollution	3.91	6.45	0.17	0.00	10.53	M.ha
Pw	Waterlogging	3.49	3.84	1.45	0.03	8.80	M.ha
Cph	Heavy metal pollution	1.26	6.26	0.27	0.00	7.79	M.ha
Cpr	Radio-active contamination	2.88	3.46	0.06	0.00	6.39	M.ha
Cs	Salinisation	1.57	2.77	0.68	0.00	5.01	M.ha
Wd	Water erosion (terrain deformation)	0.10	1.66	3.18	0.00	4.94	M.ha
Other						1.23	M.ha
Non-degraded						383.52	M.ha

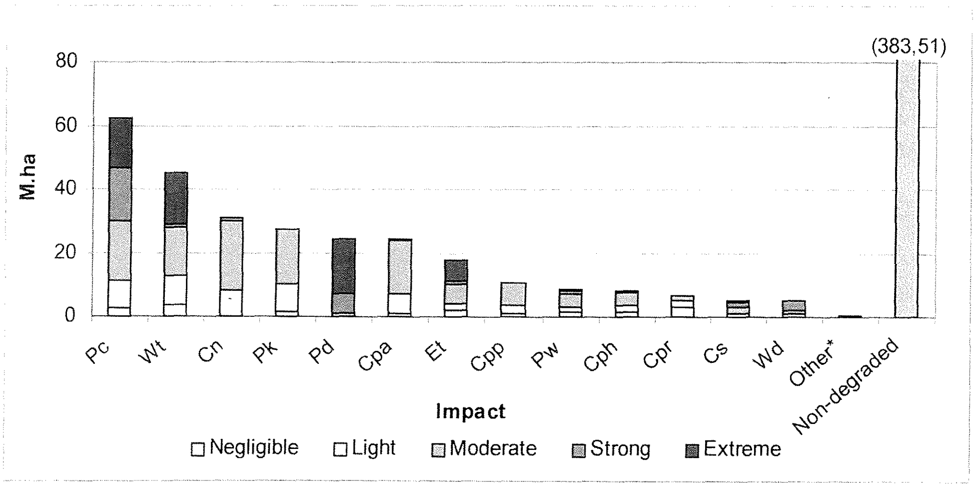


Figure 1: Impact of different degradation types in Central and Eastern Europe

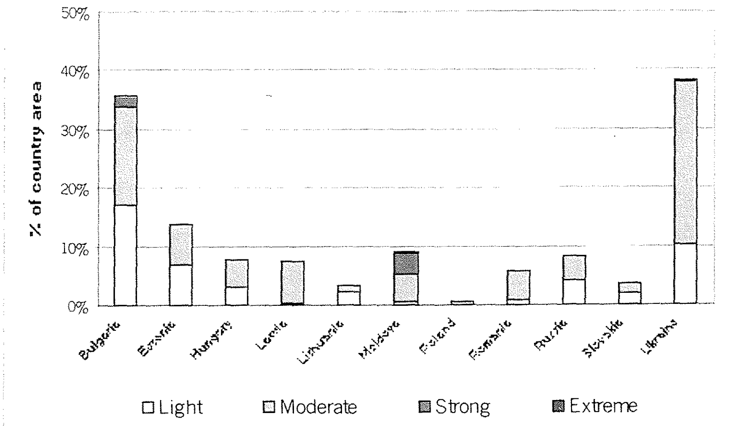


Figure 2: Degree of compaction in Central and Eastern Europe

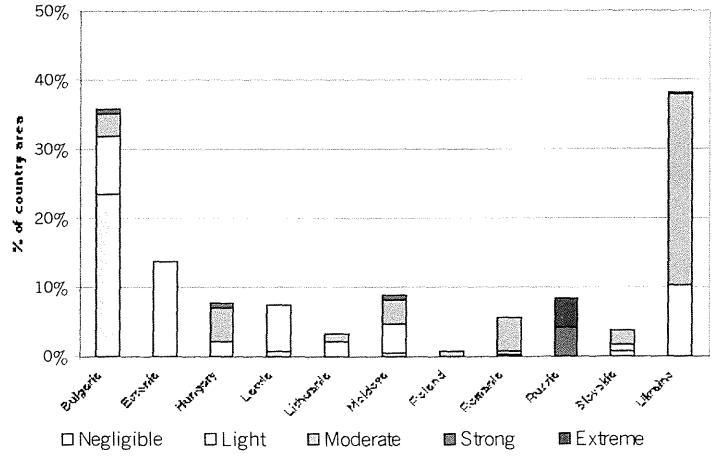


Figure 3: Impact of compaction in Central and Eastern Europe

The degree of degradation is lower for compaction than for water erosion, but the perceived impact is more or less similar. (see figure 1). While this picture applies to the region as a whole, the distribution per country is quite variable. Compaction and crusting were mentioned in almost all countries in the region, but occur most extensively in Bulgaria and Ukraine. In these two countries, over 35% of the country area is affected at a light to moderate degree (see figure 2), but a low impact is indicated in the case of Bulgaria and light to moderate in the case of the Ukraine (figure 3).

During a mid-project workshop, some national contributors mentioned a general decrease in compaction problems in the region during the last decade, because of reduced mechanisation intensity as a consequence of fewer investments in agriculture since the political changes in the early nineties. This trend however is not truly reflected in the figures that were provided for the recent past rate throughout the entire region: of the entire area affected by compaction, some 56% shows no change in degradation, while a slow to moderate increase is indicated for 21% and 13% respectively. A slow decrease in degradation is noted for about 10% of the affected area.

3. Assessment of soil vulnerability to pollution

Soil vulnerability is defined as the 'capacity for the soil system to be harmed in one or more of its ecological functions'(Batjes and Bridges, 1993). Regional differences in static and dynamic soil properties will affect a soil's capacity to control movement of pollutants, and hence its vulnerability to a given pollution scenario. The assessment of soil vulnerability, as considered in the SOVEUR project, forms the first stage in identifying areas considered at risk from 'delayed and then sudden, non-linear' occurrences of pollution. This concept, originally described by the metaphor of 'Chemical Time Bomb' (CTB), is discussed elsewhere (Stigliani, 1988). In summary, it stresses: (1) the (changing) capacity of the soil reservoir to hold or release contaminants, and (2) a trigger system. In the above sense, the most vulnerable soils are those with high but finite capacities for storage of potentially harmful and mobilizable chemicals (Salomons and Stigliani, 1995; Stigliani et al., 1991). The chemicals of concern with respect to CTB-occurrences are the long-lived species most resistant to chemical decomposition, especially heavy metals and persistent organic chemicals. Irrespective of scale, a key issue in any assessment of soil vulnerability will be how to decrease the functional complexity in relation to the adopted scale of mapping. The smaller the map scale, the greater the need will be for an explicit methodology to simplify the information available, while remaining realistic at the same time (Batjes, 1997).

There is a wide diversity of soils in Central and Eastern Europe (FAO and ISRIC, 2000). Each of these soils may be viewed as a chromatographic column, or system of geochemical barriers, with respect to contaminant behaviour (Glazovskaya, 1991). Depending on its inherent 'capacity controlling properties' (CCP), each soil will react in different ways to pollution and environmental changes. For example, the most important CCPs affecting heavy metal binding are depth of soil, texture, content and type of organic matter, soil pH-redox conditions, the content of oxides of Fe, Al and Mn (Hesterberg et al., 1992). The type of metal is also important in this respect. The type of pollutant and research purpose thus will determine which soil attributes or single value maps are of importance in each special case. Important processes (triggers) that can influence a soil's capacity to hold and release various contaminants and pollutants include: acid precipitation, eutrophication, salinisation, water erosion, loss of organic matter, structural degradation, as well as changes in climate, hydrological conditions and land use (Bouma et al., 1998; Hesterberg et al., 1992; Japenga et al., 1997). The 1:2,500,000 scale SOVEUR project developed a procedure for rating the vulnerability of soils to 'heavy metal mobilization, inducible by acid deposition'.

Criteria for rating the metal binding capacity were taken from Blumme and Brummer (1991). Their rating scheme takes into account that the relative binding strength of a soil with respect to heavy metals will vary with the organic matter, clay content, and clay mineralogy, drainage conditions and content of sulphides. The scheme can be used to rate the binding strength and retention against uptake by plants and groundwater pollution for 11 metal ions: Cd, Mn, Ni, Co, Zn, Cu, Cr(III), Pb, Hg, Fe(III), and Al. Batjes (2000a) elaborated the procedure for the SOVEUR area, using Cd, Zn and Pb as examples. Median values for the main CCPs, by soil unit, were derived from the profile data held in the soil and terrain (SOTER) database for the SOVEUR area (Batjes, 2000b). For each soil component in a given SOTER unit, the binding capacity (fin_d) for the metal under consideration, was obtained from:

$\text{fin}_d = \text{b\_ph} + \text{b\_orgc} + \text{b\_text} + \text{b\_feox} + \text{b\_sulf} + \text{m\_drain}$

where:

d is the depth range under consideration: *top*soil (0 - 0.3 m) and *sub*soil (0.3 - 1 m).

b_X is the relative binding capacity due to capacity controlling property *X*.

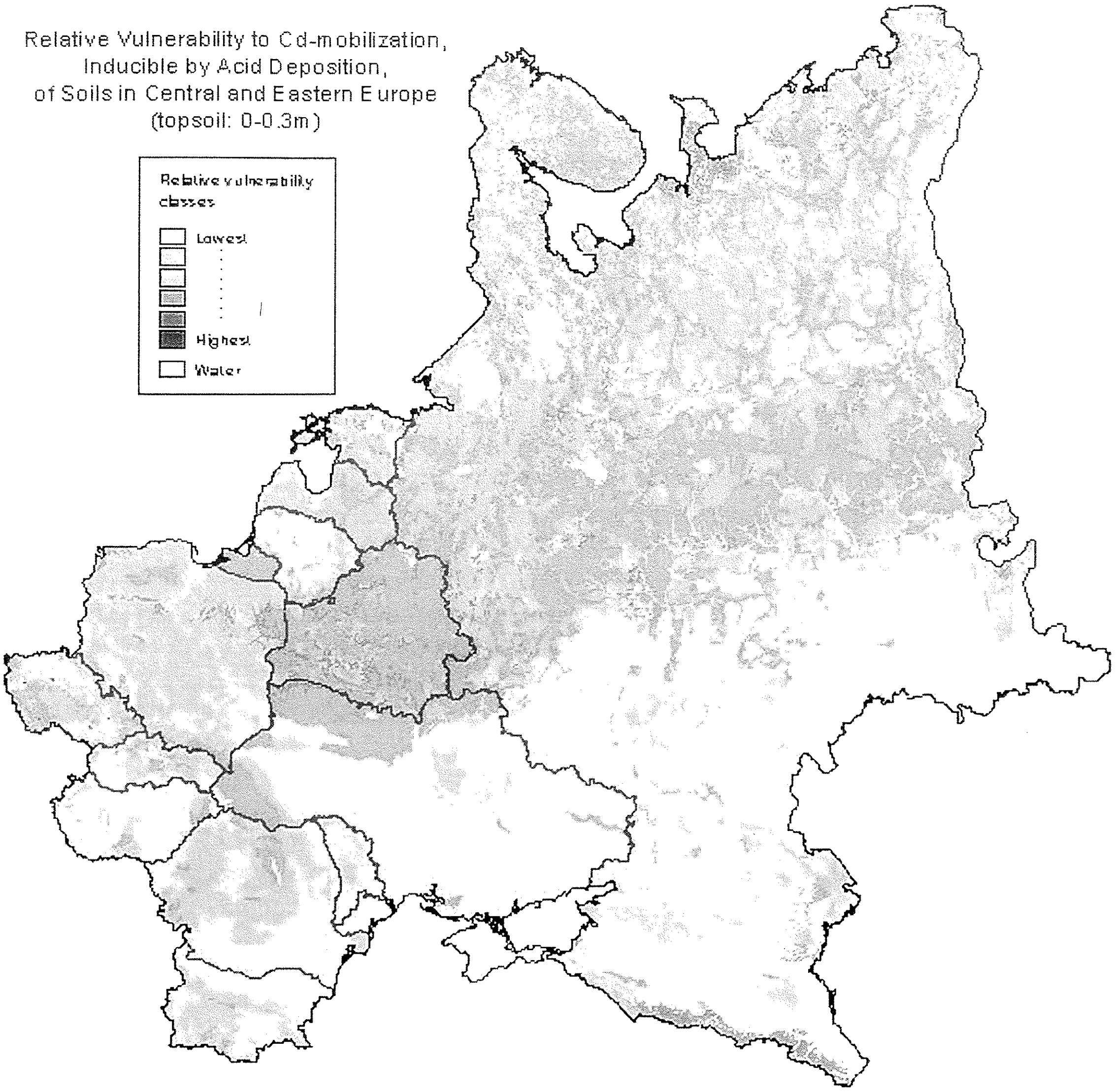
m_drain is a metal-mobilization factor associated with strongly alternating wetting/ drying conditions.

A depth-weighted rating for the metal binding capacity, for the soil unit and metal under consideration, was computed next and converted into five relative binding strength classes. Finally, an area-weighted rating for the relative metal binding capacity was calculated by SOTER unit.

As has been indicated earlier, the capacity of a soil to hold a contaminant can change under the influence of a 'trigger system', such as acid deposition. Deposition of acidifying substances, although on the decrease since about 1985, still exceeds critical loads in about 10% of Europe's land area, mainly in northern and central Europe (EEA, 1999). According to Van Lynden (2000), acidification is the most widespread type of pollution in the SOVEUR area. Similar to what has been the case for the heavy metal binding capacity, a depth-weighted rating for the relative 'sensitivity to acid deposition' was determined by SOTER unit, from the ratings for its component soil units. The latter were assessed using the median base saturation and CEC as main differentiating criteria, using the methodology of Cindery et al. (1998).

Finally, the relative vulnerability of each SOTER unit to 'heavy metal mobilization, inducible by acid deposition', was determined from the depth-weighted ratings for 'sensitivity to acid deposition' and 'binding capacity with respect to heavy metals' of its individual soil units (Batjes, 2000a). Examples of results may be found on the CD ROM that resulted from the SOVEUR project (FAO and ISRIC, 2000). An example of which is reproduced below.

Uncertainties associated with data and errors in the model are prone to be significant at the scale of 1:2,500,000; the various types of uncertainties are difficult to resolve and quantify, and they will vary according to the various national data sets and models used (Batjes, 1999). Nonetheless, soil vulnerability maps, of the type described above, can be combined with maps of actual loadings to identify broad areas considered most at risk from re-mobilization of selected types of heavy metals. The actual identification of these areas, however, will first become feasible once there is unfettered access to existing, auxiliary databases of chemical loads for Central and Eastern Europe which is now not the case



4.Conclusions

The update the soil map of the world under the global SOTER programme is not yet finalized and additional resources are needed to achieve this.

Regional SOTER databases such as the one for Central and Eastern Europe have provided the base units for applied inventories of soil degradation for instance and also generate estimates for specific soil parameters that permit to test models such the one illustrated on vulnerability to soil pollution.

The evaluation of the soil degradation findings is that physical soil deterioration, in particular compaction is the the dominant degradation type in terms of spatial distribution in Central and Eastern Europe. Compaction and crusting occur most extensively in Bulgaria and the Ukraine.The impact on production is judged low (Bulgaria) or or light to moderate (Ukraine).

Latest findings also indicate a general decrease in compaction problems in the region, mainly as a consequence of reduced mechanization intensity since the early nineties.

Vulnerability maps to soil pollution were generated for each SOTER unit taking into account the metal binding capacity for the soil and the sensitivity to acid deposition of 11 metal ions. These type of maps are able to indicate areas most at risk when compared with information of actual loads of these ions.

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Determination of the susceptibility of subsoils to compaction and ways to prevent subsoil compaction

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Abstract

Soil compaction is estimated to be responsible for the degradation of an area of 33 million ha in Europe. Wheel loads still increase and compaction expands more and more into the subsoil. This deserves special attention because subsoil compaction is very persistent and possibilities of natural or artificial loosening are disappointing. Subsoil compaction has been acknowledged by the EU as a serious form of soil degradation and therefore the EU finances two concerted actions on subsoil compaction. The concerted actions involve 49 institutes in 27 countries in whole Europe. The general objective of the concerted actions is to make an inventory of existing knowledge and experiences with the distribution and impact of subsoil compaction in Europe, formulation of recommended methods and field experiments, and development of ways and guidelines to prevent subsoil compaction. The two concerted actions collaborate in the construction of two databases: (1) on literature on subsoil compaction; (2) on soil mechanical properties and impact of subsoil compaction on soil nutrients, physical properties, crop production and environment. Parts of the preliminary results of the concerted actions are two concepts for the determination of susceptibility of subsoils for compaction and how to prevent subsoil compaction. One concept is based on a deterministic approach taking into consideration the strength of the subsoil in relation to the stresses in the soil exerted by the wheel load, the effect of compaction on soil physical properties and rooting depth and crop growth, and the possibilities for loosening and natural recuperation. The other concept is based on an empirical approach taking into consideration the same aspects however based on experience. The deterministic approach is the scientific sound and universal way to determine the susceptibility to subsoil compaction and the resulting guidelines, recommendations and management decisions to prevent subsoil compaction will have accordingly a sound basis. However this deterministic approach requires a lot of additional data and research. The empirical concept lacks this sound basis and is not universal because it is only valid for experience with local soils, climate, management and crops. The main advantage of the empirical approach is that it needs less additional data and research to formulate guidelines to prevent subsoil compaction.

Keywords: subsoil compaction, soil degradation, soil quality, soil physical properties, soil mechanical properties

Introduction

Not everybody has the same definition for the subsoil. In the concerted actions on subsoil compaction and in this paper the subsoil is the soil below the cultivated layer. In this definition the panlayer is the upper part of the subsoil. The panlayer is in many cases denser and less permeable for roots, water and oxygen than the soil below it and is therefore many times the bottleneck for the functioning of the subsoil.

It has been estimated that in Europe, 25 % (72000 km^2) of all agricultural land, 35 % (54000 km^2) of all pasture land and 92 % (26000 km^2) of all forest and woodland is affected by some kind of soil degradation (Van Lynden, 1995). Soil compaction is estimated to be responsible for the degradation of an area of 33 million ha in Europe (Soane and Van Ouwerkerk, 1995). About 32 % of the subsoils in Europe are highly vulnerable to subsoil compaction and another 18 % is moderately vulnerable to subsoil compaction (Fraters, 1996). Due to the ever increasing wheel loads in agriculture, compaction is increasingly expanding into the subsoil. This deserves special attention because subsoil compaction is very persistent (Håkansson et al., 1987, Håkansson, 1994, Alakukku, 1996) and results of natural loosening or artificial loosening techniques have been disappointing (Kooistra et al., 1984). Deep ripping of compact subsoil of pedogenic origin has been successfully used in Germany (Schulte-Karing, 1970), and expanded under specific soil and climate conditions in many East-European countries (Stanga et al., 1973; Zaidelman, 1992). Compacted subsoil is economically and environmentally sub-optimal. It results in decreased crop production and crop quality and requires an increased input of energy, nutrients and water. At the moment, it is common practice to compensate the detrimental effects of soil or subsoil compaction on crop production by improving drainage and supplying more nutrients and water (irrigation). These "solutions" lead to excessive use of water and nutrients and pollution of the environment. Healthy subsoil, which is a habitat for soil fauna and flora, is an environmental aim in itself and a precondition for organic and integrated farming systems. Subsoil with good soil physical qualities allows plants to make optimal use of nutrients and water and permits reduction of inputs. Severely compacted subsoil has a decreased infiltration and storage capacity, resulting in an increased surface runoff promoting erosion and pollution of surface water with soil, nutrients and chemicals used in agriculture.

The costs of subsoil compaction in Europe are not precisely known, but Arvidsson et al (2000) estimated the subsoil compaction effect of a self propelled six-row harvester on yield losses to be 3 % per year. Assuming that such harvesters are used on at least 500,000 ha in the EC this results in an annual loss of sugarbeet yield of 50,000 kEURO. It is expected that these heavy harvesters will be increasingly used. Alblas et al. (1994) estimated that traffic-induced subsoil compaction has reduced the total production of silage maize in the Netherlands by 7%. This results in an annual loss in the Netherlands of 21.000 kEURO. For the USA, where much higher wheel loads are used than in the EC, long-term average maize yield reductions of 6% have been estimated (Voorhees, 1992). A report of the European Environment Agency, 'Europe's Environment, The Dobris Assessment' (Stanners and Bourdeau, 1995) reported yield losses of 5 - 35%, with an average of 12% on severe compacted subsoils. In the countries of the former USSR heavy equipment is used even on wet soils, and yield losses up to 50% by soil compaction were reported in former Soviet agriculture (Libert, 1995). Total yield losses caused by soil compaction in the former USSR countries are estimated at 13 - 15 million tons of grain (7 - 8% total yield), two million tons of sugarbeet (3%), and half a million tons of maize (4%). During ploughing, annual fuel consumption is claimed to be one million tons higher than necessary because of soil compaction. It is not possible to calculate what part of these losses can be attributed to subsoil compaction, but very persistent subsoil compaction, going deeper than 80 cm, has been registered in large areas of the former USSR.

In Romania it is estimated (Canarache et al., 1984b) that 55 percent of the arable area is subject to topsoil and upper subsoil compaction of man-made origin, and 11 percent to subsoil compaction of pedogenic origin, with some 5 percent decrease in the total country crop yield, and also some 5 percent increase in fuel consumption for tillage operations. One of the impacts of subsoil compaction is that the nutrient usage efficiency decreases which means that the loss of nutrients in the environment increases. Alakuku and Elonen (1995) found that the decrease of nitrogen yield can be many times the decrease in grain yield.

Overviews on soil compaction and subsoil compaction can among others be found in Håkansson (1994), Soane and Van Ouwerkerk (1994), Van den Akker et al. (1999), Arvidsson et al. (2000), Birkas et al. (2000), Horn et al. (2000), Van den Akker et al. (2001).

The EU finances two Concerted Actions on subsoil compaction. One concerning the EU countries by the FAIR program and one concerning the Countries of Central Europe and the New Independent States by the INCO-Copernicus program. The FAIR CA started the first of January 1998 and the INCO-Copernicus CA started the first of December 1998. Both are 3-year projects. Improving ways to prevent subsoil compaction are a main goal of the concerted actions. Prevention of subsoil compaction is essential for an economically and environmentally sustainable agriculture. Knowledge of the susceptibility of subsoils to compaction and the load-bearing capacity of subsoils would enable manufactures to design subsoil-friendly equipment and would help farmers decide whether, where and when they should use this kind of equipment. Scenario and land evaluation studies frequently neglect the aspect of subsoil compaction, due to a lack of knowledge of the impact of subsoil compaction on the soil physical quality and the diminished rooting possibilities and crop growth resulting from this compaction. Improved knowledge of these aspects would improve the analysis of the impact of political decisions and agricultural practices on environment, crop production and the use of natural resources. A result of the FAIR concerted action on subsoil compaction is a concept for the determination of the susceptibility of subsoils to compaction. This concept requires detailed data which can be partly found in a database constructed as a result of both concerted actions (Trautner and Van den Akker, 2001). The database includes soil mechanical data needed to calculate the bearing capacity of the subsoil, and soil physical data needed in crop growth models and results of field experiments to verify modeling and for analyzing the susceptibility to compaction of subsoils. This concept and its relation with the database will be presented in this paper.

An other result of the FAIR concerted action on subsoil compaction that will be presented in this paper is the development of an empirical concept for the determination of the susceptibility to compaction of subsoils (Alakukku et al., 2001, Jones et al., 2001, Chamen et al., 2001a, 2001b and Spoor et al., 2001). This empirical approach is less reliable and universal, however, requires less data and additional research and resulted in the determination of preliminary guidelines for the maximum inflation pressure of tyres to prevent subsoil compaction and an European map presenting soils in five subsoil susceptibility classes.

A concept for the determination of the susceptibility of subsoils to compaction

Several aspects concerning soil properties, hydrological situation, climatic conditions, crop growth conditions, rooting depths, timeliness and applied wheel loads and inflation pressures must be considered in the determination of the susceptibility of subsoils to compaction.

Aspects which will make a subsoil less susceptible to compaction are:

the soil is strong

1. the impact of compaction on the soil physical properties is low
2. the impact of subsoil compaction on crop growth and environment is low

3. recuperation of structure and soil qualities by natural processes are almost complete and within a reasonable time
4. deep loosening is easy and effective and long lasting
5. the hydrological situation is optimal (well drained)
6. the climate is optimal for crop growth and natural recuperation.

A well-drained soil is a requirement because soil strength is strongly related to moisture content. For the same reason climate has a major impact on the susceptibility to compaction of soils. Recuperation of compacted soils by natural processes like shrinkage, rooting and soil biota requires drying out of the soil and diffusion of oxygen deep into the soil and into the aggregates. High groundwater tables and a wet climate will diminish the possibilities for natural recuperation of the subsoil. Moreover deep loosening requires a dry subsoil. The climate is also an important factor in the susceptibility of a subsoil because the impact of compacted subsoil with restricted rooting depth on crop growth and yield will be most pronounced in extreme wet or dry climatic conditions. If rainfall is high and lasting, then the decreased saturated hydraulic conductivity of the compacted subsoil will increase the risk for slacking and water erosion and in the growing season anaerobiosis can cause a lot of damage to the crop. Moreover nutrients will be lost by leaching and denitrification. In a long dry period the restricted rooting depth will limit the available water to the crop. By deeper drainage, irrigation and additional nutrients the impact of subsoil compaction on crop growth can be diminished, however, this will be less water and nutrient efficient and will cause extra environmental problems.

The seven points mentioned must be included in a determination procedure to assess the susceptibility of a certain subsoil to compaction. A concept for such a determination procedure is proposed. In Table 1 the layout of the concept is presented. It shows in the first column the setup of the procedure to determine the susceptibility of a subsoil to compaction and the determination of the bearing capacity (further abbreviated to 'determination procedure'). The next column shows the used methodology. What is needed for verification and calibration of the measurements and model simulations is presented in the third column. In the last column "generalization" the requirements for generalization from a local soil and situation to an other local situation or to regional, country or higher scales is presented. Generalization will make it possible to use the information and gained knowledge in praxis.

Concept for a procedure to determine the susceptibility to compaction of a subsoil.

Subsoil description: This includes registration of the location, soil, hydrological situation, climate, soil management, and crop. This should be preferably according FAO and EU standards.

Strength: The strength must be determined at several relevant soil moisture contents because soil strength depends on soil moisture content. The structural strength (often expressed as pre-consolidation load) of the subsoil can be determined in drained or undrained uni-axial (oedometer) tests. These tests can be fast or slow. A fast test represents the situation in the field under a wheel load in the best way, however, the reproduce-ability of the test is low. The slow drained test is more easy to perform and less sensitive to errors and can be reproduced easier. Exceedment of the structural strength by soil stresses generated by wheel loads results in crushing and/or flattening of the aggregates. The shear strength can be determined in direct shear tests or in tri-axial tests. The tri-axial test is better, however, more difficult and labour intensive. Exceedment of the shear strength results in homogenizing of the soil and decrease of strength and quality of soil physical properties. Examples of generalization of soil strength are the development of classification and pedotransfer functions for the strength of German soils by Lebert and Horn (1991), Horn and Fleige (2001), Fleige and Horn (2001), DVWK Merkblatt (1995). An other possibility for generalization is the use of simple and quick measurements, preferably in the field. A test for quick assessment of the strength was proposed by Schjønning (2000).

Procedure	**Methodology**	**Verification and calibration**	**Generalization**
Subsoil description	Structure, texture, physical, mechanical and chemical properties		Compatible to FAO standards and Soil Profile Analytical Database of Europe (SPADE)
Strength	Structural strength (uni-axial test) Shear strength	Image analysis Tri-axial tests Traffic experiments FEM analysis	Simple/quick measurements Pedotransfer functions Classification
Impact on soil physical properties	Restriction roots by: (1) Mechanical impedance => Penetration resistance. (2) Oxygen/water demand, diffusion, air conductivity => water retention curve, (un)sat. conductivity	Field experiments Traffic experiment Earlier field experiments Image analysis Literature	Pedotransfer functions
Impact on crop and environment	Earlier field experiments + Literature => Required phys. Prop., threshold values Crop growth/N-model	Field experiments Modeling Literature	Modeling
Natural recuperation	(Old) field experiments + Literature Sub-procedure	Field experiments Old field experiments. Image analysis	Classification
Possibilities for repair (loosening)	Old field experiments + Literature Sub-procedure	Old field experiments Literature	Classification
Determination bearing capacity	Model (SOCOMO)	Traffic experiments FEM computations	Calculation bearing capacity with standard set of tyres/inflation pressure. Classification
Final determination susceptibility to subsoil compaction	Evaluation and conclusion	Field experiments Earlier field experiments.	Interpretation soil maps and data sets => Susceptibility to subsoil compaction maps

Table 1. Layout of the procedure to determine the susceptibility of a subsoil to compaction. Relations between determination procedure, methodology, verification and generalization.

Impact on crop and environment can be derived by studying earlier field experiments, literature (Håkansson et al., 1987 and Håkansson, 1994) or by performing new experiments. A result of the FAIR concerted action on subsoil compaction are guidelines for the setup of field experiments on the impact of subsoil compaction (Håkansson, 2000). Effects of subsoil compaction can also be estimated with model simulations (Feddes et al., 1984, Lipiec et al., 2001, Moreno et al., 2001, Simota et al., 2000, Stenitzer and Murer, 2001). Although sometimes good results were derived, it is clear that subsoil compaction needs more attention in further development of crop growth models. It is also required that a combined crop growth - N-cycle model must be used to estimate effects of altered soil physical properties by subsoil compaction on crop growth and N-cycle, because denitrification and resulting decrease of crop yield and quality is a wellknown effect of compacted soils. A combined crop growth – N–cycle is also needed to simulate the impact of subsoil compaction on the environment.

Natural recuperation: The next step in the procedure is the determination of the soil physical quality after natural recuperation. This can be based on experiences in field experiments and literature (Arvidsson and Håkansson, 1996, Alakukku, 1996, Alakukku and Elonen, 1995, Alakukku, 2000, Voorhees, 2000, Wiermann and Horn, 2000). Their conclusion is that subsoil compaction is persistent and will never recuperate completely. A measurement procedure in the lab should be developed because field experiments require too much time. Probably only the positive effects of (repeated) shrinkage and freezing on structure and the soil physical properties can be determined, because it is too difficult to simulate the effect of soil biota on the recuperation of compacted soil in a limited time. This is an omission, because it is clear that recuperation of subsoil is promoted by soil biota (Larink and Schrader, 2000).

Possibilities for repair: If it is clear that rooting and water infiltration is restricted by subsoil compaction and the natural recuperation is very low, then loosening of the subsoil can be considered. However, a loosened soil is very vulnerable to recompaction and in many cases the soil physical qualities are low in recompacted soils. Original continuing macropores created by rooting and soil biota will be destroyed in the loosening process. Many times the remedy is worse than the problem. Therefore a laboratory measurement procedure should be developed to determine the susceptibility to recompaction and the resulting decrease of soil physical properties.

Determination of the bearing capacity: If the soil physical qualities of the investigated subsoil is satisfying or reasonable and compaction and distortion results in a severe decrease in soil physical quality, then there is a need to prevent compaction or distortion of the subsoil. A method to prevent subsoil compaction is to take care that the load (expressed in soil stresses) is lower than the bearing capacity (strength) of the subsoil. A more practical approach is expressing the bearing capacity as wheel-load/tyre-dimensions/tyre-inflation combinations that do not result in compactions and/or distortions. In this part of the determination procedure analytical models like SOCOMO (Van den Akker, 1994, 1997, 2000) can be used to calculate the soil stresses in the subsoil exerted by a series of relevant wheel-load/tyre-dimensions/tyre-inflation combinations and compare the stresses with the strength of the soil. The model SOCOMO, guidelines and examples can be downloaded from the Internet site: http://www.alterra.wageningen-ur.nl/subsoil-compaction/. It is also possible to use the more sophisticated and realistic Finite Element Method (FEM) (Berli et al., 2001, Poodt et al., 2001) to calculate allowable wheel loads. However, these sophisticated models need more and more sophisticated input data than analytical models, although Koolen and Van den Akker (2000) showed that many of the required soil properties can be estimated or derived from known or easy measured soil properties. Traffic experiments and FEM simulations can be used to verify and calibrate the model simulations.

Final determination of susceptibility to compaction: Assessment of the results derived with the determination procedure results in the determination of the susceptibility to compaction of the investigated subsoil.

The relation of the database “Soil mechanical properties and impact of subsoil compaction on soil physical properties, crop production and environment” to the procedure to determine the susceptibility of a subsoil to compaction.

The participants of the concerted actions deliver the data for the database “Soil mechanical properties and impact of subsoil compaction on soil physical properties, crop production and environment” in Excel workbooks. The information in the Excel workbooks is converted into an ACCESS datafile, more convenient for processing and interpretation (Trautner and Van den Akker, 2001). The structure of the workbooks is presented in figure 1. The database is still in construction. It is estimated that in total about 550 sets of data (Excel workbooks) are included in the database. In total, the database will contain approximately 10.000 spreadsheets with data. The workbook consists potentially of close to 60 spreadsheets. The sheets cover all potential measurements in subsoil compaction research, however, in praxis only a limited amount of all possible measurements are done, so many sheets are not filled in. In crop yield experiments one workbook concerns one experiment in one year. The workbook is also suited to collect just soil mechanical data measured in the lab, pot experiments etc.

As presented in Fig. 1, the spreadsheets can be divided into five categories: (1) general information, (2) soil physical parameters, (3) soil mechanical parameters, (4) crop parameters (5) chemical parameters and (6) soil fauna.

In category (1), the participant, regardless of the experiment always fills out the sheets 1-3, which contain general information about the experiment. The Proforma data-sheets supplied by the participants are the same as those used in the soil profile analytic database of the European Union (SPADE) of the European Soils Bureau (Madsen and Jones, 1995a, 1995b) and are therefore compatible with this database. The information needed in Subsoil description of the “Subsoil compaction susceptibility determination procedure” can be found in category (1) of the database.

Category (2), (3), and (4) include the parameter sheets (soil physical, soil mechanical and crop parameters). Each parameter for which treatment effects have been measured should be added in the workbook. In most cases, the number of replicate measurements, date of measurement, the arithmetic mean and the standard deviation for the measured parameters will be given. For values that are not expected to be normally distributed (e.g. soil saturated hydraulic conductivity) special instructions are applied. The data required for Strength and the Determination of the bearing capacity of the “determination procedure” can be found in category (3), sheets 19 – 22, concerning the strength and bearing capacity, and in category (1), sheets 4, 5, 7, 31 and 34, concerning the model computations with SOCOMO and FEM models. The Impact on soil physical properties of subsoil compaction is collected in category (2) and in category (3), sheet 17 and 18. Results of field experiments on the Impact on crop and environment are collected in category (4) “Crop Parameters” in sheets 24, 25, 27, 28, 29 and 38. The effect of Natural recuperation of compacted subsoils is studied in long-term experiments. Reduction of crop yield (sheet 24) and effect on penetration resistance (sheet 17) and vaneshear strength (sheet 20) are included in the database. At the moment there are no substantial results available of research concerning Possibilities for repair (loosening), however, probably workbooks delivered by the INCO-Copernicus concerted action will include data on subsoil loosening. Verification of the Determination bearing capacity is possible because the database includes results of field stress and strain measurements (sheet 22), information about the wheel loads (sheet 4) and soil strength (category (3) “Mechanical Properties”).

Up to now substantial data is available on soil strength and results of field experiments. This makes generalization by the development of “pedotranfer functions” and soil classification for soil strength possible (Fleige and Horn, 2001). Generalization by modeling the impact of subsoil compaction on crop growth and water use is possible because there is enough data available for verification and calibration in the sheets in category (4) "Crop Parameters" and in category (1) "General information", sheets 7 "weather conditions" and category (2) "Physical Parameters", sheets 9 – 13 and 36 – 39.

The database is an indispensable part of the suggested "subsoil susceptibility determination procedure". Collection of measurement results of the "determination procedure" in a common database will make it possible to get insight in the soil compaction processes and the impact on crop growth and environment; to generalize the results and make them useful to praxis. The measurements should be standardized as much as possible to make the results comparable and the generalization possible.

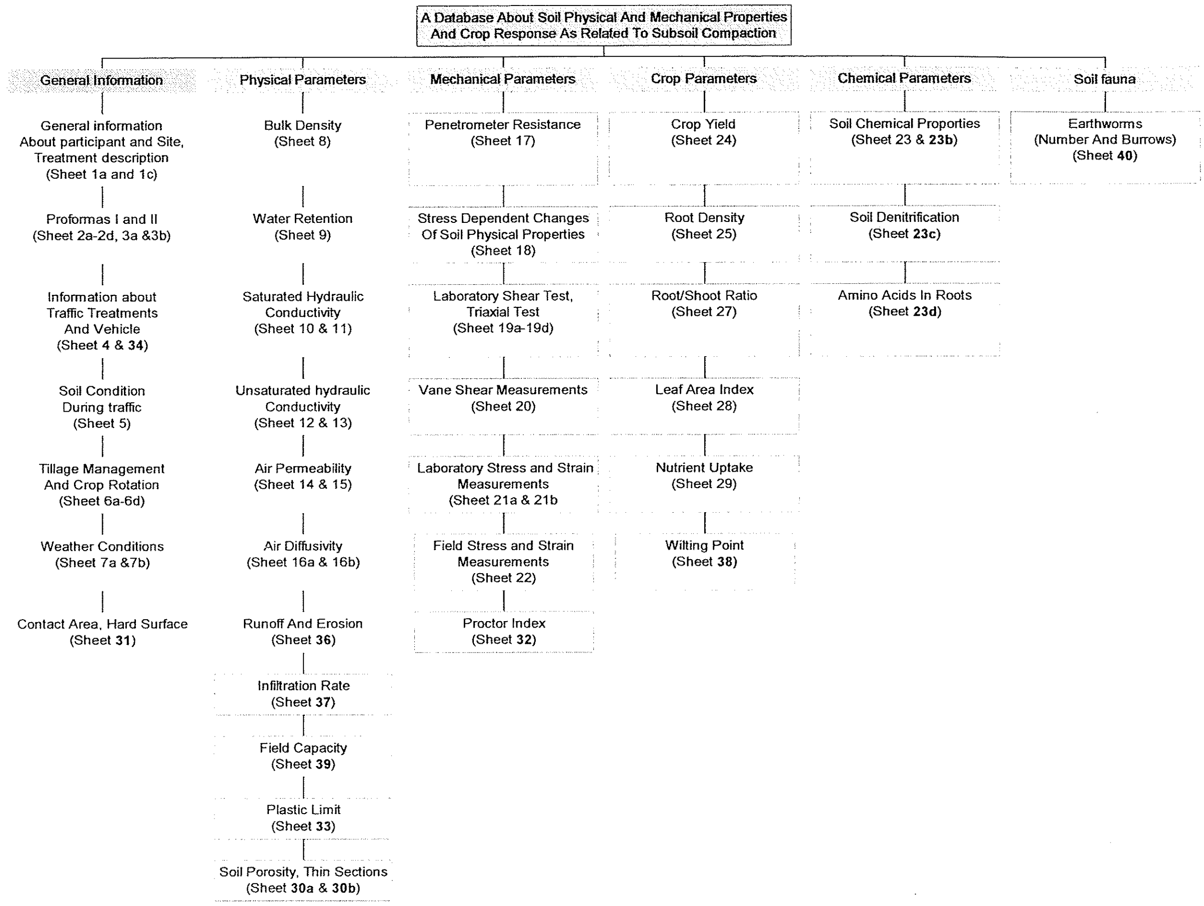

Fig.1. Structure of the CA subsoil compaction database of physical, mechanical, chemical and crop parameters (from Trautner and Van den Akker, 2001).

A simplification of the procedure to determine the susceptibility of a subsoil to compaction.

The procedure can be simplified by arguing that if the bearing capacity of the subsoil is not exceeded by the wheel load, then there will be no subsoil compaction and the determination of the impact of subsoil compaction on soil physical properties, crop and environment is not needed. Also natural recuperation and possibilities for repair (loosening) is not relevant then. In this way the "determination procedure" can be reduced to strength measurements and the determination of the bearing capacity. The susceptibility can be expressed in maximum allowable wheel loads of a standard set of tyre/inflation pressure combinations. Instead of strength measurements pedotranfer functions of soil strength properties depending on categories of soils and moisture conditions (classification) can be used. The risk for degradation of the subsoil by compaction will be very low if the determined allowable wheel loads are not exceeded. A disadvantage of the simplified "determination procedure" is that the calculated allowable wheel load can be very low, while in reality the wheel load could be higher because in many soils limited compaction does not harm the soil quality and can even improve the bearing capacity of the subsoil. The wheel load might be even being higher if the recuperation capacity of the subsoil is very good.

This simplified procedure is already in use in Germany (Horn and Fleige, 2001). Van den Akker (1997) converted data on strength properties of German soils to strength properties of Dutch soils and constructed a preliminary wheel-load bearing capacity map of the Netherlands. However, his conclusion was that measurements on Dutch soils are required to construct a realistic bearing capacity map.

An empirical assessment of subsoil vulnerability to compaction.

This description of an empirical assessment of subsoil vulnerability to compaction is a condensed presentation of the work of Alakukku et al., 2001, Chamen et al, 2001a, 2001b, Jones et al, 2001 and Spoor et al, 2001. The approach described for assessing the likely vulnerability of subsoils to compaction is based, in the absence of quantitative data, on field experience derived from profile pit observations on a wide range of soils, largely occurring in intensively farmed areas where large-scale equipment is employed. The development of the approach is described in detail in Jones *et al* (2001). The assessment is made in two stages:

1. Assessment of the *susceptibility* of the subsoil to compaction based on soil texture and density parameters
2. Combining soil susceptibility with moisture status and topsoil condition data at the time of trafficking, to convert susceptibility to compaction into a *vulnerability* class.

Subsoil susceptibility to compaction is considered to be an inherent property of the soil, and its susceptibility class is determined on the basis of subsoil texture and subsoil packing density. The vulnerability of subsoils to compaction is made on the basis of susceptibility class, soil wetness and topsoil strength, as indicated in Tables 2 and 3. The subsoil packing density is defined as (Van Ranst et al., 1995):

$$PD = Db + 0.009C$$

Where PD is the packing density in $t.m^{-3}$
Db is the bulk density in $t\ m^{-3}$
C is the clay content (%, by weight)

Situations identified as having “significant subsoil protection” are those where all loads are applied at the soil surface in the presence of a stronger pan layer at depth and where there is a strong, firm topsoil layer. The more vulnerable situations, “minimal subsoil protection”, are those where tractors operate in the furrow bottom during ploughing operations and where surface loads are being applied under loose, weak topsoil conditions. In the absence of a stronger pan layer and where the topsoil is very loose, wet and tends to flow on loading, the vulnerability rating may have to be increased further. The risks of topsoil structure damage can also be considerable in this wet topsoil situation.

Table 2. Susceptibility to compaction according to texture and packing density

		Packing density t m^{-3}		
	FAO texture	**Low**	**Medium**	**High**
Texture code	**class** (FAO-ISRIC, 1990)	< 1.40	1.40 – 1.75	> 1.75
		Susceptibility class		
1	Coarse	VH	H	M[1]
2	Medium	H	M	M
3	Medium fine	M(H)	M	L[3]
4	Fine	M[2]	L[4]	L[3]
5	Very fine	M[2]	L[4]	L[3]
9	Organic	VH	H	

Susceptibility classes: L low; M moderate, H high, VH very high

[1] *except for naturally compacted or cemented coarse (sandy) materials that have very low (L) susceptibility.*

[2] *these packing densities are usually found only in recent alluvial soils with bulk densities of 0.8 to 1.0 t m^{-3} or in topsoils with >5% organic carbon.*

[3] *these soils are already compact.*

[4] *Fluvisols in these categories have moderate susceptibility*

Table 3. Vulnerability to compaction according to soil susceptibility and soil wetness

Susceptibility	Wetness condition			
Class	Wet	Moist	Dry	Very Dry
VH	E[1] (E)[2]	E (E)	V (E)	V (V)
H	V (E)	V (E)	M (V)	M (M)
M	V (E)	M (V)	N (M)	N (N)
L	M (V)	N (M)	N (N)	N (N)

Classes of vulnerability to compaction: N: not particularly vulnerable; M: moderately vulnerable; V: very vulnerable, E: extremely vulnerable

[1] *Classes outside brackets refer to situations with significant subsoil protection.*

[2] *Classes within brackets refer to situations with minimal subsoil protection.*

Based on the classes of vulnerability in Table 3 Jones et al., (2001) constructed a "Susceptibility to Subsoil Compaction" map of Europe. Chamen et al. (2001b) recommend tyre inflation pressures according to the compaction vulnerability class of the considered soil: the recommended maximum inflation pressure for vulnerability class E is 40 kPa; for V is 80 kPa; for M is 120 kPa and for N is 160 kPa respectively.

As these susceptibility and vulnerability classifications and recommended maximum inflation pressures are still under development, it is intended for guidance only and should not be regarded as absolute. Modifications to susceptibility and to vulnerability classes and recommended maximum inflation pressures can always be made to take account of local and management factors.

Conclusions

Subsoil compaction is a wide-spread form of soil degradation causing a lot of economical and environmental damage. However, quantification of the effect of subsoil compaction on yield and environment is still questionable. Improving modeling of the impact of subsoil compaction on yield and environment requires inclusion in the model of the effect of subsoil compaction on rooting depth, oxygen demand and diffusion, on water use efficiency and nutrient use efficiency. The best strategy to prevent subsoil compaction is taking care that the stresses exerted by a wheel load are lower than the bearing capacity of the subsoil. However in only a few countries enough data on soil strength is available to compute the bearing capacities of the soils in these countries. Up to now it is not possible to formulate sound guidelines for maximum allowable wheel load/tyre inflation combinations. Natural recuperation is limited and subsoil compaction proves to be very persistent. The recuperation process is still not well understood and needs further research. The constructed database proves to be a first and essential step in understanding and quantification of the subsoil compaction problem.

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Soil mechanical properties and processes in structured unsaturated soils under various landuse and management systems

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Abstract

The effect of structure formation on changes in mechanical parameters and in strengthening soils as three phase systems can be detected and quantified by precompression stress, the shear parameters: angle of internal friction and soil cohesion and the effect of stress and soil management on flux properties like air permeability or hydraulic conductivity.
Changes in soil strength as a function of landuse, soil management and time are the more pronounced, the smaller the intensity of soil disturbance and the more negative the pore water pressure and the higher the number of wetting and drying cycles.
Possible reasons for changes in site properties can be defined as soil deformation by divergent (i.e. compactive) processes and by shearing which however can either result in a complete homogenisation at constant soil volume and in a loss of total soil strength due to the combination of drainage off excess soil water and the continuous increase in accessible particle surfaces for further swelling. On the other hand it can result in a continuous decrease in pore volume and functioning. The extent to which these processes affect site properties under varioius landuse and management systems will be described in detail in the text.

Key words: aggregate formation, precompression stress, stress/strain, air permeability, conventional and conservation tillage.

Introduction

Soils undergo intensive changes in their physical, chemical, and biological properties during natural soil development and as a result of anthropogenic processes such as plowing, sealing, erosion by wind and water, amelioration, excavation and reclamation of devastated land. In agriculture and in forestry, soil deformation by compaction and shearing as well as erosion by water are classified as the most harmful processes which not only end in a reduction of the productivity of the site but are also responsible for groundwater pollution, gas emissions and higher energy requirements to obtain a comparable yield. In forestry, especially tree harvesting and clear cutting by heavy machinery has reached a level which from the stress point of view is identical to that one in agriculture and induces not only an intense soil deformation by shearing and kneading which finally results in an increased soil erosion by water, but it also results in an organic matter loss, groundwater pollution, and gas emission which have the potential to cause global changes. These interrelationships have been recently described by Soane and van Ouverkerk (1994) and Horn et al. (2000). Additionally, it must create more serious discussions if the actual and sometimes even increasing mass of agriculture and forestry harvesting machineries are compared with the maximum acceptable mass of trucks on a highway or an autobahn in the USA or in Germany. Why are soils as 3phase systems much stronger than the such „streets“ which are intensely prepared and strongly constructed in order to carry those loads? There is an urgent need to look more in failure zone is equal to the energy required to create a new unit of surface area or to innitiate a crack (Skidmore and Powers, 1982) and is called the apparent surface energy (Hadas, 1987). Consequently, soil stability is related to strength distribution in the failure zones. In principle, soil structure will be stable if the applied stress is smaller than the strength of the failure zone, i.e. if the bond strength at the points of contact exceeds the external stress.

In homogenized soil substrates, soil strength expressed as precompression stress is the smaller,

- the higher the clay content at given bulk density values,
- the smaller the bulk density values at given texture,
- the smaller the amount of organic material at comparable grain size distribution,
- the wetter the soil is.

Pedogenic effects on mechanical strength defined as precompression stress were often quantified and show e.g. a clear interrelation to clay migration in Hapludalfs with a reduced strength in the clay deriched Al horizon and an increase in the precompression stress in the clay enriched Bt horizon due to aggregation. Calcium precipitation in the corresponding horizon of Mollisols also leads to a strength increase. Thus, at given internal parameters, aggregation always results in higher strength. Anthropogenic effects like the yearly ploughing and the tractor traffic create strong plowpans and plow layers with precompression stress values like the contact pressure of the tractor tyre or even higher due to lug effects (up to 300%). In addition, strength decreases in the A horizon due to plowing and seedbed preparation can be followed until texture dependent values are reached.

The strength values differ for various soil types, and they consequently depend on texture, structure, pore water pressure, organic matter and bulk density. Based on more than 130 soil profiles the effect of structure on strength can be derived for clayey, silty/loamy (not shown) and sandy material both for the topsoil and the subsoil and various aggregate classes. In addition a clear difference between the topsoil and the subsoil strength can be defined. In principle the arable topsoil is always weaker than the subsoil. Irrespective of the soil depth, the strength increase due to drying is very clearly to be seen which can be also explained by the X factor of the effective stress equation. Apart from the general agreement for sandy material is the strength increase due to drying less pronounced and may be even reduced with drying (not shown) due to smaller X values.(Fig 1)

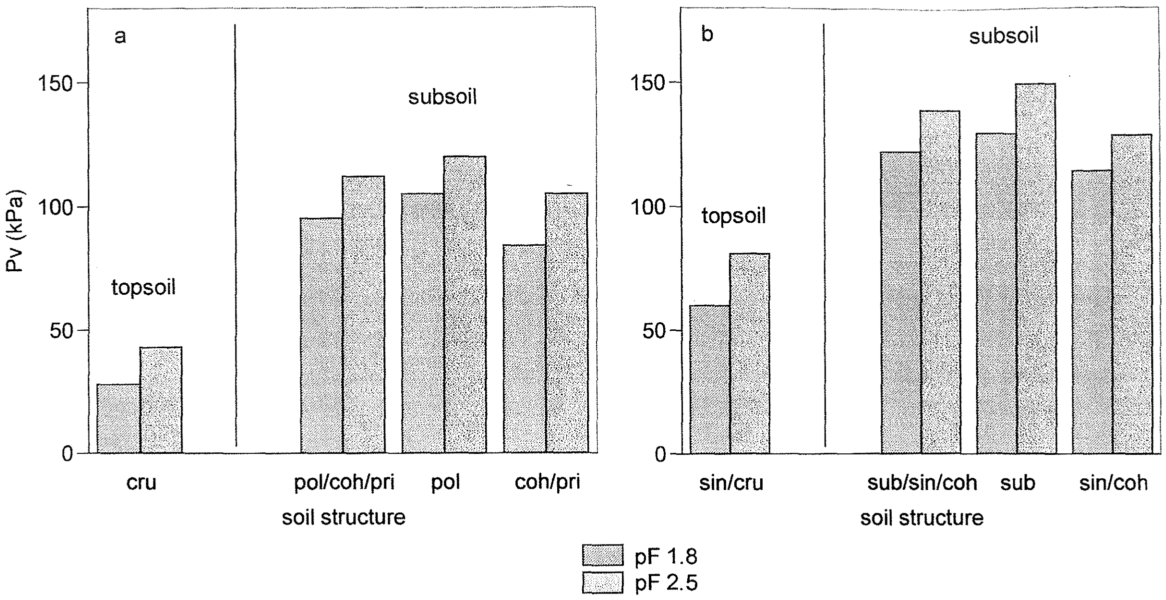

Fig. 1 Changes in precompression stress values due to soil aggregation and pore water pressure for clayey (a) and sandy (b) soils in Germany differentiated for top- and subsoils

The effect of tillage systems on soil strength expressed as precompression stress can be derived from numerous data sets (Fig. 2)

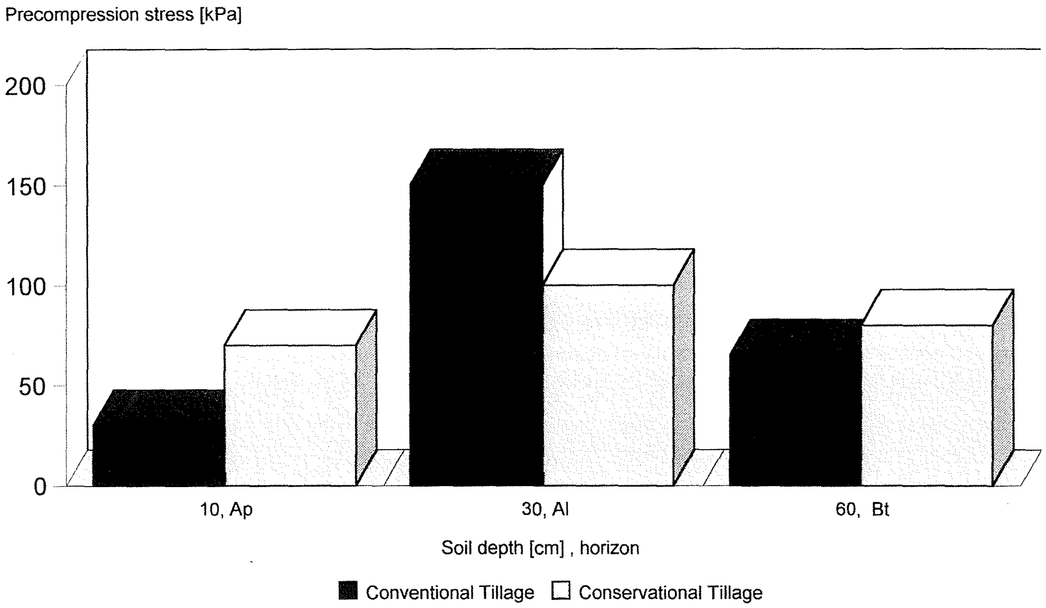

Fig. 2 Precompression stress [kPa] in different soil depths of a Hapludalf derived from loess under conventional and conservational tillage systems at a pore water pressure of -6 kPa.

It can be seen that the conservational tilled soil has a more equally distributed strength pattern than the conventionally tilled site. Especially the higher strength values in the topsopil due to a more pronounced structure formation, the only slight increase in the former plowpan layer (as a relict of the former conventional tillage with smaller units) and the slightly higher values in the deeper Bt horizon due to deeper rooting and more pronounced water uptake at deeper depth characterize the main processes for different tillage systems.

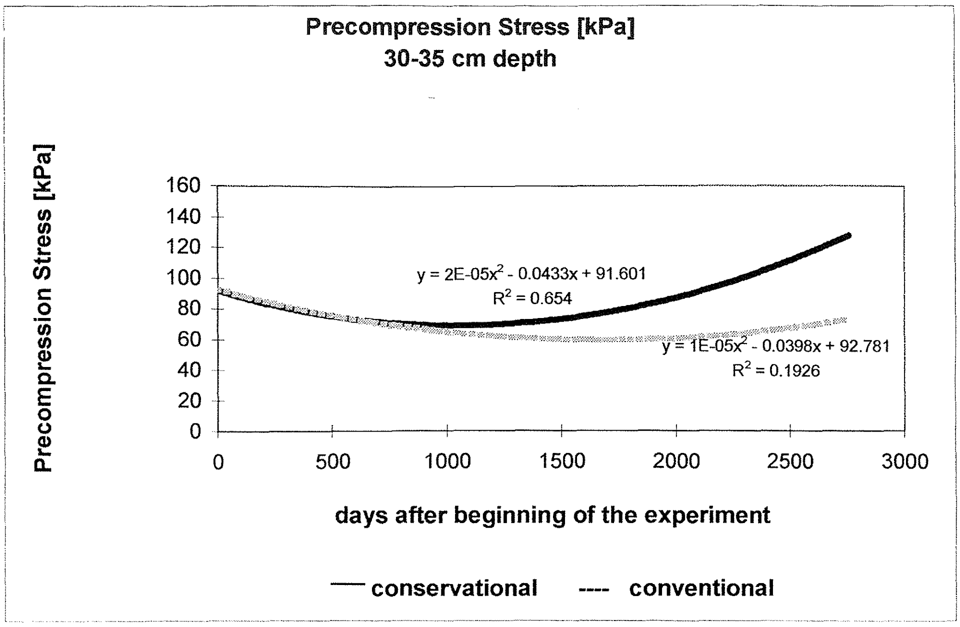

Fig. 3 Changes in the precompression stress [kPa] at constant pore water pressure (-30kPa) in a Hapludalf derived from glacial till as a function of time (days d) after starting the experiment in 1991.

However strength changes from conventional to e.g. reduced tiullage (like with the Horsch system) requires time. During longterm experiments carried out in Kiel from more than 9 years at a Hapludalf derived from glacial till it was found out that such changes in mechanical and ecological properties can be only verified after mre than 6 years of continuous application of these tillage treatments. While there were no changes in the bulk density to be seen (apart from the fact that the reduced tilled site = „conservation" had always higher values in all soil horizons as compared to the conventionally treated one) the precompression stress became much stronger in the reduced as compared to the conventionally tilled one. (Fig.3)
This strength regain can be explained by the effect of particle rearrangement in combination with the drying intensity effects as these sites showed more negative pore water pressure values down to deeper depth than the conventionally tilled site as a consequence of a more prevented root penetration through the plowpan layer.

Effect of landuse systems on shear parameters
The development of structure always results in an increase in soil strength. Secondary large pores can only be created if the aggregates become denser and stronger so as to carry the same stresses over fewer contact points. These strength differences can be defined from changes in the angle of internal friction, cohesion, and stress dependent changes in shear strength for various applied stress ranges for single aggregates, undisturbed, and homogenized material (see Horn and Baumgartl 2000).
Increased aggregation increases soil strength under comparable hydraulic conditions. Relative to the very high value angle of internal friction for a single aggregate, that for bulk soil is smaller and decreases when a certain stress range is exceeded. As applied stresses increase, the angle of internal friction resembles that of homogenized material which emphasizes that each type of structure is only valid for a well defined stress (mechanical or hydraulic) range.

When this value is exceeded, only texture dependent properties remain. The originally defined Mohr Coulomb envelope line can be easily explained by the various internal strength/stress dependent properties as it was repeatedly described e.g. by Baumgartl (1991), Horn et al. (1995). Even if the shear test is carried out under so called drained and consolidated conditions, intense changes can be determined due to time effects and corresponding effects of a delayed drainage off of excess soil water because of the detruction of existing pors systems and the rearrangement of poarticles during the shear test.

With increasing shear speed at a given texture, both parameters of the Mohr Coulomb failure line decline as a consequence of the smearing effect of excess soil water under positive pore water pressure.

At comparable shear speed, the values for the angle of internal friction are in principle higher under CD conditions while the cohesion values are higher under U D, while under dry conditions reduced shear speed results in higher ❸ values and a slightly reduced cohesion. With increasing water content, the differences in the ❸ values get smaller and even disappear because of the increasing positive pore water pressure during the test in combination with the delayed drainage off the soil water as a result of the smaller hydraulic conductivity. Thus, the strength effects, which can be determined have to be linked to the boundary conditions. Additionally, the effect of particle rearrangement or the effect of strengthening the skin of soil samples can be analysed by a special shear device, which is very sensitive to the composition of the top 2 mm of the soil sample. (Zhang et al. 2001) The authors defined significant effects of strength increase at the soil surface resulting in very high values for the angle of internal friction and of the cohesion which vanished at higher stresses applied.

Tab. 1 Angle of internal friction and cohesion values for homogenized clayey samples at constant bulk density of 1.65 g/cm³ as a function of water content and type of shear test (C -consolidated for 20 min – D – drained -; or U - unconsolidated - D)

Water content (✂$_{w}$ (%)	Shear speed (mm/min)	Consolidation type	Angle of internal friction (®)	Cohesion c (kPa)
0	0.2	C D	39,1	43,2
0	0.2	U D	35,2	64,2
0	0.02	U D	39,4	59,8
15	0,2	CD	38,6	11.9
15	0.2	U D	37,6	13,3
15	0.02	U D	32,8	18,2
25	0,2	CD	25,1	8,7
25	0.2	U D	23,1	0
25	0.02	U D	23	6,8

Such tillage dependent changes shear stength as can be verified in longterm experiments. With increasing time the cohesion values are increased in the reduced tillage plot while thase in the cvonventionally plowed site are eiuther reither reduced with time (as a consequence of deeper tillage) or remain constant. (Fig. 4)

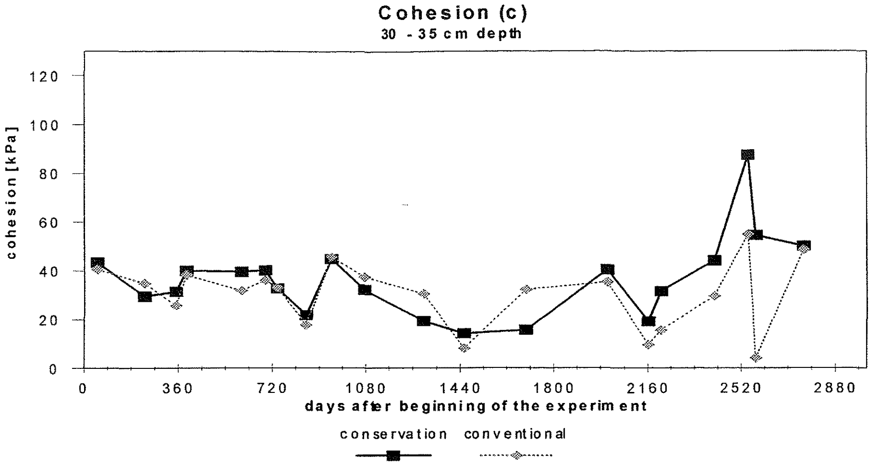

Fig.4 Changes in the cohesion values at constant pore water pressure (-30 kPa) at a depth of 30 – 35 cm in a Hapludalf derived from glacial till under conventional and conservation tillage (type Horsch)

Stress Distribution in Soils

Any load, applied at the soil surface is transmitted to the soil in three dimensions by the solid, liquid and gas phases. If air permeability is high enough to allow immediate deformation of the air filled pores, soil settlement is mainly affected by fluid flow.

Under in situ conditions, stress attenuation is greater in soils with comparable physical and chemical properties if they are more aggregated. If however internal strength values are smaller than the external forces applied, repeated traffic results in increased soil strength. For example, if the wheeling experiment will be carried out under wetter soil conditions e.g. at pF 2.5 in a loessial Hapludalf (which was repeatedly traversed at constant water content), horizontal minor stresses decrease while the major vertical stress increases. These soil strength changes increase the concentration factor values (as a consequences of deeper stress transmission), and each loading consequently results in a smaller effective stress relative to neutral stress (i.e.less negative pore water pressure). In contrast to this, dry and /or very strong soils (because of plowpans or other kind of hardpans) are less sensitive to soil deformation and/or only after several wheeling events they show a more intense stress propagation to depth. It can be seen that repeated wheeling result in an increase of the octahedral shear stress and the major principle stress ($\sigma 1$) while the mean normal stress remains the same. (Fig.5)

If the complete stress field is determined during a wheeling event, it can be shown that apart from the major vertical and horizontal stresses also mean normal and octahedral shear stresses show complete different pattern as detected in conservation and conventional tillage plots. Although the physical and chemical properties are the same, the stresses determined at single depth are much greater at the conventional site as compared to the conservationally tilled one (Fig. 6).

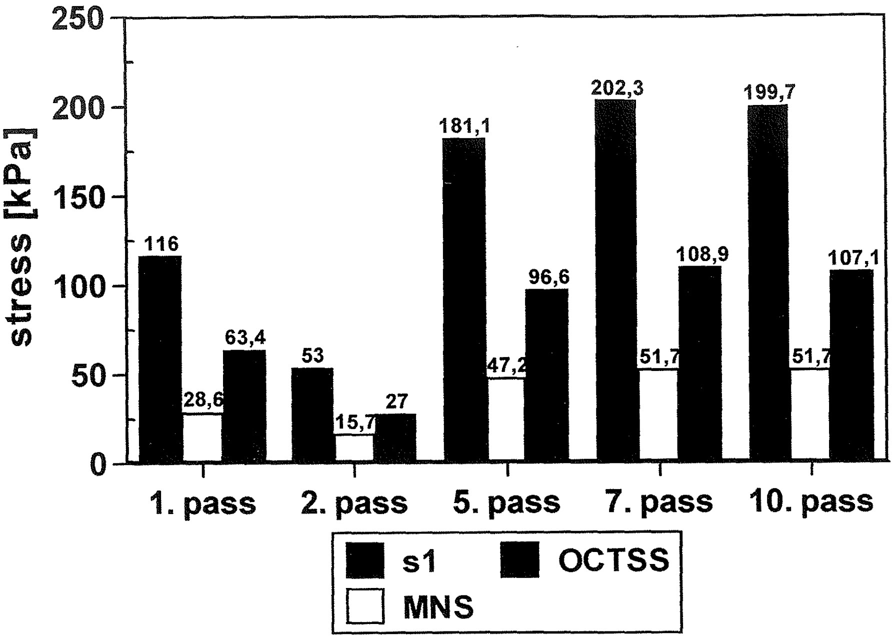

Fig.5 Effect of repeated wheeling on stress distribution at a depth of 15 cm.
(Hiwassee clay, water suction: approx: pF 3, tractor front wheel load: 3.8 Mg, 16.9R30; rear wheel load: 5.5 Mg, 18.4 R46)

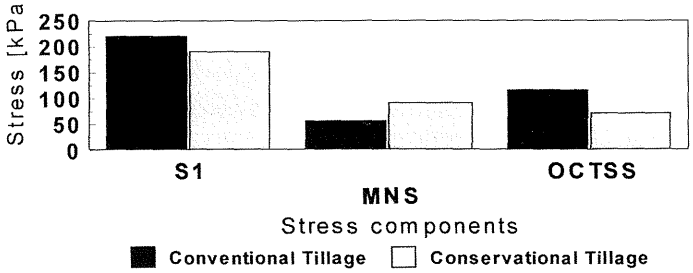

Fig. 6 Effect of wheeling with a load of 5 Mg on changes in the stress components at 10 cm depth in conventional and conservational tilled soils at a matric potential of -6 kPa. S1 = vertical major stress, MNS = mean normal stress, OCTSS = octahedral shear stress. (from Wiermann, 1998)

Effect of Stress Application and Attenuation on Soil Strain

If external stress is smaller than internal soil strength, no further deformation results and *vice versa*. The extent to which soil strain occurs during traffic and the extent to which various tillage implements (conventional/conservation) deform a soil at a given pore water pressure, is shown in Fig.6. In the conventional tillage treatment in a loessial Hapludalf, passage of a tractor (front/rear wheel) results in a pronounced vertical (up to 8 cm) and horizontal forward and backward (up to 2 cm) displacement. Under conservation tillage, these soil deformations are smaller because of a higher internal soil strength leading to a maximum vertical displacement of < 4 cm after 2 traffic events and a much less pronounced horizontal displacement.(Fig. 7)

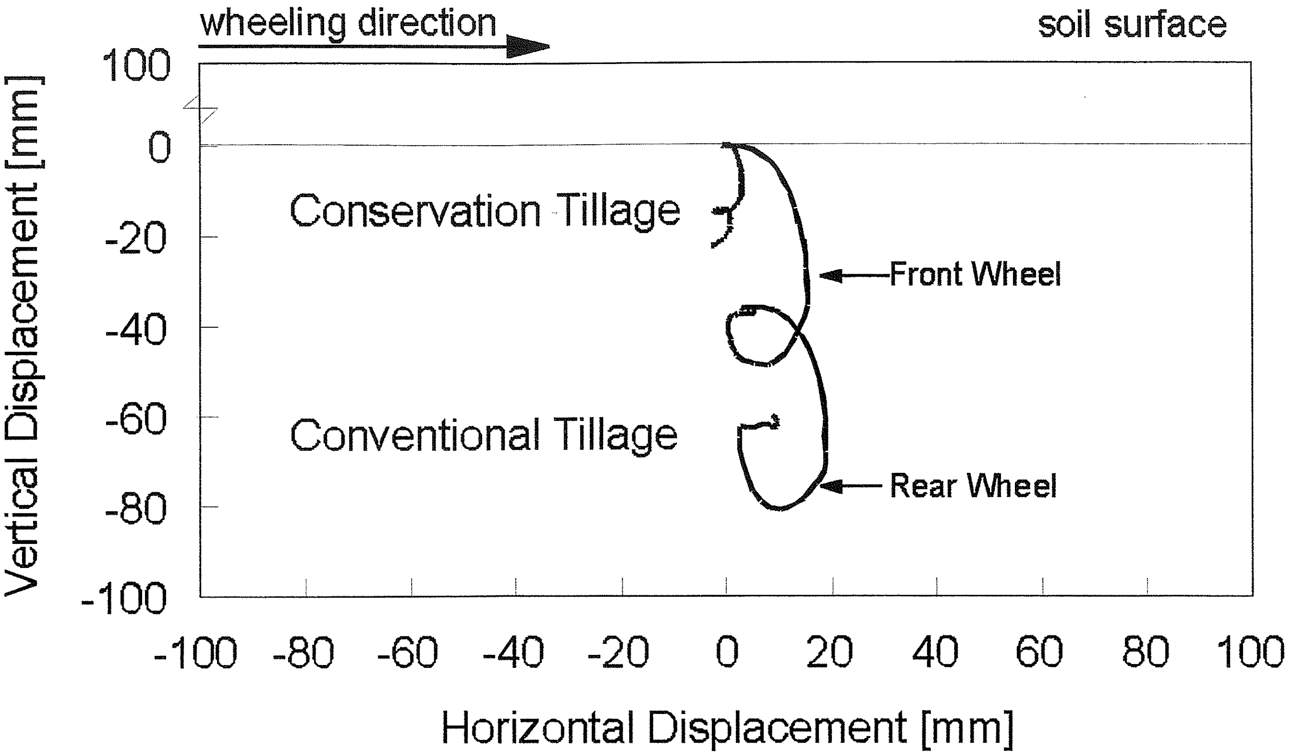

Fig. 7 Vertical and horizontal soil displacement, induced by a wheel load of 5 Mg in a Hapludalf derived from loess at a pore water pressure of –6kPa for conventional and conservational tilled plots. (from Wiermann 1998)

With increasing aggregate development, soil strength increases and aggregate deterioration is less pronounced during displacement and alteration of the pore system due to the infilling of interaggregate pores by smaller particles. Nevertheless, all stresses which are not attenuated to levels below soil strength result in volume alterations, even if the applied stresses vary for different soil types, land uses and management systems, and environmental conditions.

In addition Wiermann (1998) showed that the strength regain under conservation tillage systems was more intense than under conventional tillage down to 55 cm depth which can be explained by the repeated disturbance over the years during wheeling of a weaker soil structure. Thus, not only the divergent processes but especially the shear processes during wheeling with even only a small tractor on top of the site resulted in a continuous disturbance of the structure elements.

Slip effect on soil displacement

Stress strain effects are further altered by the intensity of slip as many management systems increase either the effectivity of pulling by the application of rubber belt driven systems and/or by higher slip during management operations.

Generally, pure shearing always results in a volume constant displacement of particles (Fig. 8)

If in addition, divergent processes also occur during land management a further and normally more detrimental deterioration of

- the pore system because of particle parallelisation and reduction in pore space,
- the mechanical properties because of soil weakening even at higher bulk density,

- pore functioning due to increased tortuosity, and
- possibly a delayed or reduced plant growth which may result in yield decline.

If the slip effect is increased e.g. by the application of rubber belt driven machine units the shear effect gets more important which on the one hand will not primarily result in soil compaction but it will lead to a complete disturbance of the pore system and functioning The particle displacement at a given depth of 15 cm and at 15 and 30 % slip resulted in a tangential particle backwards up to 3 or 6 cm in the horizontal direction and 1 or 3 cm downwards. (Horn and Rostek 2000)

Fig. 8 Soil displacement as a result of slip

A corresponding effect can be also detected, if the energy is transmitted by a wider tire even at lower tire inflation pressure as compared to smaller tire in a Hapludept derived from sand loess. (Tab.2) At constant slip the air permeability declined at a depth of 20 cm under a wide tire with decreasing inflation pressure, while at a smaller slip rate under a standard tire the air permeability even remained constant.

The shear parameter: cohesion was increased under the wide tire and high inflation pressure, while it was further reduced if the inflation pressure was smaller at constant slip of 25%.

With reduced slip and under a standard tire (20.8 R38) the cohesion was increased for both inflation pressure values but there were slight differences inbetween both treatments.

Tab. 2: Effect of slip on changes in physical properties in a Hapludept derived from sand loess /Braunschweig at a depth of 20 cm. The wide tire was 650/65 R38 with a slip of 25 %, while the standard tire was 20.8 R38 and was driven by 15 %slip

Parameter	Before	Wide tire	650/65 R38	Standard tire	20.8 R38
Inflation pressure (kPa)		260	194	280	224
Air permeability 10^{-8} cm^{-2}	6	6.1	2.7	1.7	2.2
Cohesion (kPa)	26	37	23	41	36
Angle internal friction ❸ (®)	37	38.2	35.1	38	37.1

Effect of landuse and management on changes in air permeability

As a consequence of strength regain under reduced energy input also the pore continuity gets improved after at least 6 years of continuous alteration in tillage systems. It could be shown that the air permeability is increased at a depth of 30 – 35 cm while (not shown) the same effects also start in deeper depths after a longer period of different treatments.

Conclusions

(1) The determination of soil strength requires the measurement of volumetric stress and strain

(2) Structure development in arable and forest soils always results in increased soil strength. With increased aggregation, strength increases and the increase in strength with decreasing pore water pressure depends on the pattern of the water retention curve for single aggregates and bulk soil

(3) The effect of landuse on precompression stress and changes of air permeability with time under various management systems underline the fact, that particle rearrangement and structure alteration depend on pore water pressure effect and number of wetting and drying cycles. Additionally the more intense rooting, the higher the drying intensity and the more pronounced is the change in precompression stress even down to deeper depth

(4) Slip effects are the more pronounced the smaller soil strength and the more soils get homogenized. A reduction of tire inflation pressure seems no measure for soil protection both for wider and for standard tires at given inflation pressure

(5) The possibility of soil structure protection requires the preservation of natural soil structure properties as the shear strength parameters (angle of internal friction and cohesion) are always higher for single aggregates than bulk soil for a given applied stress. As soon as the applied stress exceeds internal soil strength, the aggregate or bulk

aggregated soil will become homogenized. Thus, the pattern of the Mohr Coulomb failure line resembles that of the homogenized material after exceeding this stress value.

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Soil Structure: the key to soil function

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Abstract

Soil structure is defined and is related to soil function. Aspects of soil structure of importance for water infiltration and storage, for plant growth and for microbial activity are discussed. Structural features which make soil managable are considered in terms of the friability and the soil water contents at which tillage may satisfactorily be done. It is shown that the structure of sandy soils can be considered in terms of spatial heterogeneity. Organic matter is shown to play key roles in the formation of soil structure and its stabilization. There may exist critical contents of soil organic matter for different soils which must be maintained if the soils are to be fully functional. Soil structure is shown to be of fundamental importance for all aspects of soil function.

Soil structure

Definition

Soil structure was defined by Dexter (1988) as "the spatial heterogeneity of the different components or properties of soil". This definition is meant to be comprehensive and includes within it earlier definitions about arrangements of particles and pores and also larger-scale features such as cracks, biopores and even heterogeneity on larger scales.

Optimum structure is that which enables the soil to have the widest range of possible uses. That is, when the soil "functionality" is maximum. Soil structure is mostly usefully discussed in terms of soil function.

However, for functionality to persist, the soil structure must be stable. The soil must be able to withstand imposed stresses, such as raindrop impact, without undergoing significant structural change.

The hierarchical nature of soil structure

Soil which is in good structural condition is strongly heterogeneous on a wide range of size scales. This can arise naturally because of the hierarchical nature of soil structure which is illustrated symbolically in Fig.1. This shows how a soil aggregate may be composed of micro-aggregates which are themselves composed of clay domains. Similarly, it would be possible to show how a clod is composed of aggregates. These "particles within particles" are often only "incipient" - that is, they are not completely surrounded by surfaces of zero strength, but may be partially joined to adjacent particles. In this case, only relatively small inputs of energy are required to destroy the larger particles and to release the smaller particles. The particles thus released are then no longer "incipient", but are "free".

Different processes and mechanisms operate on the different size scales as described by Dexter (1988). Clay particles are held together by electro-chemical forces. Micro-aggregates may be bound by polysaccharides which are exuded as mucilages by soil organisms. The water stability of micro-aggregates is also enhanced by polyvalent cations (e.g. Ca^{++}) which can form bridges between the organic colloids and particle surfaces (Edwards and Bremner, 1967). Larger aggregates derive much of their water stability from being enmeshed in living or partially-decomposed plant roots and fungal hyphae (Oades, 1989).

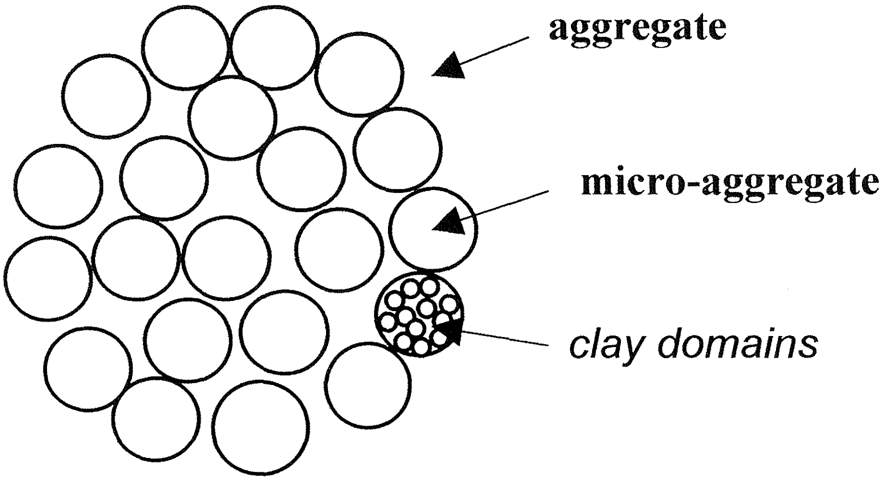

Fig.1. Symbolic representation of a soil aggregate showing the hierarchical internal structure comprising incipient microaggregates which are themselves composed of clay domains.

Micro-aggregates are also strengthened by mechanical compression as the soil dries from saturation. The compressive forces are generated by the "effective stresses" produced by a combination of matric water potential and the surface tension in water menisci. Examples of effective stress theory and effects are to be found in Mullins and Panayiotopoulos (1984) and Nearing (1995).

Macropores

In addition to the hierarchical or matrix aspects of soil structure there usually exists a macropore structure which is superimposed onto this. Macropores may be desiccation (shrinkage) cracks or may be biopores which are formed by soil flora or fauna. Desiccation cracks are produced at spacings which depend on both the soil mechanical properties and the shape of the drying front which is itself governed by the soil hydraulic properties in conjunction with the prevailing meteorological conditions. Typical biopores are root channels formed by roots of plants which have subsequently decayed, or earthworm tunnels. The sizes and forms of these depend upon the species which produced them.

Macropores provide key pathways for exchange of water and gases across the soil surface. They can also provide paths of low resistance for root growth.

Macropores may also reduce the buffering or filtering aspects of soil function by providing paths for rapid transport of not only water but also of nutrients, pesticides and pathogens from the soil surface towards field drains.

Organic matter effects

Organic matter has huge effects on soil structure. This is well-illustrated by the effects of clay content (C %), and organic matter content, (OM %), on soil bulk density, D. Dr. J. H. M. Wösten of Wageningen (personal communication) has analysed 91 Dutch clay soils (clay content > 8 %) and has produced the regression:

$$1/D = 0.581 + 0.00325\ C + 0.0303\ OM,\ \ m^3\ Mg^{-1},\ \ r^2 = 0.78. \qquad (1)$$

This shows not only that, on average, D is smaller when the contents of clay and organic matter are greater, but also that the effect of organic matter is about 9 times greater than that of clay.

Organic matter also has large effects on the stability of structure and on other soil physical properties. For example, an increase of organic matter content from 1.1 % to 1.4 % in a soil with 3 % clay content from Grabów in Poland is associated with an 33 % reduction in the content of readily-dispersible clay (Dexter and Czyz, 2000), and a 4-fold increase in saturated hydraulic conductivity (Dexter, et al., 2000). For Polish soils, the average organic matter content is 1.9 % and the average clay content is 7.4%. There is a trend of increasing organic matter content (OM %) with increasing clay content (C %):

$$\begin{array}{l} OM = \underset{(\pm 0.07)}{1.58} + \underset{(\pm 0.007)}{0.048}\ C,\ \ p < 0.001 \end{array} \qquad (2)$$

This positive correlation is an indication of the affinity of organic matter for clay and perhaps even of the role of clay in physically protecting organic matter.

Soil function

Soil has numerous functions which include:

Transmission and storage of water

The key role of the soil surface cannot be over emphasized. All infiltration and evaporation of water occurs through the soil surface. If the surface has good, stable structure then infiltration will be fast (and run-off will not occur), and evaporation will be slow. This combination is most efficient for storage of water. If the structure of the surface is degraded, however, infiltration will be slower and evaporation will be faster. Both of these changes reduce water storage.

When the soil has macropores, such as cracks, water can flow rapidly through these to depth and therefore by-pass the majority of the soil matrix.

Because this flow is relatively rapid, the water is not in any place long enough to reach equilibrium with the surrounding soil. Therefore exchange processes such as buffering or leaching will occur only to a smaller extent. This shows that attempts to use conventional adsorption isotherms or other physico-chemical properties which have been obtained using homogenized (e.g. ground) soil samples which are in equilibrium with water are inappropriate as has been shown by Hartmann, et al. (1998).

A wide distribution of pore sizes gives the best soil physical properties. Such a soil will have a high infiltration rate, will store a lot of water, will release water at a steady rate with decreasing (i.e. more negative) water potentials. Additionally, it will be aerobic at field capacity; and it will usually be friable and easy to manage.

Support plant growth

Plant roots usually occupy less than 2 percent of the soil volume and often much less than this, yet they are essential for plant growth and crop yield. Some plant nutrients (e.g. P and K) are essentially immobile and remain within the top-soil. However, deep penetration of roots is desirable for plants to extract mobile nutrients such as water and nitrate. Uptake of water from deep in the soil profile is an essential drought-avoidance strategy.

For roots to penetrate, either the soil must be sufficiently weak to enable the roots to push it aside as they elongate or there must be pre-existing macropores within which they can elongate with little or no impediment. Weak soil is usually soil which has a low-medium density, and therefore which has not been heavily compacted.

Roots also require a supply of oxygen, and therefore there must exist a continous network of air-filled pores at field capacity. However, not all of the soil needs to be aerobic - only the parts where the roots are.

Plant roots play a key role in drying soil often to the wilting point (about -1.5 MPa matric water potential). This is essential both for formation and stabilization of soil structure. This has been shown in experiments where plants have been grown in initially-homogenous soils. When the soil was kept moist, then there was no structure generation by the roots. However, when the soil was allowed to dry considerably before each irrigation, the wetting and drying cycles in the soil adjacent to the roots resulted in the generation and stabilization of aggregates (Horn and Dexter, 1989; Materechera, et al., 1992).

Therefore, there is a kind of positive feed-back mechanism operating in which roots require soil structure for aeration, etc., in order to wet and dry the soil to generate soil structure. On the other hand, if the soil is homogeneous and anaerobic, then rooting will not occur and there will be none of the structure generation associated with root activity. In this case, the soil will remain structureless. However, it may be possible to ameliorate such a soil by growing specialized plants, such as reeds, which can "pump-out" the excess water and hence provide soil conditions in which more normal crop species can be grown

Support microbial activity

Microbial activity is often considered to be a key indicator of soil "health" or "quality". Microbial activity may be quantified by the rate at which carbon dioxide is respired. Although there are both aerobic and anaerobic microbes, the former are much more active and are responsible for most of the respiration and mineralization in normal agricultural soils. At any given water potential, Ψ, soil pores larger than $d = -4\sigma/\Psi$ (where σ is the surface tension of water) are air-filled and pores smaller than this are water-filled. At field capacity (the water content to which a soil will drain naturally after heavy rain or irrigation), the water potential is about -100 hPa, and the corresponding pore size is 30 μm. It is logical to expect that aerobic microbes will normally exist in pores which are normally air-filled, and therefore which are larger than 30 μm. This is shown by the fact that microbial activity is maximum at field capacity as shown in Fig. 2. When the soil is drier than this, the microbes are less active as a result of water stress. When the soil is wetter than this, they are less active because the pores in which they exist become water-filled, and their oxygen supply is therefore cut-off.

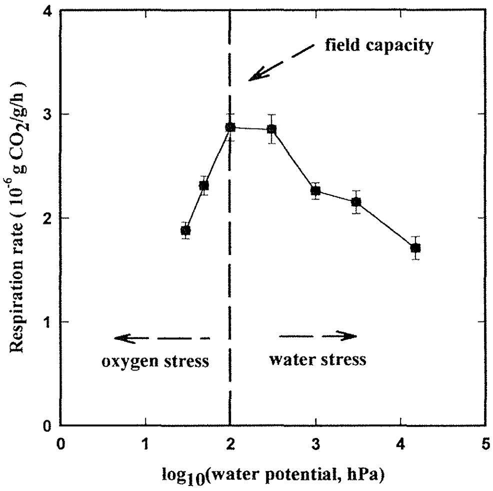

Fig. 2. Respiration rate of micro-organisms in soil from Highfield at Rothamsted in England as a function of soil water potential.

Managability

Although not exactly a function, it is necessary for soil to be managable. For example, when it is tilled, it must break-down readily to produce a seed bed for the next crop. That is, the soil must be friable. The friability can be quantified in the laboratory using simple tests (Dexter and Watts, 2000). Organic matter has a large effect on friability as can be seen for the example of a British soil in Fig. 3. Because friability depends on the existence of surfaces of weakness within the soil, it is a consequence of the micro-structure. Therefore, the micro-structure is directly controlling the macro-structures produced by tillage.

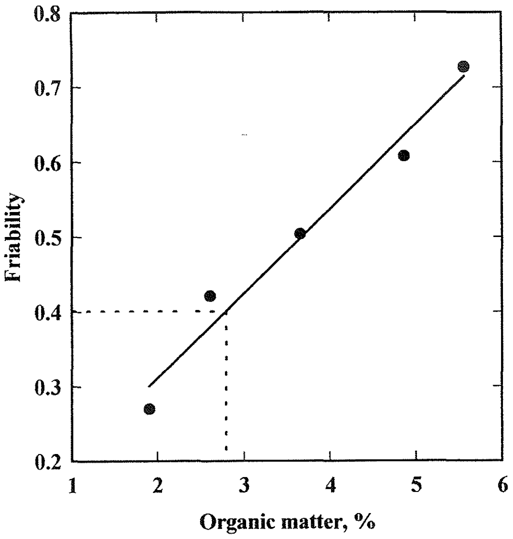

Fig. 3. Measurements of friability of soil samples with a range of organic matter contents collected from Highfield at Rothamsted in England.

On the basis of a range of experiments and observations, it seems that soil is difficult to manage when the friability, as measured by the method of the coefficient of variation (Dexter and Watts, 2000) is smaller than 0.4. This value and the corresponding value of organic matter content is shown for the Highfield soil (clay content = 25 %) in Fig. 3.

The workability of soil depends also on its water content. It has been shown that the optimum water content for tillage and the range of water contents for tillage can be predicted from the parameters of the soil water retention curve (Dexter and Bird, 2001). This also involves the concept of heterogeneity because workability of the soil depends on the existence of a network of air-filled pores which provide surfaces of weakness on which the soil may fracture preferentially.

Predictions from the Dexter and Bird (2001) model show that the range of water contents over which tillage can satisfactorily be done becomes smaller when soil becomes physically degraded. As an example, the effects of soil bulk density on the range of water contents for tillage is shown for a model soil with 15 % clay content and 3 % organic matter content in Fig. 4. Here, increases of density could be a result of compaction by vehicles or could be a consequence of losses of soil organic matter as predicted by Eqn.(1).

A consequence of this is that when soil is structurally degraded, the opportunities for tillage are reduced, and therefore there will be fewer days each year when the soil is at a suitable water content for tillage.

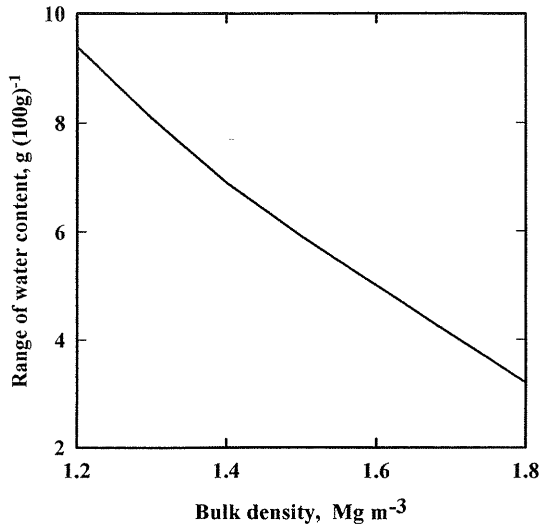

Fig. 4. Predictions of the effects of soil bulk density on the range of water contents for tillage. A range of 4 g (100g)$^{-1}$, for example, indicates the difference in gravimetric water content between the upper (wet) tillage limit and the lower (dry) tillage limit.

In spite of our knowledge of friability and the effects of soil water, it is still not possible to make accurate predictions of the soil structures which will be produced by tillage. However, it seems clear that the soil properties have greater effects on the results of tillage then the details of the tillage machinery used.

Structural stability

Although there has been a lot of research on soil structural stability, this subject has suffered greatly from the fact that experimental methodologies are not standardized. As a result of this, results obtained by different laboratories can seldom be compared. This situation arises because the subject is very complicated. For example, if soil samples are allowed to become drier than thay have ever been in the past, then the stability and other characteristics of the soil may be changed irreversibly (e.g. Katou, et al., 1985). Similarly, the way that soil samples are wetted can influence subsequent soil behaviour. Therefore, just as the history of wetting and drying that the soil has experienced in the field affects the behaviour, so the wetting and/or drying during pre-treatment in the laboratory will also affect the observed behaviour.

Attempts to standardize pre-treatments by adjusting the initial soil water content or potential, for example, must be done with extreme care otherwise the soil stucture and behaviour may be changed significantly and the soil which is being measured will not be the same as it was in the field. It is not only changes of soil water content which is important but also the rate of change (especially of wetting) can have profound effects.

Clay dispersion

Clay and other colloid particles provide the basic building blocks of soil structure. If the clay is not stable, then soil micro-aggregates and aggregates cannot exist. When the clay particles disperse in water, the soil structure is not be stable. Such a soil will be only mud when wet, and will dry into very strong blocks. The content or readily-dispersible clay in soil has been shown to be strongly and positively correlated with the strength of the soil when dry by Chan (1989) and Watts, et al. (1996b). This is because of the cementing effect of this readily-dispersible clay which can move to the points of contact between particles as the soil dries.

However, if the clay particles exist in stable arrangements and do not disperse in water, then any heterogeneity or structure will persist.

Whether clay particles disperse or do not disperse depends on the cations adsorbed on the surfaces of the clay particles. Calcium ions favour stability whereas sodium ions favour spontaneous dispersion. However, dispersion depends not only on the adsorbed cations, but also on the electrolyte concentration of the soil water. Dispersion may occur with pure water but not with water containing dissolved salts. There exists a critical electrolyte concentration, which is characteristic for each soil, which must be maintained or exceeded if the structure is to remain stable (Quirk, 1986).

Other factors also affect the dispersion of clay from soil. For example, increased content of organic matter in the soil reduces the content of readily-dispersible clay (e.g. Dexter and Czyz, 2000). Mechanical energy inputs also increase the content of readily-dispersible clay, and this effect is discussed separately below.

Slaking

The term slaking refers to the break-down of aggregates into micro-aggregates in the presence of free water. There may be at least two mechanisms of slaking. In the first, materials cementing micro-aggregates together may dissolve (or disperse) in the presence of water, thereby “ungluing” them. In the second, the rapid wetting of dry soil in contact with free water may cause micro-cracking of soil which reduces tensile strength, increases friability, and which may result in the production of micro-aggregate sized pieces (Grant and Dexter, 1989, Kay and Dexter, 1992). With both of these mechanisms, the result is the destruction or significant weakening of aggregates and the persistence of micro-aggregates. The loss of macro-pores when aggregates are destroyed can cause drastic reductions in hydraulic conductivity and other transport processes in soil.

Organic matter is often hydrophobic, especially when the soil is dry. This can reduce wetting rates and hence reduce soil disruption by slaking. This is one of the factors which contributes to the greater stability of soils with higher organic matter contents.

Slaking can occur independently of clay dispersion. In contrast, clay dispersion destroys structural features on all size scales larger than clay particles.

Effects of mechanical energy inputs

The mechanical energy inputs to soil during tillage have been quantified in many agricultural engineering studies. The specific energy (i.e. the energy input per unit mass or per unit volume of soil) depends on the details of the tillage implement and on the soil conditions. Specific energy inputs of the order of magnitude from 50 J kg^{-1} for tyne tillage, 100 J kg^{-1} for ploughing and up to 300 J kg^{-1} for rotary tillage have been reported (e.g. Patterson, et al., 1980).

Experiments in the laboratory and in the field (Watts, et al., 1996 a,b) have shown that these energy inputs can destabilize soil structure through increasing the content of readily-dispersible clay. The type of response observed is shown in Fig. 5. It can be seen that when soil is drier than the plastic limit, PL, then energy inputs have no effect on the content of readily-dispersible clay. However, when the soil is wetter than PL, then the content of readily-dispersible clay increases with both water content and the input of specific mechanical energy. This observation is consistent with the finding that the upper (wet) limit for tillage is usually assumed to be equal to PL (Dexter and Bird, 2001).

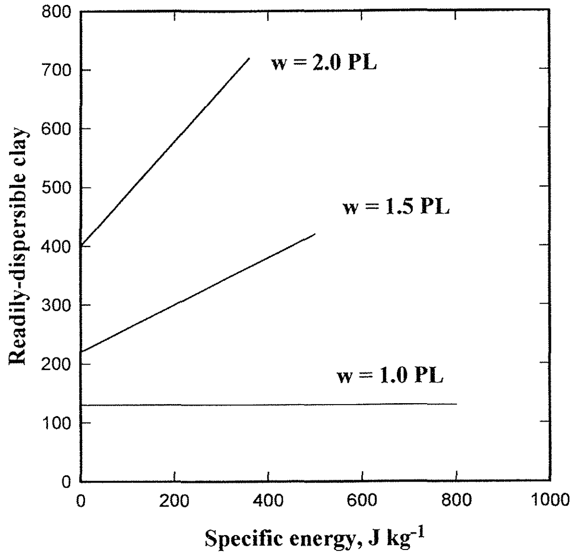

Fig. 5. Effect of specific mechanical energy input on the content of readily-dispersible clay in soil at three water contents, w, expressed in terms of the lower Plastic limit, PL.

The structure of sandy soils

Because a soil has a sandy texture and therefore may not be visibly aggregated, it does not mean that it does not have structure. This structure is manifest in various ways, for example in the spatial variability of saturated hydraulic conductivity, K_{sat}. As values of K_{sat} are log-normally distributed, the standard deviation of the logarithms (to base 10) of the values can be used as an index of the heterogeneity or structure of the soil. An example using data from soil at Grabów in Poland is shown in Fig. 6, where the slope of log-probablity plots is related to the standard deviation such that a vertical line indicates zero standard deviation or completely homogeneous (or stuctureless) soil.

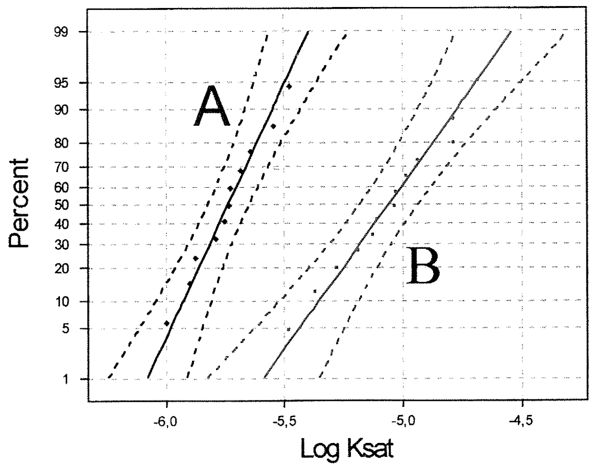

Fig. 6. Probability plots of values of the logarithms (base 10) of saturated hydraulic conductivity for soil A with 1.08 % organic matter content and for soil B with 1.32 % organic matter content.

It is easy to see that soil B, with the higher organic matter content, is more heterogeneous than soil A. Soil B therefore has more structure according to the definition given at the beginning. The relationship beteen soil heterogeneity and crop yield is explored in Fig. 7. Here, the high-yielding parts of fields are compared with low-yielding parts. At the Grabów site, the high and low yielding parts were different experimental plots. However, on the fields at Baborówko, the high and low-yielding parts had identical treatments and were identified on yield-maps obtained with a combine harvester equipped with GPS. Therefore, the variability was naturally-occurring and was not artificially-imposed. It can be seen in Fig. 7 that, in all three cases, the high-yielding part has greater heterogeneity than the low-yielding part as quantified by the standard deviation (s.d.) of the measured values of $\log_{10}K_{sat}$. Further research will be necessary to determine whether this observation is more generally valid.

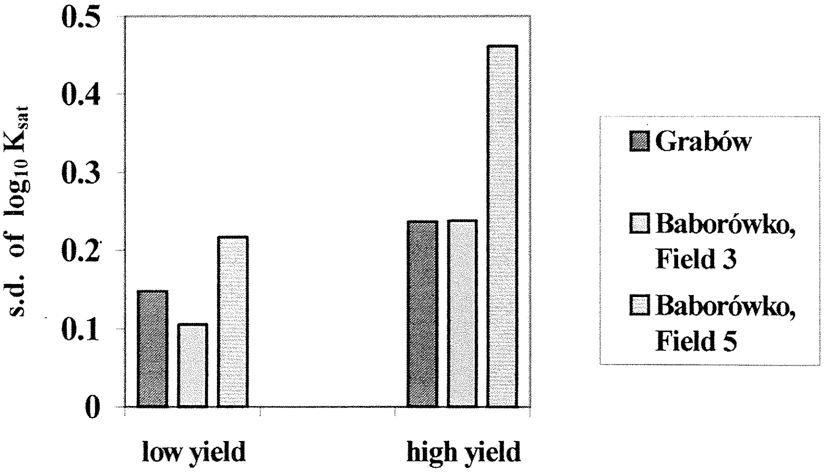

Fig. 7. Higher-yielding parts of fields are associated with greater soil heterogeneity as quanitified by the standard deviation (s.d.) of values of the logarithm (base 10) of the saturated hydraulic conductivity.

Heterogeneity of processes in sandy soils is also shown by the phenomenon of fingering flow. In this, water infiltration does not occur uniformly, but occurs faster (and hence deeper at a given time) at some places rather than others. The name "fingering" has been given because the shape of the wetting front looks like fingers extending into the soil. Fingering flow arises when the wetting front is unstable which can arise in several situations as described by Raats (1973). Fingers in water-repellent sandy soil have been found to recur in the same places. The greater water movement and leaching within the fingers relative to the soil between the fingers may produce and sustain considerable heterogeneity of soil properties (Ritsema and Dekker, 1998 a,b).

Soil structural quality

If the criteria which have been introduced above for distinguishing between "good" and "poor" soils are used, it is possible to obtain approximate estimates of the critical values of organic matter which must be exceeded if soil is to have an adequate structure and to be acceptably stable. To do this, I have considered only three soils with which I am familiar, and the results are presented in Fig. 8.

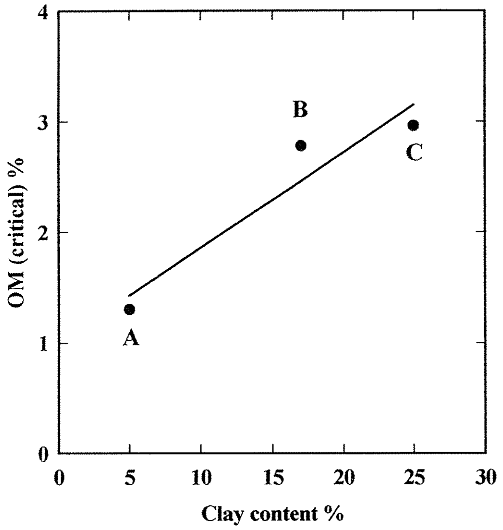

Fig. 8. Estimates of the critical contents of organic matter in soils of different clay content which are required for soil "functionality". Soil A is from Grabów, Poland, soil B is from Adelaide, Australia, and soil C is from Rothamsted in England.

With the use of the regression line in Fig. 8 in combination with a small data base of soil properties, it may be concluded that about 30 % of Polish arable top-soils have organic matter contents below the critical levels which are required for full "functionality".

It should be realized that the regression line in Fig. 8 and any conclusions resulting from its use are of a very provisional nature. Further good data are required to develop and improve this type of analysis.

Conclusions

Soil with the optimum soil structure will suffer from none of the constraints discussed above. It has good storage of water, has a continuous network of air-filled pores at field capacity. It has adequate stability and resiliance which is achieved largely through having an organic matter content which is above the critical level which is required for full "functionality".

There is no need for compromise. For agricultural purposes, most soils can have all the desirable structural characteristics and properties simultaneously, provided that they are managed appropriately.

Acknowledgements

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Soil Pore System as an Indicator of Soil Quality

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Abstract

The need to reduce the environmental impact of agricultural activities and to control soil structure degradation is one of the main aims of land management, especially in the vulnerable environments. Intensive cultivation of some agricultural soils can lead to deterioration in soil structure and other physical properties of the soil and, consequently, decreased crop yields. The strong modifications of soil structure mainly involve changes in soil porosity. Therefore the measurements of such a physical property can help to quantify the impact of management practices on soil. This is now possible because of the increasing use and availability of the technique of image analysis allowing the measurement of soil porosity on thin sections or impregnated soil blocks, prepared from undisturbed soil samples.

Soil porosity is, therefore, the best indicator of soil structure quality. To quantify the pore space in terms of shape, size, continuity, orientation and arrangement of pores in soil allows to define the complexity of soil structure and to understand its modifications induced by the management practices and, therefore, to identify those more compatible with environmental protection. The characterisation of the pore system provides realistic basis for understanding water retention and water movements. Significant correlations have been found between elongated continuous transmission pores and hydraulic conductivity that can be useful to develop and improve models for predicting water movements. Soil porosity shows a strong correlation with penetration resistance: the decrease of porosity is generally associated with an increase of penetration resistance. The pore shape and size distribution are also strictly related to chemical and biochemical properties, like enzyme activity, and root growth.

Key words: Soil Structure, pore size distribution, pore shape, pore continuity, image analysis.

Introduction

To evaluate the impact of management practices on the soil environment it is necessary to quantify the modifications to the soil structure. Soil structure is one of the most important properties affecting crop production because it determines the depth that roots can explore, the amount of water that can be stored in the soil and the movement of air, water and soil fauna. Soil quality is strictly related to soil structure and much of the environmental damages in intensive arable lands such as erosion, compaction and desertification originate from soil structure degradation. To quantify soil structural changes following agricultural activities, besides traditional measurements such as aggregate stability and hydraulic conductivity, pore space measurements are being increasingly used. In fact, it is the size, shape and continuity of pores that affect many of the important processes in soils (Ringroase-Voase and Bullock, 1984). Detailed insight into the complexity of the pore system in soils can be obtained by using mercury intrusion porosimetry to quantify pores with equivalent pore diameter < 50 μm (micropores) within the soil aggregates (Fiès, 1992). Image analysis on thin sections prepared from undisturbed soil samples allows pores > 50 μm (macropores) to be quantified, which determine the type of soil structure (Pagliai et al., 1983, 1984). Technological and theoretical advances, regarding both sample preparation and image analysis, have improved the methods for direct quantification of soil pores. These methods allow the quantification of the effects of tillage practices on soil porosity and structure and in turn the definition of optimum tillage needs for sustainable agriculture (Mermut et al., 1992; Moran and McBratney, 1992).

The quantification of the soil pore system

Soil structure may be defined either as "the shape, size and spatial arrangement of individual soil particles and clusters of particles (aggregates)" or as "the combination of different types of pores with solid particles (aggregates)". Soil structure has generally been defined in the former way and measured in terms of aggregate characteristics. These can be related to plant growth only empirically. In fact, it is the pore shape, the pore size distribution and the pore arrangement which affect many of the most important processes in soil that influence plant developments such as storage and movement of water and gases, solute movements and ease of root growth. For this reason measurements of pore space are increasingly being used to characterize soil structure. In fact, between the particles arranged singly or in aggregates, there is an intricate system of pore spaces on which plant roots, micro-organisms and soil fauna depend for the storage and movement of water and air.

Soil porosity represents the liquid and gaseous soil phases. To characterize the pore system it is necessary, first of all, to determine the size distribution and shape of pores because the agronomic functions of pores depend on their size and shape.

Using the technique of image analysis it is now possible to characterize soil structure by the quantification of soil porosity in all its aspects (pore shape, pore size distribution, irregularity, orientation, continuity, etc.) on thin sections, prepared from undisturbed soil samples (Bouma et al., 1977, 1982; Murphy et al., 1977a, b; Pagliai et al., 1983, 1984; Pagliai, 1988). This morphometric technique has the advantage that the measurement and the characterization of pore space can be combined with a visual appreciation of the type and distribution of pores in soil in a particular moment of its dynamic evolution. For this analysis it is necessary to prepare thin sections of soil following a procedure which consists in taking undisturbed soil samples using appropriate implements, containers and techniques taking care that the interior structure of the soil samples remains undisturbed. Then the soil samples, carefully packed, are transported to the laboratory, dried to avoid pronounced shrinkage phenomena, using appropriate methods, e.g. acetone replacement of the water (Murphy et al., 1986), and impregnated, under vacuum, with a polyester resin, which has the characteristic of polymerising slowly at room temperature without alterating in any way the structure of the soil. Practically, this resin fills the pores of the soil. When the soil samples are hardened (generally after 4-6 weeks) they are made into vertically or horizontally thin sections by using appropriate machines (Murphy, 1986). Their thickness is about 30 μm so that they can be analysed by the microscope in transmitted light. The size depends on the kind of machines available; for porosity measurement a size larger than 6X6 cm should be recommended. The image analysis can be used not only on soil thin sections but also on polished faces of large soil blocks impregnated directly in the field with (fairly cheap) materials such as paraffin wax (Dexter, 1988), or plaster of Paris (FitzPatrick et al., 1985), or resin (Moran et al., 1989).

The soil thin sections are analysed with image analyzers (Murphy, 1977a, b; Pagliai et al., 1983, 1984). Two-dimensional images obtained can be transformed into data representing three-dimensional area percentages that are representative for three-dimensional volumes. Stereology techniques have been applied to achieve this objective (Ringrose-Voase and Bullock, 1984; Ringrose-Voase and Nortcliff, 1987; Mele et al., 1999).

Basic measurements of image analysis on pores include number, area, perimeter, diameters, projections, etc., and these are supplemented by derived measurements such as shape factors, size distribution, continuity, irregularity and orientation.

Pore shape

The shape factors allow division of pores into different shape groups such as, for example, more or less rounded (regular), irregular and elongated pores (Bouma et al., 1977; Pagliai et al., 1983). Pores of each shape group can be further subdivided into a select number of size classes according to either the equivalent pore diameter for rounded and irregular pores or the width for elongated pores. The equivalent pore diameters are calculated from the area of regular and irregular pores, while the width of elongated pores is calculated from their area and perimeter data using a quadratic equation because it is assumed that elongated pores are long narrow rectangles (Pagliai et al., 1984).

The regular pores are obviously those of a rounded shape and can be distinguished in two types according to their origin: the spherical pores formed by entrapped air during soil drying and the channels and chambers formed by biological activity (root growth and movement of soil fauna). Their distinction on soil thin sections is very evident because spherical pores (vesicles, according to Brewer, 1964) have very smooth walls, while channels, even though cut in a transversal way on thin section, present rough walls with deposits of insect escrements or root exudates. The presence of many spherical pores of the first type (vesicles) creates a vesicular structure typical of soils with evident problems of degradation.

The irregular pores are the common soil voids with irregular walls (vughs, according to the micromorphological terminology of Brewer, 1964) and can be isolated (packing voids) or interconnected. The dominant presence of these pores produce the typical vughy structure (Bullock et al., 1985). In cultivated soils these pores can be originated by the effect of soil tillage implements.

The elongated pores can be distinguished in two types, i.e., cracks and thin fissures (planes). The former are typical of clay soils with a depleted soil organic matter content and they are visible at the surface when the soil is dry and has shrunk. The thin fissures are the most important, especially from an agronomic point of view, in fact, they are the typical transmission pores. An adeguate proportion of this type of pore (over 10% of the total porosity) generally creates an angular to subangular blocky structure of good quality. Obviously for this to be true it is necessary for these pores to be homogeneously distributed in the soil matrix. In fact, for these pores characterization by image analysis, besides the identification of their shape and width, must also determine their length. With the same procedure of width determination it is also possible to determine the length of these elongated pores, which may reflect their continuity, and it is well known that the flow of water through soil depends on the continuity of large pores. Therefore the analysis of pore patterns allows the characterization and prediction of flow processes in soils.

For root growth and water movement not only the size and continuity of elongated pores are important but also their irregularity and orientation. The ratio convex perimeter/perimeter or convex area/area of elongated pores gives information about their irregularity, tortuosity and re-entrancy. As regards water movement, for example, the very regular and the moderately regular elongated pores play a different role. The very regular elongated pores are flat and smooth pores with accommodating faces, which tend to seal when the soil is wet, thus preventing water movement. In contrast, the moderately regular elongated pores have walls, which do not accommodate each other. Therefore, these pores permit water movement even when the soil is wet and fully swollen (Pagliai et al., 1984). The ratio vertical/horizontal dimensions gives the orientation of elongated pores (Pagliai et al., 1984). It is easily understandable that many soil processes such as water movement, leaching, clay migration, etc., are strongly related to the orientation of pores in soil and these processes radically change depending on whether a vertical or horizontal pore orientation is dominant.

Pore size distribution

As already said, to characterize the pore system it is necessary, first of all, to determine the shape and size distribution of pores because the agronomic functions of pores depend not only on their shape bur also on their size. According to one of the most widely used classifications, that of Greenland (1977) reported in Table 1, the very fine pores less than 0.005 μm, called "bonding pores", are critically important in terms of the forces holding domains and aggregates of primary particles together; pores of less than 0.5 μm are the "residual pores" for the chemical interactions at the molecular level; pores which have an equivalent pore diameter ranging from 0.5 to 50 μm are the "storage pores", i.e. the pores that store water for plants and for micro-organisms; and the pores ranging from 50 to 500 μm are those called "transmission pores" in which the movements of water are important for plants, and, moreover, they are the pores needed by feeding roots to grow into. The water content when pores larger than 50 μm have drained, corresponds to the field capacity of the soil. The wilting point commences when most pores larger than approximately 0.5 μm have emptied.

Pores larger than 500 μm can have some useful effects on root penetration and water movement (drainage), especially in fine-textured soils. However, a high percentage of this latter type of pore (above 70-80% of the total porosity) in soils is usually an index of poor soil structure, especially in relation to plant growth. This is because surface cracks, which develop after rainfall, when the stability of soil aggregates is poor, belong to this size classe (Pagliai et al., 1981, 1983). Until now the necessary proportion of large pores for air and water transmission and easy root growth has generally been inadequately defined. In fact, adequate storage pores (0.5-50 μm) as well as adequate transmission pores (50-500 μm) are necessary for plant growth (Greenland, 1981).

Table 1 - Classification of soil pores according to their size. Modified from Greenland (1977).

Equivalent diameter μm (10^{-6}m)	Water Potential (bar)	Name
<0.005	>-600	Bonding space
0.005 - 0.5	-600 / -6	Residual pores
0.5 - 50	-6 / -0.06	Storage pores
50 - 500	-0.06 / -0.006	Transmission pores
>500	<-0.006	Fissures

Soil pore system characterization by image analysis of thin sections can give detailed information about soil structural conditions, moreover if climate, agronomic and management data are known, the evaluation of soil physical vulnerability is allowed. Hence, the soil pore system can be considered a good indicator of soil quality, nevertheless, as for other indicators, threshold values have to be known.

According to the micromorphometric method a soil can be classified as follows where the total porosity represents the percentage of area occupied by pores larger than 50 µm per thin section (Pagliai, 1988):

Soil very compact	when total porosity is	<5%
Soil compact	when total porosity is	5-10%
Soil moderately porous	when total porosity is	10-25%
Soil highly porous	when total porosity is	25-40%
Soil extremely porous	when total porosity is	>40%

Total macroporosity value of 10% is considered the lower limit for good soil structural conditions, anyway, only the complete evaluation, both quantitative and qualitative, of soil pore system can produce exhaustive information on actual soil quality.

Relationships between soil porosity and water movements

The relationships between pore size distribution and soil water content are expressed by the capillary model, while the relationships between pore size distribution and water movements at specific water potentials are developed by several physical equations and models (Marshall, 1958; Childs, 1969).

The main limitation of these models is due to the assumption of the cylindrical shape of pores or the spherical shape of soil particles. The development of micromorphological techniques and the image analysis allow to improve such models. For example, Bouma et al. (1977) developed a method based on the preparation of undisturbed soil columns, saturated and then percolated with a 0.1% solution of metylene-blue that is adsorbed by the clay particles on the pore walls. Then vertical and horizontal thin sections are prepared. Pores are divided into three shape groups as already explained and then the pore size distribution is carried out. For the planar elongated pores the total area, the area of the blue-stained pore walls, and their lengths, and the spatial distribution of the widths and lengths of the pores with blue-stained walls are determined. Particular attention should be paid to the measurement of the width of the necks of elongated pores because the hydraulic conductivity is determined by the necks in the flow system. Following this procedure the hydraulic conductivity (K_{sat}) can be calculated as proposed by Bouma et al. (1979). Further studies of Bouma (1992) confirmed that morphological information on soil pore system were essential for the realization of water flux models.

The software evolution for the image analysis, that allows to obtain precise information about shape, size, continuity and arrangement of pores in soil, permit to simplify the modellistic approach. For example, Figures 1 and 2 show a highly significant correlation between elongated pores and hydraulic conductivity. Such a correlation is more significant as the value of elongated pores is lower.

Combined with the image analysis, the use of fractal and fractal fragmentation models can help to characterize the geometry of a porous medium in relation to transport process (Kutilek and Nielsen, 1994). For example, the fractal fragmentation leads to a better understanding of relationships between aggregation, n-modal porosity and soil hydraulic properties.

Relationships between soil porosity and penetration resistance

Several studies on the effect of compaction caused by wheel traffic on porosity and structure of different types of soils have showed a strong correlation between soil porosity and penetration resistance (Pagliai et al., 1992; Marsili et al., 1998). Fig. 3 shows a good correlation between porosity, measured by image analysis on soil thin sections, and penetration resistance in the surface layer (0-10 cm) of both compacted (porosity values below 10%) and uncompacted areas. The decrease of porosity in compacted areas was associated with an increase of penetration resistance.

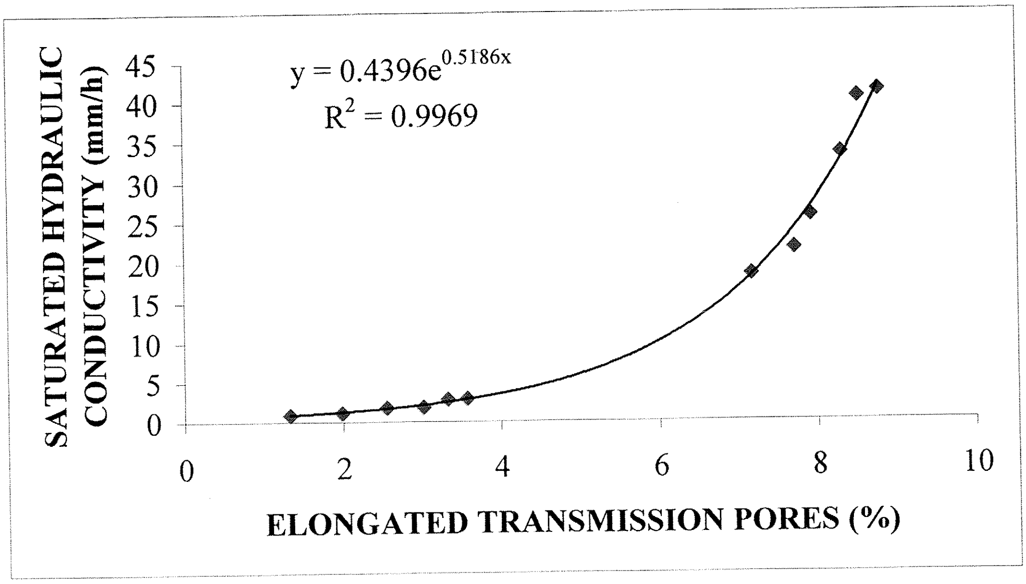

Fig.1 – Correlation between soil porosity, formed by elongated pores, and saturated hydraulic conductivity in the surface layer (0-10 cm) of compacted and uncompacted areas of a clay soil.

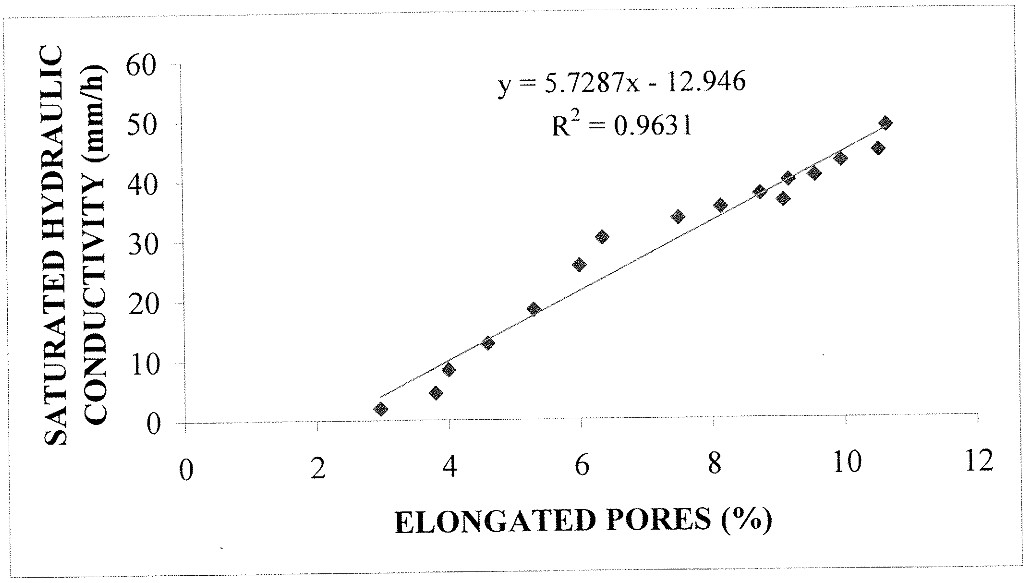

Fig. 2 – Correlation between soil porosity, formed by elongated pores, and saturated hydraulic conductivity in the surface layer (0-10 cm) of a loam soil cultivated to maize.

Relationships between soil porosity and some chemical and biochemical properties

It is well known that the soil structural qualities strictly depend on the interaction with organic matter: micromorphological techniques can give useful contributions in the studies dealing with the interaction of organic matter-soil structure by means of the microscopic examination of soil thin sections. Fig. 4 shows accumulation of organic matter distributed as a coat along the walls of elongated pores. These coats on pore walls can effectively seal pores from the adjacent soil matrix, thus stabilizing the pore walls against the destructive forces of water and assuring the functionality of the pores. These favourable conditions, with respect to soil structure, are not permanent. In fact, when the organic matter is totally decomposed and mineralized it loses its capability as a cementing substance, therefore the pore walls collapse and close the pore. Therefore it is evident the possibility of correlation between soil porosity and some chemical and biochemical soil properties. For example, Sequi et al. (1985) and Pagliai and De Nobili (1993) have found a linear correlation between soil porosity represented by pores ranging from 30 to 200 μm equivalent pore diameter, and soil enzyme activity, like ureasi (Fig. 5). Such relationships between pore size and enzyme activity were confirmed by Giusquiani et al. (1995) in soils treated with compost.

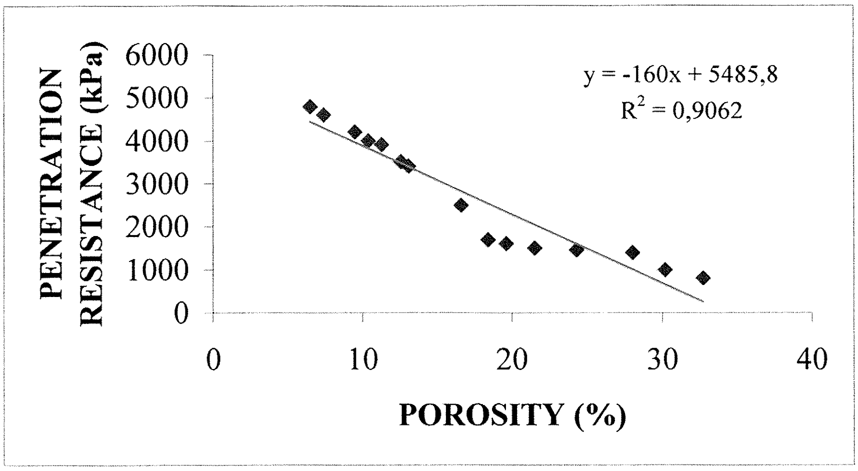

Fig. 3 – Correlation between soil porosity and penetration resistance in the surface layer (0-10 cm) of a clay loam soil.

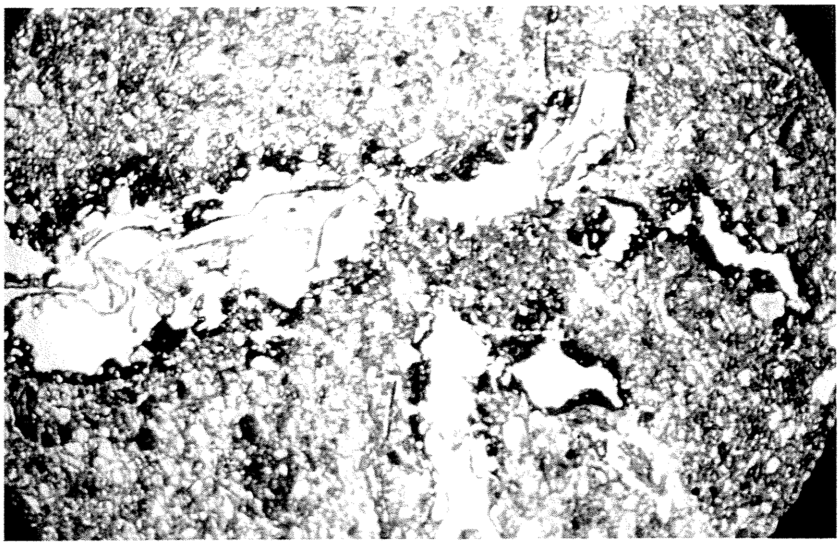

Fig. 4 – Macrophotograph of a vertically oriented thin section. It is evident the organic materials as coats on pore walls. Plain light; pores appear white. Frame size 5 mm.

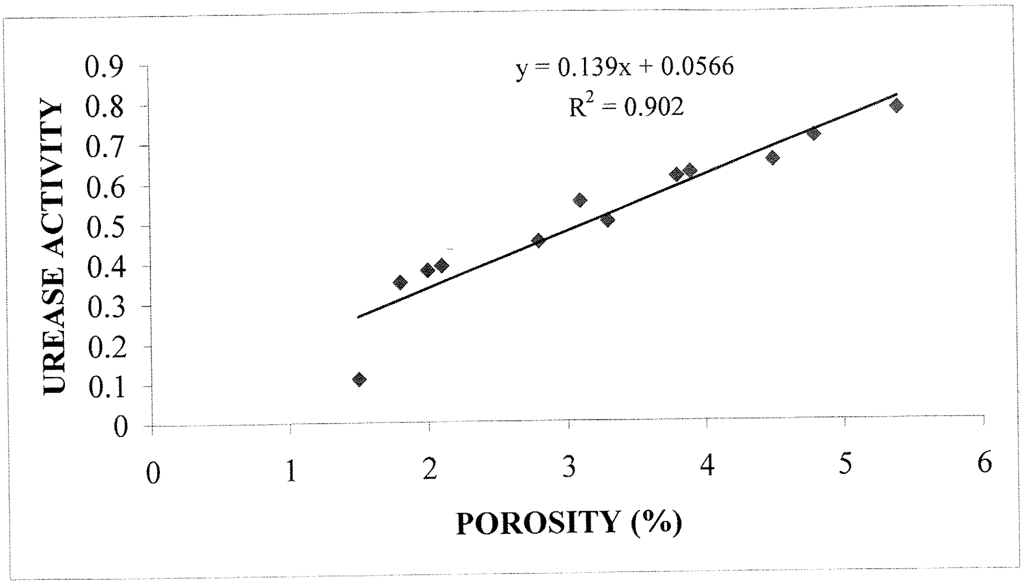

Fig. 5 - Correlation between soil porosity in the range 30-200 μm and urease activity (μmol ammonium release h^{-1} g^{-1} soil) in the surface layer (0-10 cm) of a clay loam soil.

Relationships between soil porosity and root growth

The soil structure modifications, the decrease of soil porosity, the increase of penetration resistance following compaction may hamper root growth besides reducing water infiltration. This aspect was studied in a sandy loam grassed soil cultivated to peach orchard (Pezzarossa and Pagliai, 1990). The porosity and root density were measured until a depth of 50 cm in the areas compacted by the continuous wheel traffic for all management practices (pesticide treatments, harvesting, etc.) and in the adjacent inter-row areas. Results are summarized in Fig. 6.

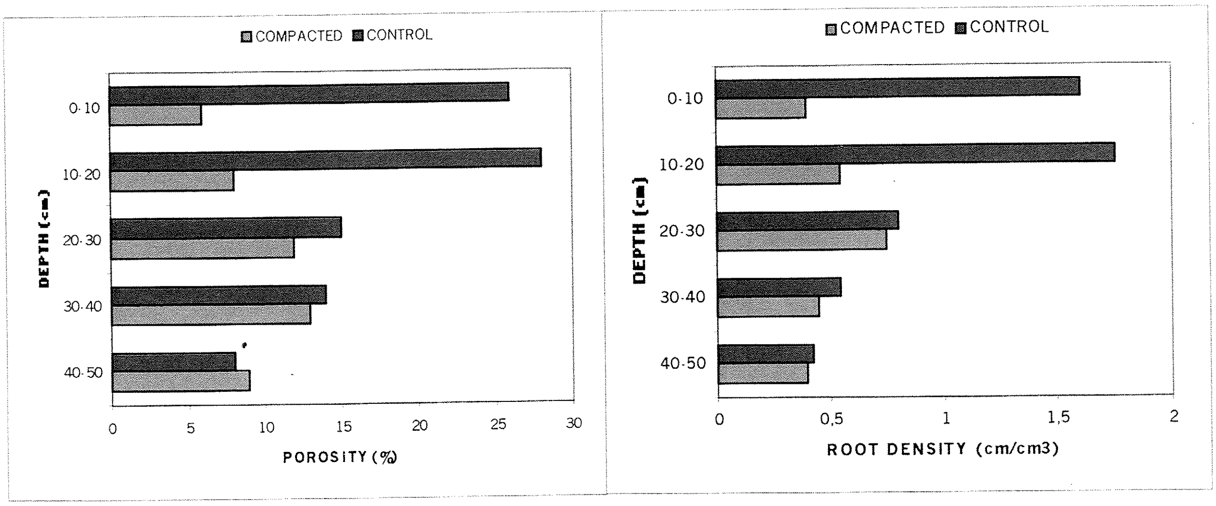

Fig. 6 – Effects of soil compaction, caused by wheel traffic of machines in a peach orchard, on soil porosity expressed as a percentage of area occupied by pores larger than 50 μm per thin section (on the left) and on root density expressed as root length/cm^3 (right).

The large reduction of porosity in the 0-20 cm layer of the compacted areas is evident, while in the 20-30 cm layer porosity increased, even though its value remained lower than in uncompacted areas. The root density, measured by image analysis and expressed by root length per cm^3 of soil (Pezzarossa and Pagliai, 1990), showed the same trend: in the 0-20 cm layer of the compacted areas it showed a value about three times lower than in the same layer of adjacent uncompacted areas. In the 20-30 cm layer, where the effect of compaction was lessened, the root density increased showing approximately the same value as in uncompacted soil.

Similar results were obtained in a previous study where no-tillage and conventional tillage were compared in a clay loam soil under viticulture (Pagliai and De Nobili, 1993). The distribution of the roots in the Ap horizon showed a higher root density in the no-tilled soils than in those which were conventionally tilled, following the same trend of the distribution of elongated transmission pores (50-500 µm). These finding confirmed the importance of transmission pores for root development. Thus for the soil examined in that investigation, no-tillage systems seemed to be more appropriate in maintaining favourable soil porosity by preserving the elongated transmission pores which allow for good root development.

Conclusions

The characterisation of soil pore system gives essential indications about the soil quality and vulnerability in relation to degradation events mainly connected with the human activity. Particularly such a characterisation allows to study the relationships between soil physical, chemical and biochemical properties and to provide a realistic basis for understanding water retention and water movement in soil. In fact, the quantitative evaluation of water movement and solute transport along the macropores, open new horizons to realise the modelisation of these phenomena. This is one of the new approaches in soil study since up til now the water movement in the macropores is not adequately considered. Some traditional concepts of soil physics need to be reconsidered or modified: for example, the concept of available water for plants should be associated to the concept of accessible water.

The characterisation of soil pore system, by means of image analysis on thin section, can provide basilar information on soil study. The major disadvantage of the development of this technique can be represented by the difficulty and the time consuming for the preparation of soil thin sections. However, now many public and private laboratories are equipped for the preparation of soil thin sections and the strong development of softwares for image analysis makes easy their utilisation.

When the obstacle of the acquisition of soil thin sections is overcome, it is possible to benefit of the potentiality of this technique, first of all to quantify the modification of soil structure following human activities. Therefore, on the basis of the acquired experiences, it is possible to go deep into the analysis on soil thin sections in relation to the aspects connected with water movement. The quantification of the size, continuity, orientation, irregularity of elongated pores allows the modelisation of water movement and solute transport, or, at least, allows to predict its changes following the soil structural modifications, or following soil degratation due to compaction, formation of surface crusts, etc. The quantification of the damage caused by the degradation processes also allows to predict the risk of soil erosion.

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Effective approaches for modelling chemical transport in soils supporting soil management at the larger scale

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Abstract

Modelling chemical transport processes in soils is a powerful engineering technique. However, the current modelling approaches suffer from a series of drawbacks which limits their use in a soil management framework, especially at the larger scales. Shortcomings are related to inappropriate modelling structure, lack of appropriate modelling data and deficiencies in good modelling practice. In this paper, examples and explanations for these shortcomings are given. Recommendations are formulated to develop robust approaches for chemical transport modelling in soil supporting soil management in an effective way.

Introduction

According to Duda (1993) 30 to 50 % of the earth surface should be adversely affected by non-point source pollution. Therefore, there is indeed an urgent need to improve large scale soil management in relation to environmental pollution. The agricultural sector contributes significantly to this problem since agricultural activities result in the movement of fertiliser, agro-chemicals and soil particles from the soil into rivers and streams via runoff and erosion, and into subsurface soil and groundwater via leaching (Corwin *et al,* 1999). The modelling of chemical transport in soils is considered as a powerful engineering technique which supports the definition of improved soil management. With this technique, the impact of variable soil management on the environment can be evaluated and hence, optimal management strategies could be identified.

Abundant literature exist now on possible applications of chemical transport modelling in soil management. A typical example is the evaluation of agricultural nutrient management in relation to water pollution (Steenvoorden et al., 2001). The loading of surface water and ground water with crop nutrients continues to be a major issue in Europe, as well as in the United States (Kolpin *et al,* 1999). Piñeros-Garcet et al. (2001) e.g. shows how a N fate and transport model can be used to evaluate catch crop management strategies in relation to the long term N loading of a deep groundwater body. In a similar way Christiaens et al. (1996) shows how N leaching models can be adopted to map vulnerability of groundwater systems supporting the implementation of N management plans at the regional scale. Van Uffelen et al. (1997) illustrates how these models can support spatially distributed fertiliser management at the field level in a precision agriculture context.

Yet, notwithstanding the scientific evidence that advanced modelling - and in this example advanced nutrient transport modelling - can contribute effectively to an improved management of soils, in practice, no modelling or only basic modelling is performed by soil professionals to develop their management plans. In a recent analysis, EURAQUA analysed how nutrient management is practically implemented in the different countries of the European Union and this in relation to the EU Nitrate Directive (Euraqua, 1998). The consultative forum on the environment and sustainable development considered that modelling was insufficiently developed and that knowledge based approaches, including advanced nutrient balance modelling, should be further promoted to improve soil management in the union. Similar conclusions would be obtained when analysing the management practice in relation to the control of other non-point source pollution problems such as the contamination of surface and ground waters with residues of plant protection products. We therefore may wonder why chemical transport modelling in soils is so little used in the practice of soil management. Quite some potentials exist to use advanced chemical transport modelling in engineering applications. However, full benefit of the existing techniques in practical soil management have not been taken so far. Within this paper, we try to formulate some reasons for this and give recommendations to bridge the gap between the world of soil academic research and in-situ soil management.

What's wrong with the approaches for modelling chemical transport in soil within a soil management context ?

The process of soil management is a complicated process, involving many decision makers and stakeholders at different levels. In this process, chemical transport modelling can be used to define suitable management options respecting a set of predefined criteria and conditions. The power of modelling situates in its potential to simulate possible system responses in terms of some predefined test solicitations, thereby answering typical 'what-if' questions. In a soil management context, a soil manager will have the possibility to combine a given model with a given modelling scenario to generate this plausible system responses in terms of the predefined testing scenarios. Inefficiencies and errors in chemical transport modelling can therefore be generated at different levels : first in the way how a system is conceived in the selected simulation model; second in the way how the model input and parameters have been generated; and last, but definitely not at least, in the way the model user, i.e. the soil manager, uses the model and interpret its outcomes.

Model errors at the conceptual level arises when process are inappropriately described in a given model or when process descriptions are forced to be used in an application for which they were not initially conceived. The ignorance of preferential flow - a process for which a consensus exist that it is extremely relevant for describing chemical transport in soils (Flühler et al., 2001) - in many soil management models is an example of inappropriate process conceptualisation. The adoption of a small scale validated process model to describe large scale behaviour is an example of inappropriate model use (Beven et al., 1999).

Input and parameter generation problems arise when modelling data are not available to deal with the extreme spatio-temporal variability of the system within the management application exercise. Many of the actual chemical transport models rely on the availability of detailed soil data which unfortunately are often unavailable for the specific conditions of the management case. A typical example is the evaluation of the large scale non-point source pollution problems with spatially distributed modelling approaches, which relies very often on the availability of the soil physico-chemical properties at the scale of each grid of a constructed soil information systems. Unfortunately, only limited hard data are available in most soil information systems and many grid scale modelling parameters need to be generated from interpolation, extrapolation or other predictive modelling approaches. The soil's hydrodynamic properties, e.g., were never considered as a descriptive property in a classical soil survey exercise but, obviously, are extremely essential in any chemical transport modelling exercise. Therefore procedures like up-scaling, geostatistical modelling, pedo-transfer modelling, and others, need to be readily operational to generate easily these properties at the scale of a grid. These procedures should however be operational for all the parameters of the management model.

Another aspect of data availability is related to the definition of the scenarios that will be used in a management exercise. Due to limited computing and data resources, the model will only be calculated for a limited series of 'sensitive' scenarios which, in comparison with what may occur in reality, will only yield a small sample of possible realistic scenarios. An example is the use of scenario analysis with a pesticide leaching modelling as a support of the lower tier registration of plant protection products in Europe (FOCUS, 1995; FOCUS, 2000). Boesten et al., (1999) proposes to use only 9 'worst case scenarios' in the first level screening of pesticide leaching risk at the pan European level to evaluate a nearly infinite number of potential scenarios. From a statistical point of view, it is however difficult to evaluate if this limited sample will be an unbiased sample of the unknown population of 'worst case scenarios' (Vanclooster et al., 2001).

Finally, a lack of good modelling practice restrains the advanced use of modelling in soil management. In the past, most modelling work was merely performed within an academic context. The modelling codes were often not well documented and limited in pre- and post-processing capabilities. The lack of appropriate interfacing, and advanced pre- and post-processing possibilities may introduce an additional and often insurmountable burden for the soil manager. This will also introduce an additional risk of modelling error due to user subjectivity, as was clearly illustrated by Jarvis et al. (2000) and Boesten (2000).

Before giving some recommendations on how to deal with all these problems, we analyse first more in detail the model error component in the modelling error.

What's the problem with the actual models for describing chemical transport in soils ?

The validation status of chemical transport models is low

The physical laws of mass, energy and momentum conservation are also applicable when dealing with chemical transport in soils. These fundamental thermodynamic laws are combined with appropriate flux formalisms such as Darcies law or Ficks law, to yield the governing transport formalisms for flow and transport in soils. These are the Richards equation for flow, which for 1-dimensional flow yields:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial z}\left[k(h)\frac{\partial h}{\partial z} - k(h) \right] - Sw \qquad (1)$$

where θ, is the volumetric moisture content (L^3 L^{-3}); h, the matrix head (L); Sw, the sink source term for water (T^{-1}); k(h), the hydraulic conductivity relationship (L T^{-1}); t, z, the time (T) and space (L) co-ordinate; and the convection dispersion equation for transport (van Genuchten et al., 1999):

$$\frac{\partial[\rho.s]}{\partial t}+\frac{\partial[\theta.C]}{\partial t}=\frac{\partial}{\partial z}\left[\theta.D\frac{\partial C}{\partial z}-Jw.C\right]-Ss \qquad (2)$$

where s, the mass of solute absorbed on the soil (L^3 M^{-1}); C the mass of solute in solution (M L^{-3}); r, the soil's bulk density (M L^{-3}); Jw, the Darcian flux (L T^{-1}) and Ss the solute sink term (M L^{-3} T^{-1}). Many soil management models therefore solves the flow and transport equations (1), (2), or a simplification of it, subjected to the boundary conditions occurring at the soil interfaces. Although easily established from a conceptual point of view, it is important to realise that the governing flow and transport equations (1) and (2) rely on a series of simplifying assumptions such as i) the existence of a Representative Elementary Volume; ii) the gaseous phase plays an unimportant role in the process; iii) Darcy's law is valid within the soil's porous system; iv) the osmotic, geo-static and electrochemical gradients in the soil water potential are insignificant, v) the fluid density is independent of solute concentration and temperature; vi) the matrix and fluid compressibilities are small; vii) the effective phenomenological properties like the hydraulic conductivity relationship k(h), can be defined; and viii) all the water is mobile.

For soil management applications, it is of a paramount importance that (1) and (2) and their associated simplifying assumptions are valid. Following Webster's dictionary (1993), validation implies the evaluation of the agreement of the model with the facts. However the evaluation of flow and transport models in soils will be cumbersome. First because it is difficult to separate in a modelling exercise the input and parameter estimation error from the structural model error. It will therefore be difficult to quantify the model structure error. Second because the observation of the "facts" will always be limited in space and time, as compared to the number of processes and scenarios for which we envisage to apply the models.

Indeed, when analysing the residue between observed system response and modelled system response, the structural model error will be lumped with parameter estimation error and observational error. Supposing that no measurement errors occur, a series of different parameter sets may lead to similar model performance which is the core of the equifinality problem (Beven et al., 1999). Non-uniqueness of parameters are typically observed in soil hydrodynamic modelling such as illustrated e.g. by Simunek et al., 1998; Romano and Santini 2001; and Lambot et al. 2001 and will therefore complicate the identification of the model structure error.

But even if we would be able to separate appropriately model structure and parameter estimation error, the model validation would be complicated by the scale problem (Beven et al., 1999). Indeed, the number of cases on which the theories and models can be tested will always be far inferior to the number of cases for which the models potentially will be used in a management exercise. For pesticide leaching modelling, the number of validation studies such as presented by Bergstrom and Jarvis (1994), Thorsen et al. (1998), and Vanclooster et al.(2000) will always be very limited as compared to the number of potential chemicals that need to be evaluated in a given environmental setting. The scale problem implies that the fate of each chemical in an environmental condition is unique. This explains also why transport models are often performing badly in a pure predictive blind validation mode such as illustrated by Gottesbüren et al., 2000, and would justify the recalibration of transport models when applying them to unvisited cases. However, the need for a-posteriori re-calibration limits seriously the use of the model in a pure extrapolation and, hence a management mode.

Process descriptions are deficient

Notwithstanding the difficulty to identify clear model structural errors in practice, there seems to be a consensus among scientists that a series of process descriptions needs a facelift in current chemical transport codes. A series of recommendations for leaching models were summarised elsewhere (Vanclooster et al., 2000) and will not be repeated here. Only one particular point of concern will be discussed here: the issue of preferential flow.

In terms of physical transport, there is now a large consensus that preferential transport have an important impact on the mobility of tracers, pesticides, radio-nuclides, phosphates and other chemicals in soils. This preferential transport can be due to the existence of structural macroporosity, the instability of wetting fronts, the availability of repellent water zones in the soil, or simply the soil heterogeneity (Nieber, 2001). Preferential flow will not only have an impact on the breakthrough of the chemical in the soil profile (e.g. Flury et al., 1995), but also on its physico-chemical processes like e.g. the sorption process (Bundt et al., 2001). Notwithstanding this obvious scientific evidence, an importance resistance exist for using preferential flow concepts in soil management models. This is of course related to the lack of a 'general' concept to consider preferential flow and the unavailability of robust techniques to consider preferential flow in a predictive mode. Most of the preferential flow models work only appropriately in an a-posteriori parameter identification approach which limits their applicability in a management context (Flühler et al., 2001).

The scale and scaling problem complicates chemical transport modelling

A lot of literature is now available illustrating the extreme variability in space and time of the material properties affecting chemical transport in soils. The variability is present at different spatial scales ranging from the pore scale (Cislerova, 1999), the core scale (Vanderborght et al., 1999), the field scale (Mallants et al., 1996; Jacques et al., 1998 ; Ritsema et al 1998; Hupet et al., 2001), the landscape scale and regional scale (Roth et al., 1999). The time variability of material properties has often been ignored but is also clearly present. The impact of mechanical stress on the soil hydraulic properties is well illustrated in literature (e.g. Roth et al., 1999). Yet, also other factors should be considered for explaining temporal variability. Moutier et al., (1999) and Toride (1999) for instance illustrated the temporal change of the unsaturated hydraulic properties in terms of water quality parameters. Vanderborght et al., (1997) illustrated the temporal variability of the solute dispersion length in terms of the governing flow regime. Given this extreme variability, a scale and scaling problem should be considered.

The scale problem suggests that different chemical transport models will be needed at different spatial and temporal scales. The scaling problem deals with the use of small scale process models at larger scales (Beven et al., 1999). The major issue for the scale problem is the uniqueness of place and time. Each chemical transport event in a soil occurs at a unique time and at unique place, and a perfect repetition of this event can never occur. Hence, a model inferred from an observation in a given space and time framework can never be tested since this observation is unique. The major issue for the upscaling problem is the non linearity of the processes. Small scale chemical transport process cannot simply be averaged at, let's say, the grid or time step scale, especially if these process are strongly non-linear such as when preferential flow takes place.

This will have of course, serious consequences on the modelled transport process. Suppose that at the local scale the process are well understood, and equations like (1) and (2) are valid at the small scale. Than we can wonder whether the process can be modelled at the larger spatio-temporal scales starting from these equations. The conventional way of dealing with the larger scale spatial problem is that we can disaggregate the region in a series of unique spatial units (a series of grids), that descriptive data for each spatial unit are available in a GIS type of format, and that all these data can be linked with a local scale model like eqs. (1) and (2) to yield an integrated assessment. Exemples of this spatially distributed approach are given by Christiaens et al., (1996) and Piñeros-Garcet et al. (2001), amongst many others. Yet this will result in serious problems. First we do not know whether eqs. (1) and (2) are indeed valid at the scale of a grid. Second, we never have all the model parameters for each grid, and by inversion we do not arrive at getting all the parameters by grid. Third, given the non-linearity of the system and the ignorance of some spatial continuity (and hence dependency) of the processes across the grid boundary, bias will be introduced in the larger scale assessment. So, a crucial question is: how can we than use the chemical transport theories and process knowledge collected at the local scale to model chemical fate and transport at the larger scale in a soil management context?

Towards effective approaches for predicting chemical transport in soils in a management context

Scale dependent effective modelling approaches

Following Beven (1995) and Beven et al., (1999), we propose to use a pragmatic approach. We are of course interested in knowing the functional response of the system. Hence, the representation of the large system by means of an ensemble of small scale modelling systems, is one - but only one of the many others- way of describing the functional response of the system. If the small scale modelling system is based somehow on governing transport models like eqs. (1) and (2), it has the merit of being based on a physical concepts, since it considers some process knowledge in the modelled system. But this is not necessarily the most appropriate way of conceiving the small scale process. Similar functional behaviour at the small scale could equally well be described with a pure empirical model.

Consider now indeed that we have accepted a given model formalism for the small scale process such as e.g. a solution of the eqs. (1) and (2), and that a spatially distributed model can be constructed. Given the equifinality issue, it is obvious that a range of parameter sets in the spatially distributed model will yield similar modelling performances at the larger scale. If indeed such a functional similarity exist, then we propose to accept this and consider a range of equifinal parameter sets in a predictive (soil management) mode. Hence, we suggest to merge towards a more stochastic 'Monte Carlo' type of modelling approach where a range of plausible functional responses are predicted using a range of equifinal model parameters. Weights to the individual model responses can be assigned in terms of their previous functional behaviour, so that statistics on the most likely system response can be generated. However, given the possible large ranges of model parameter sets, important predictive uncertainties will be generated. Still, as more information on the real system behaviour is obtained, for instance when monitoring of the system goes on, functional behaviour of the different model and parameter sets can be re-evaluated using Bayesian rules, and inappropriate parameter sets be rejected. In this case, the uncertainty on the model predictions will be reduced as the modelling prediction will be conditioned to the observed system data, and more unlikely modelling parameter sets be rejected.

We may now question in which form we should represent the small scale process in a spatially distributed model and whether solutions of equations like eqs. (1) and (2) are an appropriate base for modelling large scale processes? From the previous discussion, it is clear that not a single general model or parameter set can be considered as 'valid' model for describing small scale processes in a large scale management application. However, it could be that the solution of (1) and (2) is one of the valid solutions, one amongst the many others. Yet, if it is the case, will it also be the most efficient one? Or, in other words, do we start with detailed numerical solutions of eqs. (1) and (2) if we are faced indeed with a large scale soil management problem? Let's consider the example of pesticide leaching modelling as a support to pesticide registration. Notwithstanding some advanced (and probably also well performing) numerical and process-based pesticide leaching models, based on the solution of eqs. (1) and (2) are available, their use in an European spatially distributed risk management context is prohibited, given the computational burden and the lack of available modelling data. Therefore, at the pan-European scale, a much more 'simpler' modelling approach is needed which on the one hand can be parameterised based on data available in European data bases, but on the other hand, respects as much as possible the functional behaviour of the system, and therefore mimics as close as possible the more detailed process oriented numerical model which solves equations like eqs. (1) and (2).

A way to do this, is by performing modelling reduction, in which the complex numerical model is synthesised, thereby retaining only the sensitive parameters which can be spatialised based on available data. Such an approach is actually considered in the EU project 'Effective approaches for predicting environmental concentrations of pesticide (http://www.agro.ucl.ac.be/geru/recherche/projets/apecop-pub/) where the potential pesticide mass leaching towards the groundwater system is modelled using the reduced analytical model of Van der Zee and Boesten (1991). Such a reduced model allows to capture the most important functional features of a complex numerical model in a set of simplifying effective relationships. In this case, the reduced model is a steady state analytical solution of the linearised flow equation (2), for which the parameters are calibrated using the detailed numerical solutions. The advantage of using analytical solutions is that some physics are retained in the final model formulation. However, it should be noted that in any of these simple 'physical based' models, effective parameters are used which are obtained by means of calibration. These effective parameters are most often lumping all these processes which are not considered in the reduced model. Hence, the physics in reduced physical based models are only considered to a limited extent. As an alternative to physical based reduced models, pure statistical meta-models can be considered. When appealing on statistical modelling techniques, the model structure is not a-priori defined and a larger flexibility is obtained. Given the recent advances in data mining technology such as artificial neural network modelling, it is expected that these modelling techniques will become more important for the construction of meta-models in the future.

In any of these modelling approaches, whether it is now an empirical based meta-model or a physical based reduced model, it is imperative that most model parameters can be identified at the scale of interest. In the case of the reduced physical based pesticide leaching model, all the parameters but one, can be identified from the European soil map and associated soil data base (Jamagne et al., 1994). The remaining unknown effective model parameter is calibrated on a detailed numerical model for a series of pilot areas in Europe. Being calibrated on a more detailed numerical model, and not on real data as one would expect, will add an additional component in the uncertainty of the prediction. However, given the previous validation studies of the detailed numerical model, this uncertainty can be quantified. Calibration of the model using real world data is currently impossible since reference data of groundwater quality at the pan European scale are not available. However, it is expected that the implementation of groundwater monitoring network in the context of the Water Framework Directive will yield the necessary data which will allow to improve the effective model calibration in the future. In this case effective model parameters will be upgraded and conditioned to the new observations, thereby reducing the uncertainty in the modelling predictions (Freer et al., 1996).

Therefore, it is of paramount importance to invest in environmental monitoring. Current information technology allows to store and represent data related to non point source pollution, yet continuous scope exist to improve the quality of the large scale data sets. A particular attention should thereby be paid to remote sensing technology which, by definition, has the capability to monitor environmental variables at the larger scale. Satellite remote sensing techniques are now available to characterise land cover and land use, drainage patterns and topography, surface temperature, snow and surface soil moisture (Engman, 1999). But most of these techniques will only sample significantly the soil at the surface, while chemical transport in soils may be significantly affected by what is happening deeper in the soil profile. Hence, methods need to be developed which allows to characterise and monitor the subsoil at larger scales. In a recent study, Hoeben and Troch (2000) showed how information on the subsoil moisture profiles could be inferred from radar images using a data assimilation framework. Similar information can be obtained by using new applied geophysical techniques such as subsurface resistivity measurements or ground penetrating radar tomography in a nearby remote sensing context (Noon et al., 2000). However, still quite some research is needed to improve the interpretation of the signature of all these devices in terms of chemical transport properties of soils.

Improving the pedo-transfer functions for chemical transport modelling

Notwithstanding the actual availability of a series of large scale soil data in appropriate soil information systems, there still exist a gap between the parameters that a physical based chemical transport model needs, and the parameters available in the soil data bases. Pedo-transfer functions allow to bridge this gap by translating the basic soil data in functional model data. Most available pedo-transfer functions, however, have been developed using data collected on a series of small scale samples. Given the aforementioned discussion on scale and scaling, it would be unsound to consider a pedo-transfer as a way to obtain directly an effective functional model parameters of, let's say, a grid in a spatially distributed model. The role of pedo-transfer functions is not to give this exact effective functional model parameter, but rather to generate a realistic a-priori estimate of the model parameter which should constrain the parameter space in a more generic Bayesian parameter estimation framework. Quite some pedo-transfer functions are actually described in the literature. Good

reviews of the use of pedo-tranfer functions in hydrology are given by Pachepsky et al. 1999, and in a series of papers of van Genuchten et al., 1999.
For the hydrological component of the chemical transport codes (eq. 1), we observe that a series of well performing approaches exist to estimate the matrix hydraulic properties such as the matrix moisture retention and hydraulic conductivity relationship. Several empirical and quasi-physical methods exist, but the vast majority of the methods are empirical, and are based on linear regression models, non-linear regression models or even artificial neural networks (e.g. Schaap and Bouten, 1996). However, these approaches are not appropriate for well structured soils. In general, structure is far less quantified in soil data bases, and therefore much more difficult to be used in a pedo-transfer approach (Jarvis et al., 1999). In dual porosity models, the matrix and macropore hydraulic properties need to be predicted. Where, the saturated conductivity of the matrix can likely be predicted by a pore size distribution model, the saturated conductivity of the complete soil, including the macropores, is best predicted using pedotransfer functions based either on field survey descriptions of soil structure or measurements of drainable or effective porosity (Rawls et al., 1993, 1996; Jarvis et al., 1997; Rawls et al., 1998, Rawls et al., 2001), but concern should be raised about the robustness of these procedures. In particular for the exchange term between preferential and matrix flow, appropriate models have not been made available so far (Flühler et al., 2001). The lack of robust pedotransfer functions for preferential flow models, especially for the exchange terms, put an additional burden on the use of preferential flow models in a soil management context.

In contrast to the range of literature available on pedo-transfer functions for the soil hydraulic properties, little literature is available dealing with pedo-transfer for the solute transport properties of eq. (2). This is a little surprising since the flow properties will of course directly influence the solute transport, and solute transport tracing will therefore yield direct information on the effective flow behaviour in soil. This is of course partially due to a lack of appropriate measuring techniques which makes the characterisation of chemical transport in soils a difficult task. However, recent advances in chemical tracing with techniques such as TDR (Vanclooster et al., 1993; Vanclooster et al., 1995) or dye tracing (Gächwiller et al., 1999) allows now to quantify chemical solute transport at the field scale with a high spatial and temporal resolution. It allows also to explore the existing relationships between macroscopic water transport and solute transport, and hence infer solute transport properties from flow properties and vice-versa.

Vanderborght et al. (2001) gave an overview of a series of tracer experiments which were carried out in Belgium at the scale of soil monoliths (ca. 1 m^3) under controlled boundary conditions. He summarises the observed relationships between basic soil properties, flow properties and transport properties. Using the multi-domain transport model of Steenhuis et al. (1990), the relationship between the flow and transport velocities were evaluated. In cases where matrix driven flow was expected, solute properties could be well predicted from the flow properties. However, in cases were preferential flow is expected to occur like e.g. in an anthrosol, such prediction did not work at all. Similar conclusions were obtained from field scale studies. Using matrix based stochastic continuum modelling approaches, Kasteel (1997) and Vanderborght et al., (1997) predicted solute transport from a statistical description of the flow properties at the field scale in a macroporous soil. Although partially successful in the unsaturated range, important underestimations of the solute fluxes were observed when soil reached saturation and therefore when the macropore domain contributed significantly to the chemical transport. Therefore a plea is made to improve the prediction of preferential flow parameters using combined soil water and solute tracing approach.

As a final remark, we only considered in this paragraph issues related to physical transport. Many problems of soil management are related to reactive chemical transport. Therefore, similar discussions on the reaction and sorption properties should be considered, however, issues related to the chemical fate are not considered in the present paper.

Need appropriate scenarios

As already stated before, the benefit of a chemical transport model in a soil management exercise resides in its potential to evaluate a range of alternative scenarios, and in its potential to answer 'what-if' questions. Therefore, the power of a scenario analysis in a soil management will closely be related to the quality with which the scenarios were identified. Indeed, if the quality of the scenario has not been carefully checked and irrealistic scenarios have been developed, than the modelling in a soil management context may degenerate into a 'rubbish in – rubbish out' exercise. The problem with scenario analysis is that the evaluator needs to cover sufficiently the variability of all situations that may occur in the real system within a limited set of modelling scenarios, without having a deterministic and quantitative description of all real world situations. The construction of appropriate modelling scenario is therefore the problem of statistical sampling of a population which is badly known.

Consider again the use of pesticide leaching models for registration. At the European scale, the EU 91/414 directive regulates the registration of plant protection products adopting uniform principles. For the implementation of these uniform principles, standardised risk and hazard assessment methods need to be implemented (FOCUS, 1995). The FOCUS working groups proposes to use only 9 different soil-crop-climate scenarios to evaluate the likelihood of leaching of a potential product towards the groundwater system as a starting basis for registration (Boesten et al., 1999). The scenarios were constructed based on expert judgement, and it is hard to proof that the limited number of scenarios are indeed an unbiased and stratified sample of the situations that may occur in reality. Therefore, it is our opinion that the quality of the expert judgement should be carefully evaluated by comparing expert judgement approaches with statistical based approaches (Vanclooster et al., 2001).

Need appropriate good modelling practice

Last, but definitely not at least, the appropriate use of effective chemical transport modelling in soil management can only be done if the different actors in the soil management process have had an appropriate training. The often surprisingly poor modelling results in a user inter comparison ring test (e.g. Boesten 2000), clearly elucidates the need for advanced education and training in chemical transport modelling and the implementation of strict guidelines for good modelling practice. The model user is responsible for understanding the model and its appropriate usage. He is also responsible for estimating the model parameters and the input for a selected scenarios. He must further keep in touch with the evolution of the model versions of the model documentation He is further responsible for developing modelling reports that contain sufficient and reliable information. Most of the state of the art modelling approach are developed by the research community and need to be further shared by soil professionals. A tremendous gap still exist between models available in the research community and those used in soil management applications.

Therefore a plea is made to upgrade existing scientific models into real engineering tools, to improve the training of the potential model user, and to implement strictly the concepts of 'Good Modelling Practice' (van Genuchten et al., 1999). The idea of this latter is to make the modelling process completely transparent by documenting each step of the modelling process such that it can be independently executed by any other model user. An example of how this can be done in the context of modelling for the plant protection product registration is given by Resseler et al. (1997).

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Impact of human activities on soil loss. Direct and indirect evaluation[1]

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Abstract

Soil erosion is the most important cause of soil degradation worldwide. New forms of soil erosion not present in nature are tillage erosion and land levelling for which the term "soil loss" assumes a different meaning compared to water erosion, due to the different dynamics of the process involved. The paper present a synthesis of the most important methodologies and prediction models for detecting soil erosion on different scales. Some examples of application are also presented to clarify the effectiveness of models in performing a qualitative analysis of CAP agrienvironmental measures.

Key words: Soil erosion, survey, prediction models, Common Agricultural Policy

1. Introduction

In the past 30 years world population has increased by about 1.5 billions people. Global agriculture has made remarkable progress in expanding world food supplies, at the price however of increasing environmental impact, specially where conservation measures were not adopted. In the last decade this evidence has provoked growing world-wide pressure to protect both natural resources and the environment (Swindale et al., 1989) and an effort to define Sustainable land management systems based on economically viable agriculture resulting in the improvement of the quality of life for mankind and other species, maintenance of the natural resources, and enhanced opportunities for future generations (Douglas, 1984).

Among the human activities that cause the degradation of the environment, the conversion of natural soil to agriculture, mechanization, irrigation and the indiscriminate use of pesticides and fertilizers are the most important factors determining the loss of natural habitats and soil degradation (WRI, 2001).

Oldeman (1994) estimated that, by 1990, 562 million hectares had been degraded by non eco-compatible agricultural practices, this value corresponding to about 38% of the 1.5 milliard hectares in cropland worldwide.

Although soil degradation does not occur at the same levels of intensity everywhere, an appreciable extension of land results severely harmed, with a decrease in its productive capacity.

Although it is not easy to recognize soil degradation, due to the masking effect of the increasing use of agro-inputs, the phenomenon is still continuing to increase. UNEP (1997) estimated that since 1990 worldwide degradation-affected lands has increased by about 5-6 million hectares per year

2. Soil erosion

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Soil is not a renewable resource. In fact, pedogenetic processes are in general very slow, requiring from 200 to 1,000 years to form 2.5 centimetres of topsoil under normal agricultural conditions (Kendall and Pimentel, 1994). Barrow (1991) estimated that, depending on the region, topsoil is currently being lost 16 to 300 times faster than it can be replaced.

The generally recognised division of soil erosion into two categories of natural or geological erosion and accelerated erosion does not seem fully appropriate. In general, although man's activities are responsible for the increase in soil erosion, in some cases erosion might be decelerated by conservation practices (e.g.: wall terraces or sand dune fixation). Thus, a more appropriate distinction should be proposed in terms of "natural" and "anthropogenic" soil erosion, to include the possibility of a decrease of soil erosion due to human activities.

As shown in Figure 1 soil erosion is the most important component of land degradation around the world. About two thirds of soil erosion is caused by water with another third caused by wind (WRI, 1992).

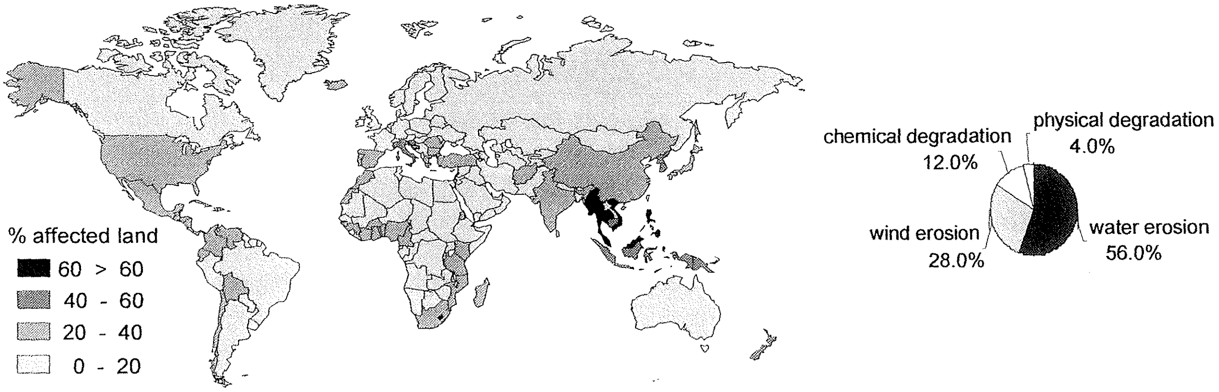


Figure 1. Land with erosion risk (FAO 2001, redrawn) and Worldwide status of human-induced soil degradation (Oldemann et al. 1990, redrawn)

The World Resources Institute (WRI, 2001) reports that different regional studies have localized losses of soil productivity due to soil erosion. In Africa, production losses from soil erosion alone are estimated at just over 8 percent (Lal, 1995). Data from several different studies indicate that the decline in productivity resulting from soil erosion and degradation may exceed 20 percent in a number of Asian and Middle Eastern countries (Scherr and Yadav, 1996). These losses are predicted to worsen as soil degradation continues. Though the total global harvest may not reflect such losses immediately, they may be noticeable in some areas, especially where erosion and other degradation components are severe and progressing quickly. For example, soil erosion is expected to seriously compromise production in southeast Nigeria, Haiti, and the Himalayan foothills, as well as in some parts of southern China, Southeast Asia, and Central America.

2.1 Non natural erosion forms

2.1.1 Tillage erosion

Recently, tillage has also been included among the causes of soil erosion. Mechanical tillage on steep slopes, done with instruments that completely or partially turn the soil upside down, determine the soil translocation over a landscape. These variations typically result in soil loss from convexities and soil accumulation in concavities and the cumulative effect during the years can change the landscape with environmental and societal impacts.

The soil flux per unit surface (tillage erosion) can produce soil losses that exceed those due to water erosion (Govers et al., 1996; Lobb et al., 1999; Quine et al., 1997) and represents an important factor of soil degradation specially in industrialised countries where the energetic input in agriculture is high.

Although the earliest studies on tillage erosion date back to the early 1940s it is only since the 1990s that research work on this form of land degradation has been on the increase (Govers, 1999; Mech and Free,1942). This is due to the fact that the effects of tillage erosion became visually evident only after some decades following the introduction of mechanical tillage.

High rates of soil removal on hillslope convexities due to tillage erosion can rapidly lead to significant and possibly adverse changes in soil properties. Such changes will affect soil quality and productivity and may also influence water and wind erosion rates by exposing erodible subsoil.

2.1.2 Land levelling

Land levelling is generally applied on undulating land for efficient water application and conservation before terracing. Also, bulldozer is often used for removing the natural vegetation or the residues of old plantations, with the consequent scalping of the soil.

In the Mediterranean basin bulldozing is usually used for clearing and levelling the land to obtain uniform easy to cultivate slopes. Furthermore this operation is usually performed in summer or autumn, which is the period of the most erosive rainfall. After levelling, slopes being prepared for plantation are almost always characterised by the presence of large amounts of incoherent earth materials accumulated with scraper. In this vulnerable condition, a few summer storms can easily cause soil losses exceeding 500 Mg $ha^{-1}y^{-1}$ (Bazzoffi and Chisci, 1999).

2.1.3 Water erosion on tracks

Wheeltrack compaction is the most important cause for runoff in soil affected by wheel pressure. When the tractor is forced always to pass on the same tracks it determines compression-induced waterways that tend to become deeper over the years due to the combined action of mechanical deformation and soil erosion. This behaviour was observed on hilly vineyards of central Italy, with plant-row direction along the maximum slope (Bazzoffi and Chisci, 1999).

Compression tracks in the open field too, can increase runoff and soil erosion that seems impossible to mitigate even using low-pressure tractor tyres. In fact, Bazzoffi et al. (1998a) found a negative effect of low-pressure tractor tyres with respect to traditional tyres on soil erosion due to increased runoff volumes and the fine fraction of sediment. Compaction due to low-pressure tyres, although lower than with normal tyres, involves a larger surface of soil because of the wider tread. Consequently, the wheel-pass tracks are larger when low-pressure tyres are used and the number of isolated aggregates on the soil surface decreases.

3. Soil erosion and sustainable management

Sustainable soil management can be defined as the adoption of management strategies and practices that allow agriculture to continue on a piece of land in perpetuity.

In order to evaluate the impacts of management practices on soil erosion and to plan the conservation strategies, two approaches are possible: direct survey of soil erosion under different agricultural management systems and application of prediction models for scenario analysis.

It is particularly important that both approaches should be integrated in monitoring-network programmes at different temporal and spatial scales to perform the *ex-ante* and *ex-post* evaluation of agrienvironmental measures adopted under the Common Agricultural Policy (CAP) schemes of support (European Commission, 2000) that might impact on soil erosion.

3.1. Different significance of direct-survey measurements of soil erosion.

3.1.1. Runoff and erosion measuring and sampling

To evaluate the effect of soil management on soil erosion by water at different scales, different tools can be used. In Table 1 a summary of different approaches in relationship to survey scale is presented.

Erosion and runoff data derived from laboratory and field studies are used to model formulation, calibration and testing. Generally, very little information regarding the type data and confidence limits for the measuring is given. The nature and significance of data with the same name (e.g. soil erosion Mg/ha) can be very different for different scales of observation. At microplot scale soil erosion is totally collected and measured as weight, while at plot scale the measurement starts becoming less precise due to the error induced by runoff partition devices and sediment sampling methods. At micro-plot scale and slope scale the measurement units of soil erosion should be consistent with the area of the investigated surface. For example, reporting data of soil erosion from 1-2 m^2 plot in terms of Mg ha^{-1} is unexceptionable for the SI units system, but erroneous for the areal significance of the measurement.

The measurement of runoff volume and hydrograph at watershed outlet can be considered acceptable in relation to the geographical scale, specially with the use of electronic instruments and data logger. On the contrary, at the same watershed scale, the measuring of sediment can be very event-dependent and unpredictable; due to the impossibility of sampling clods that creep and hop on the bottom of the flume (specially during high extreme events which we are most interested in measuring).

From this short review it is clear that different scale-dependent significance of erosion should be taken into consideration by model developers and validators. Models based on the kinematics wave concept should take into account the changing scale factor for erosion significance and uncertainty.

3.1.2. Tillage erosion measurement

Unlike water erosion, tillage erosion is not measurable as a flux at the outlet of a plot or watershed; but as a change of landscape. Thus a more complicated survey must be utilized and the measuring of tillage erosion always incorporates the measuring of the effects of other processes of landscape evolution such as water erosion, surface and deep mass movement.

The indirect methodology that uses Cs^{137} as a tracer of tillage erosion (Quine at al., 1997; Vanden Berghe and Gulinck, 1987; De Roo, 1991; Quine et al., 1994) is promising although difficult to apply. The most effective direct method for detecting the spatial distribution of territory morphology changes due to soil translocation induced by tillage is the lag-time analysis of the land morphology changes made by the comparison of different Digital Terrain Models (DTM) derived from close aerial photos taken in different years. Obviously, this method can be applied when tillage translocation represents the main process dominating the morphology evolution of the investigated area. This very well known methodology (Frazier and McCool, 1981; Morgan et al., 1980; Vandaele et al., 1996) has recently been improved by Bazzoffi (2000), through the over determination of topographic points for the placement of stereoscopic models and statistical analysis of photorestitution replicates.

SCALE	**METHOD**	**USE**	**PRECISION CONFIDENCE**		
			Runoff volume	**Runoff hydrograph**	**Erosion**
Laboratory	Rainfall simulator, box, flumes	Process and parameter investigation	high	high	high
Subfield	Confined microplots 1-2 m^2 (with or without simulated rainfall)	Process and parameter investigation	high	high	high
Open field	Isolated pins	First approximation	none	none	low
	Observation of natural or artificial markers of the antecedent soil level (painted rocks, roots, poles)	First approximation measure of erosion. Localization of erosion and tillage erosion occurrence	none	none	low
	Gerlalch trough	First approximation measure of erosion.	medium	none	medium
	Profile meters (erosion pins and laser)	Precise monitoring of soil roughness, shape and cross-section area of rills.	none	none	medium
	Multiple sequence of profiler meter sections	monitoring of rill volume.	none	none	medium
Slope	Small scale plots representative of slope processes with cumulated sampling of runoff (Coshocton wheels, multi-slot or multi-pipe divisor)	Land use comparison, model testing.	medium	medium	medium
	Small scale plots representative of slope processes with electronic monitoring of discharge and runoff sampling	Land use comparison, process modelling, runoff dynamics.	high	high	medium
	Rainfall simulators on micro amd small scale plots	Process and parameter investigation. Land use evaluation	high	high	high
	Cs137 survey	Soil erosion and tillage erosion	none	none	low
Gully field	Grid-organized pins	Monitoring bank collapse and change of surface level	none	none	medium
	Lapse-time analysis of DEMs	Regional investigation	none	none	medium
Watershed	Runoff measurement and sampling. Outlet turbidity station	Direct measure, model validation and parameter calibration .	medium-high	medium-high	low
	Lapse-time analysis of DEMs from close up aerial pictures	Tillage erosion measure. Gully and badlands evolution	none	none	medium
	Reservoir sediment survey and computation	Average soil erosion measurement.	none	none	medium

Table 1. Summary of the most common typologies of erosion survey and expected precision of measurement.

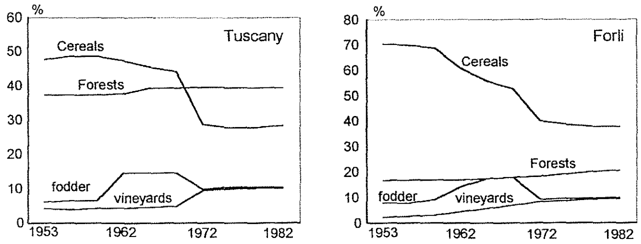
Due to the different processes involved in water and tillage erosion, these quantities, although both expressed as Mg/ha, have a completely different meaning and environmental relevance. In fact, in the water erosion process the grain size distribution of sediment is generally different than the original soil. Furthermore it always moves downslope and tends to deposit as sediment, sometimes very distant from the zone of origin in relatively small areas. On the contrary, tillage erosion can move soil upwards on the slope, the distribution pattern of the translocated material is not always concentrated and the “eroded” material is not a sediment.

3.1.3. Sediment yield measuring.

Lapse time analysis of sediment load by river can be used as an aggregated indicator of the effect of changes of agricultural systems on soil erosion if the prevailing cause of watershed sediment yield is agriculture. This is the case of the Arno and Savio rivers, respectively in Tuscany and in Emilia Romagna in the province of Forlì, where the analysis of suspended sediment was performed to give an example of application of this methodology.

Two sediment gauging stations were selected, respectively at Rosano, 11 km before Florence, where the Arno's watershed measures 4083 km^2 and at the San Vittore (Emilia Romagna) where the drainage area of the Savio river measures about 700 km^2. The considered period spans 1952-1982 and was divided into the three decades: 1952-1962, 1963-1972 and 1973-1982. This rough division has been made on the basis of considerable land use changes in the three periods (Figure 2).

By applying ANOVA to the monthly values of sediment yield, a significant reduction of sediment yield from both watersheds was found. This result appears due to the decrease of the cereal surface and to the increase of the land devoted to fodder and forests. Vineyard and orchard lands increased to about 10% in the last decade, determining a slight increase of sediment yield in the Arno's watershed.



	Arno watershed at Rosano			Savio watershed at San Vittore		
Decades	*1953 1962*	*1963 1972*	*1973 1982*	*1953 1962*	*1963 1972*	*1973 1982*
Mean sediment yield Mg km^{-2}y^{-1}	343 a	152 b	249 ab	1592 a	1186 b	982 b
Mean Rainfall mm y^{-1}	977 a	1052 a	986 a	1135.6 a	1040 a	1009 a

Figure 2. Scenario changes in Tuscany and Forlì province (% of the agricultural and forest area in 1953) and mean monthly sediment during the three decades.

These results demonstrated the influence of land use change on the variation of erosion and of sediment yield and the applicability of the analysis of suspended sediment at river gauging stations to quantify the effect of changing agricultural systems in terms of delivered sediment to river network.

4. Water erosion models and sustainable management

4.1 Models

In general models are used to estimate soil erosion for different combinations of existing factors (land use, soil type and morphology, climate) and for scenario analysis to predict the environmental impact of global change (climate evolution and reform of the agricultural policy) and to estimate different effects of erosion and runoff on productivity losses, reservoir and channel sedimentation, water quality and for planning conservation measures to be adopted inside watersheds.

Table 2 shows a review of the best known soil erosion models and their principal features.

When tested on measured erosion data, models are almost always disappointing and inadequate (Favis-Mortlock, 1998; Jetten et al., 1999; Parsons and Wainwright, 2000). In general they need calibration for the set of specific conditions of application and have a tendency to overestimate or underestimate erosion values (Nearing et al., 1999).

Jetten et al. (1999) indicated that calibration is imperative where spatial variability influences the simulation and, for the same catchment for which the model has been calibrated, good results cannot be expected if the event is outside the range of calibration. Furthermore, a great amount of unexplained variability is the major cause of error in model-predicted values (Wendt et al. 1986).

4.2. Use of erosion models for environmental impact analysis of changing scenarios under the pressure of Common Agricultural Policy (CAP).

Due to uncertainty of acquiring exact estimates of soil erosion with predictive tools, it is clear that the application of both empirical and physically-based models is not possible for detecting the quantitative impact of different agricultural land managements on soil erosion, specially if we consider that it is almost always difficult to represent the changes in soil parameters in erosion models, due to the spatial complexity, variety and modular application of agricultural management practices. Furthermore the effect of agrienvironmental measures on soil erosion might be feeble and masked or annulled by other environmental components.

Despite these limits, physically-based prediction models can still be used to perform the *ex-ante and ex-post* evaluation of agrienvironmental measures adopted under the Common Agricultural Policy (CAP) schemes of support (European Commission, 2000) that might impact on soil erosion.

The evaluation procedure should aim to determine the relative, instead of quantitative, effectiveness of the agrienvironmental measures in controlling erosion.

Erosion models	Empirical/Physical process based	Lumped/Distributed parameters	Single/Continuous events	Field/Basin /Landscape-Regional	Low/Medium/High data request	Low/Medium/High Complexity	Low/Medium/High GIS integration	Low/Medium/High difficulty to use
USLE (Wischmeier and Smith 1978)	E	L/D	C	F/B	L	L	M	M
EPIC/APEX/ALMANAC (Sharpley and Williams 1990)	E	L	C	F	M	M	L	M
RUSLE (Renard et al. 1991)	E	L/D	C	F/B	M	L	M	L
AGNPS (Young, R.A. et al. 1989).	E	D	S/C	F/B	M	L	H	L
MUSLE (Williams, 1975)	E	L/D	S	F/B	M	L	L	M
USPED (Mitasova et al. 1996),	E	L/D	C	F/B	M	M	M	L
CREAMS (Knisel, 1980)	P	L	S/C	F	H	M	L	H
SWRRB (Arnold et al.1990)	P	D	C	W	M	M	L	L
PSIAC (1968)	E	L	C	L	L	L	M	H
SPUR (Hanson et al. 1992)	P	D	C	F/B	M	H	L	H
SWAT/HUMUS (Arnold et al. 1995)	P	L/D	C	B/L	M	M/H	H	M
GLEAMS 2.1 (Knisel, 1993)	P	L	C	F	H	M	M	H
CASC2D (Julien and Saghafian 1991).	P	D	S/C	B	M	M	H	L
MULTSED (Simons et al. 1980)	P	D	S	B	H	H	L	H
ARMSED (Riggins et al 1989)	P	D	S	B	H	H	L	H
WEPPprof/basin (Flanagan and Nearing 1995)	P	D	C	F/B	M	M	L	M
SIMWE (Mitas and Mitasova, 1998)	P	D	S	F/B	M	M	H	M
ANSWERS (Beasley et al., 1980)	P	D	S	F/B	M	M	H	M
KINEROS (Woolhiser et al., 1990)	P	D	S	F/B	H	M	L	M
EUROSEM (Morgan et al.1993)	P	D	S	F/B	H	H	L	M
SHE (Abbott et al.1986a,b)	P	D	S/C	F/B	H	H	M	M
SEMMED (De Jong and Riezebos 1997).	P	D	S	B/L	H	M	M	H
CSEP (Kirkby and Cox, 1995)	P	L	C	B/R	L	M	M	M
MEDRUSH (Kirkby, 1998)	P	D	C	B	H	H	H	M
EROSION3D (Werner and Schmidh, 1997)	P	D	S	F/B	H	H	H	M
ACRU (Schulze, 1990; New and Schulze 1996)	E	L	C	F/B	H	H	L	H
PISA/NEUPISA (Bazzoffi,1993; Bazzoffi et al. 1998b)	P	L	C	B	L	L	H	L
AGQA (Ciccacci et al. 1987)	P	L	C	B/R	L	L	H	L

Table 2. List of best known soil erosion models and characteristics.

Prediction models should be applied by using the existing or default values of input variables, then changing - one at a time - the values for parameters more prone to change under the effect of the given agrienvironmental measure, within a range of realistic values according to the different intensity of the measure. The same procedure can be repeated by combining the variation of more than one parameter at a time. In this way, assuming that the most fundamental processes are sufficiently well described by the models, it is possible to determine the efficiency of an agrienvironmental measure.

As an example of the application of this “sensitivity simulation” we can consider the effect of variation of Ksat, slope steepness, slope length and vegetation cover on a plot (75x15 m, clay soil) at Vicarello (Tuscany), simulating the effect of the increase of these parameters one by one under the effect of a CAP measure.

By applying WEPP (Flanagan & Nearing 1995) and EUROSEM (Morgan et al., 1993) models to a real rainstorm event of 28.4 mm which occurred in March 1995, with a peak intensity of 59.6 mm/h and net soil erosion of 0.4 Mg/ha, we obtained respectively an estimated soil erosion of 3.7 Mg/ha and 0.89 Mg/ha. Although the estimated value through WEPP is quite different from the observed erosion, the EUROSEM value appears quite good. However, if the real value of erosion for this event was not known, the contrast between the two models might disappoint the model user.

By applying the “sensivity simulation” we got the results shown in Figure 3, from which it is possible to recognize to what extent the values of different parameters should be increased or decreased to obtain the desired reduction of soil erosion for the studied environment.

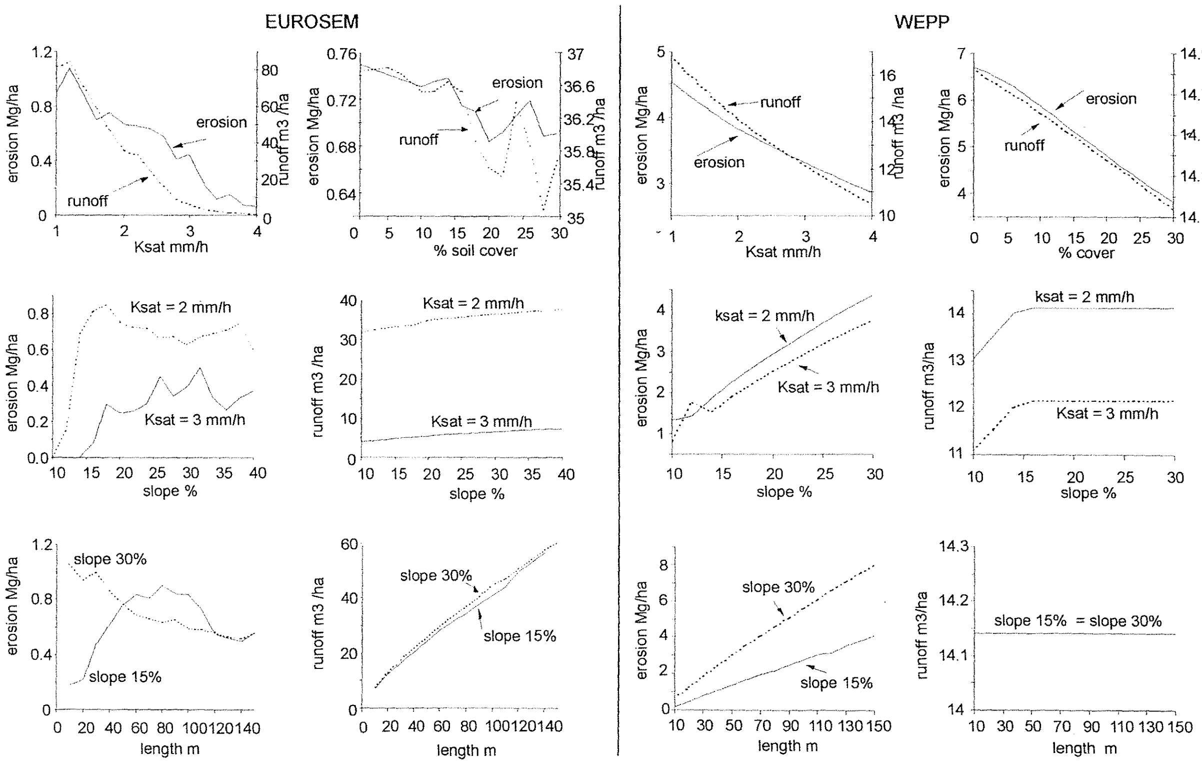


Figure 3. Sensitivity simulation through EUROSEM and WEPP for evaluating the efficiency of CAP agrienvironmental measures .

The same exercise can be repeated for different soil, slope parameters and storm typologies to tune the chosen agrienvironmental measure for high-extreme or frequent events.

This procedure can also help the user to understand the sensitivity of different models to take into account the variation induced by a specific agrienvironmental measure on soil parameters. For example, Figure 3 shows that, for erosion response, EUROSEM is more sensitive than WEPP to variation of Ksat. The same can be observed for variation of the slope steepness in the range of 0-18% for a value of Ksat of 2 (etc.). On the contrary, WEPP does not seem sensitive to variation of slope steepness as regards runoff volumes when changing the slope length.

Still assuming that the processes are well represented by model's functions, the user should judge the effectiveness of a CAP measure from this disaggregated analysis rather than from a crude value of soil erosion predicted by different models.

5. Conclusions

Although soil erosion is considered worldwide to be the most important cause of soil degradation, it is still difficult to quantify this environmental parameter both in term of direct measurement and predictive estimates. Despite these difficulties, great effort is applied to control soil erosion, but the effectiveness of the application of agrienvironmental measures still cannot be satisfactorily quantified at watershed or regional scale. Greater effort should be devoted to create or increase the efficiency of monitoring-network systems for soil erosion, also in view of ameliorating predictive models.

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Databases and simulation modelling in compaction and erosion studies

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Introduction

Soil survey and related fields of science generated since their early development large quantities of data from both field and laboratory work. Frequently their potential to generate full information was only partially exploited because of the limitations in manual handling of these data recorded or included in voluminous written documents.

General development in the last several decades of computers undoubtedly lead to a quick, efficient and systematic way of storing, processing and using such data for various purposes. Serious changes and advances became possible in many field of science, including in branches of soil science as soil survey, soil evaluation, soil management, soil degradation and conservation, soil and environment, statistical processing of soil data and of many other related ones. New methods and procedures started to be implemented and even new fields of science as geographic information systems or support decision systems came into use. A discussion on some of these developments, with a special focus on those related to soil compaction and soil erosion, is the object of the introductory paper to the session devoted to such subjects.

Earlier background

The concepts and the terms of database, modelling, estimation procedures a.o. have been used earlier than introduction of computer sciences and informatics, even if the meanings of these concepts were not exactly the same. Any collection of data could have been considered as a database, while various physical imitations of real objects or processes, and even equations or other mathematical formulae, used to be called models. Estimation procedures for different soil properties not directly determined were extensively done, using especially regression equations.

More recent developments and present state-of-the-art

Once computers became the main equipment used for these kinds of research activities the terms of database, simulation modelling and estimation of non-determined soil properties got more precise and a more complete senses, while additional concepts and procedures were developed. A summary of the items to be discussed is presented in Figure 1.

A collection of data is at present considered a database only when it is conceived with these data stored in a computer and use an adequate software able to allow sorting and various processing of these data. ACCESS and ORACLE are such software frequently used with soil databases. Specific software for collecting data on characteristic soil profiles are available at the European Union level (Madsen a. Jones, 1998), as well as at various countries level, e.g., in Romania, the PROFISOL database (Canarache et al., 1998). A special-dedicated software was recently developed at the FAO level for using soil and land databases (De la Rosa et al., 2000). It is a user-friendly microcomputer programme designed for storage, processing and transfer of a large amount of soil survey and monitoring data in an efficient and systematic way. Within the European Union more specific databases have been developed for soil hydraulic properties (HYPRES, Wösten et al., 1998), while databases related to soil compaction and to soil mechanical properties are in the final stage of completion and will be discussed in more details later in this paper.

A model (simulation model) is nowadays considered only when based on knowledge of individual processes contributing to a specific phenomenon and expressed through adequate equations to be computer-processed. Strictly speaking, simulation models may be of an empirical character, being based on estimated knowledge of the modelled processes, or of a mechanistic character based on well defined and scientifically substantiated such processes. In fact, most of the existing simulation models have a mixed character, with many of the included submodels of mechanistic character but also including at least some submodels of empirical character. Simulation models may refer to strictly soil processes and phenomena, but most often they include a larger area, as the SPAC (soil - plant - atmosphere continuum), a kind of models describing the flux of water within this continuum and its role in photosynthesis and consequently in crop development and yield. The first of these simulation models were developed in The Netherlands: BACROS (de Wit, 1965), focusing on leaf photosynthesis, ARID CROP (Van Keulen, 1975), suitable for arid areas and SWATR (Feddes et al., 1978) with successive improved versions. More or less similar models were developed in the USA, e.g. CERES (Richie, 1985) with several versions adjusted to different crops, in Romania (SIBIL, Simota, 1992) etc. Later simulation models have been developed in the UK for estimation of the soil organic carbon content changes under different management practices (Powlson et al., 1998), and in different other countries for simulation of nitrogen (PAPRAN, Seligman a. Van Keulen, 1981) and other nutrients behaviour (CENTURY, Parton et al., 1988)for solute transport in soils (Simunek et al., 1994; Simunek and Van Genuchten, 1994) and for other soil processes. Use of some of these models in erosion and compaction studies, as well as specific models devoted to these fields of soil science, will be discussed later.

Estimation procedures for non-directly determined soil properties are more recently known as pedotransfer functions (Bouma et van Lanen, 1987) classified as either continuous pedotransfer functions (equations enabling calculation of actual figures for the estimated soil property) or class pedotransfer functions (petrotransfer rules) which allow only establishment of a class of such figures. For continuous pedotransfer functions not only regression equations are used, but also more recent procedures as spline functions and especially neurone networks. While use of continuous pedotransfer functions is based on an existing more or less exact set of input data, for pedotransfer rules the input may be restricted to more general information as soil taxa or texture class. Continuous pedotransfer functions are frequently used in simulation modelling, while class pedotransfer functions are more often used to add new information in soil survey. Recent developments have extended the procedures used for estimation of non-determined soil properties, namely through spline functions (Erh, 1972) and especially through application of the neural network concept (e.g. De la Rosa et al., 1999).

The development of databases, simulation modelling and pedotransfer functions is closely related to the advances in soil survey and in editing and using soil maps. Classical such maps, based on field studies, description, sampling and analysis of soil profiles and correlation with landscape characteristics knew a significant progress with advent of aerial survey and, more recently, of remote sensing. Introduction of computers in soil mapping, digitising of these maps and creation of soil geographic information systems is nowadays widespread. Correlation of the databases with the GIS maps, extension of pedotransfer functions to develop new attributes and new sheets to these maps is becoming one of the main procedures and fields of interest in soil science. SSURGO at individual soil survey level, STATSGO at state level and NASIS at whole country level in the USA, subdivided in 17 major land regional areas (Soil Survey Centennial, 2000), EUSIS for the whole of Europe (Finke et al., 1998; Le Bas et al., 1998), FISBo BGR in Germany (Adler et al., 1998), LandIS in the UK (Bullock and Jones, 1996), a similar one in Romania (Rauta et al., 1998) are among the general soil databases, comprising a more or less complete set of morphological, physical, chemical a.o. properties of various contours on soil maps. Another example of application of these procedures is in progress, consisting in linking the agroclimatic IMPEL model (Rounsevell et al., 1998) and soil erosion and soil compaction models (SIDASS, Horn et al., 2000) with GIS soil databases and regional climatic data, giving the opportunity to use such simulation models on a regional, a continental or a whole world scale. Drawing of maps related to specific soil properties with use of geostatistical procedures are being tested (Simota, 1990; Paltineanu et al., 1999), even if existing data are for the time being not enough, except perhaps for very small size maps.

Use in practice of information included in databases or GIS, included those resulted from simulation modelling and pedotransfer functions, is certainly the development of expert systems and especially of decision-support systems directed to both decision makers and even to individual farmers.

Simulation modelling and databases on soil erosion

The first well known model describing the soil water erosion process and enabling estimation of the soil loss through erosion under various natural and management conditions was the USLE (Wischmeier a. Smith, 1978), developed in the USA, later improved as MUSLE (Cooley a. Williams, 1985) and then, as it is used nowadays, as RUSLE (Renard et al., 1997). All of these models are mainly empirical ones, based on an enormous number of field determinations conducted on a large variety of soils, climates and landscapes using either experimental plots of standard size with various crops and management techniques or a mobile rainfall simulator able to produce rain drops of various intensity and to record infiltration, runoff and erosion. They refer to estimation of average yearly soil loss at the watershed base produced both by rill and sheet erosion. The original USLE model is:

$$A = f(K\ R\ L\ S\ C\ P)$$

where A is the average annual soil loss (t ha^{-1} yr^{-1}), K - the soil loss (t ha^{-1} yr^{-1}) on a standard plot 22.1 long, 9 percent slope gradient and continuously managed as clean fallow, R - a rain erosivity factor, L -a slope length factor, S - a slope gradient factor, C - a cover and management factor and P - a soil conservation techniques factor.

A variant of the USLE model had to be developed in Romania (Motoc et al., 1973) as some of the input data needed to calculate rain erosivity in the USA were not available in this country. This form of the model is:

$$E = f(K\ S\ C\ Cs\ L^m\ I^n)$$

where E is the average yearly erosion loss (t ha^{-1}), K - the coefficient of climatic aggressivity available on special maps of the country, S - the soil erodibility factor, C - the soil crop factor, Cs - the soil conservation practice factor, L - the slope length (m) and I - the slope gradient (percent). On slopes with a length between 20 and 100 m the effect of the slope length and gradient (t ha^{-1} is used as resulting from $L^{0.5}$. $I^{1.4}$, this procedure simplifying a lot of the whole calculation.

A quite different soil water erosion developed, also in the USA, in a later stage, is WEPP (El-Swaify, 1989), a mechanistic model based on a more or less theoretical study of the various processes contributing to erosion. The model is considering both rill and interrill contribution to soil erosion It is permanently improved, as the various processes considered are each studied in specific research projects, often using laboratory equipment consisting in specific soil channels, rainfall simulators and recording devices. Field experiments and adequate observation in eroded areas are used in such research, and of course also for validation of the model.

More complex models include, besides soil loss, estimation of productivity of variously eroded crops (the EPIC model, Williams et al., 1983) or the relationships between the erosion and the soil pollution processes (the CREAMS model, Knisel 1980). ANSWERS (Beasley et al., 1982) is a soil erosion model taking into account this process on large catchments.

The KINEROS model developed in the USA (Woolhiser et al., 1990), as well as the European EUROSEM model (Morgan et al., 1998), were more recently developed predicting rill and interrill erosion at the level of single storm event.

Many of these models have been successful tested and validated in different countries e.g., in Romania, the WEPP and the EPIC models (Popa, 1999).

As for wind erosion, the main model now used (in the USA) is WEPS (Hagen et al., 1996), a mechanistic model which takes into account the main soil,. climate, land roughness, vegetation cover and other factors affecting this process. As for the WEPP model, each of the included submodels is studied in detail for its permanent improvement. Such research is mainly conducted with the use of specific laboratory equipment consisting of wind tunnels where various soils and different wind parameters are introduced, while blown-out and re-deposited soil is recorded. Field work for both similar research and for validation of results is also carried on.

Development and wide used of simulation models in soil erosion made necessary establishment of adequate databases. In the USA, soil properties for each of the ca. 20,000 soil series and climatic parameters for a large number of meteorological stations have been included in such a database, and these data may be directly called as input in the computer software processing most of the soil erosion models.

Databases and simulation models on soil compaction

Over-compaction of the upper soil and of subsoil layers is a degradation process relatively more recently taken into account, being a consequence of mechanisation of agricultural operations and especially of increase in the weight of equipment used. Negative effects of compaction on water regime, on crop yields and on fuel and labour consumption, as well as the difficulties in reclamation of compacted soils and subsoil are not negligible. More than other degradation processes, compaction is strongly related to soil mechanical properties which are seldom determined, estimated or included in databases. Research on various aspects of soil compaction have been conducted in many countries and their results have been published (Soane, 1983; Soane a. Van Ouwerkerk, 1994; a special International Conference edited by van Ouwerkerk, 1991) and various papers in different other journals), but an evidence and a processing of all existing results is missing.

These are some of the reasons while the European Community decided to support two Concerted Actions, planned similarly as to be able to lead to unique final products. They are entitled “Experience with the impact of subsoil compaction on soil crop growth and environment and ways to prevent subsoil compaction” and aim at providing such an evidence, at least for research carried on in Europe (Van den Akker a. Canarache, 2000). One of the two projects, within the FAIR Programme, included 34 institutes in 17 countries of Western Europe, while the second one included in the INCO-PROJECT Programme 18 institutes in 13 countries of Central and Eastern Europe. Both Projects, now in their final stage of completion, have to produce two databases: one for literature and a second one for experimental data, including soil mechanical properties. This second database is closely correlated with the EU Soil Profile Database. Besides the two databases, both Projects will produce a brochure and/or a CD-ROM, as well as two special issues of the well known Elsevier journal Soil & Tillage Research, with concluding reports on causes, processes and effects of compaction, ways to rehabilitate compacted soils and proposal for further research needed to solve still unknown aspects of the soil compaction problem. Even if not specifically mentioned in the original Project plans, items related to simulation modelling, pedotransfer functions and mapping of soil vulnerability to compaction have been approached.

The general flowchart relating these various aspects is to some extent different from the one already shown in Figure 1. In soil compaction simulation modelling should include at least two parts: the compaction process itself and the effect of compaction on crop yields (see Figure 2).

The two mentioned databases have been originally completed in Excel software: for the literature database one workbook for each partner, with as many sheets as literature sources; for the experimental; database, one workbook for each experiment field and each year of the experiment (or analysed soil profile), with 34 sheets each including one group of data (general data, soil description, climate and weather, soil management, resulted soil physical, mechanical and chemical data, crop yield and crop growth characteristics etc.). Some 1700 literature sources and some 800 workbooks with experimental data have been already included in the databases. At present the Excel workbooks are transferred to the Access software, thus making possible their sorting and processing according to various criteria. In the next future such processing as statistical calculations, graphical representations a.o. are envisaged.

Simulation modelling of the compaction process is at present in its initial stage. The SOCOMO model (Van den Akker, 1988), a finite elements model (Mouazem a. Nemenyi, 2000), a larger discussion on data required in soil deformation models (Koolen a. van den Akker, 2000) and another one on general aspects ofd compressibility (Horn and Lebert, 1994) are all based on classical knowledge concerning stress distribution and relations between stress and soil volume changes. More advanced are the procedures for simulation modelling of the effects of compaction on the soil water regime and on crop yields. Several models simulating the soil water regime and crop yields have been adjusted, introducing or emphasising bulk density and/or resistance to penetration (PENETR, Canarache, 1990) as input factors, and as such became adequate for a good evaluation of compaction effects. Two such models were tested with good results: SIMWASSER (Stenitzer a. Murer, 2000), developed in Switzerland, tested within the FAIR Project, and SIBIL (Simota a. Canarache, 1998; Simota et al., 2000), developed in Romania, tested within the INCO-COPERNICUS Project.

Soil mechanical properties are not effectively determined to allow a good knowledge of these properties, of their variability in various soils and of their relationships with other soil properties. Pedotransfer functions estimating soil mechanical properties are of such of great interest. Such estimation procedures have been developed in Germany and their testing with determined data collected in the FAIR and INCO-COPERNICUS Projects is being done. A relatively large collection of data is available in Romania and are to be used to this aim, possibly developing some new pedotransfer functions, but unfortunately these data come from engineering laboratories and refer only to lower soil horizons.

Use of existing soil maps and of the present knowledge on compaction process and on its causes made possible preparation of maps of soil vulnerability to compaction. One of this maps (Jones et al., 2000) makes use of the EU Soil Map of Europe and of a relatively reduced set of attributes available on this map, while the other one (Canarache a. Dumitru, 2000) refers only to one country, Romania, thus disposing of a larger set of input data. Comparing and possibly reciprocally using some of the procedures developed in these two maps could perhaps lead to a unique, improved methodology.

Some difficulties to be met in further actions related to databases, pedotransfer functions and simulation modelling

The relatively new procedures much developed since computers became a current equipment in research resulted in a significant progress in various fields of science, including soil science. Nevertheless, there are still several matters not yet good enough solved which need more attention to allow a better use of these procedures.

The main difficulty is probably the lack of standardisation of the data to be stored in databases or used in simulation modelling and in geographical information systems. There are still differences in concepts concerning several soil properties (e.g.: should we use classical soil moisture constants, water retention curves, or both of these?). Much more, there are serious differences in determination methods which often lead to completely non-comparable results: pre-treatment of soil samples for particle-size analysis, and even size of various particle-size classes are an example. Even if there are no such differences, the amount of data available in different countries (and even in different areas of the same country) could become a problem in tending to generalise research methods and results.

Some of these difficulties could theoretically be overcame using pedotransfer functions. Unfortunately, for the same reasons as some of these discussed above, use of such functions developed in one country, using specific concepts and methods, is often not applicable to other countries. Moreover, even when the same concepts and methods are considered, variation of parent material, mineralogy, other soil properties, climatic conditions etc. between different areas could make impossible reciprocal use of such functions in different areas.

Validation of pedotransfer functions and, moreover, of simulation models, with experimental data is to be considered as an important pre-condition before generalising the use of these procedures. Lack of enough validation is probably one of the reasons why some scientists are reluctant to the use of modelling, why perhaps some other scientists are too confident in such modelling, not giving enough attention to proper validation.

Conclusion

Recent development of computer-based techniques proved to be of great help in improving research and practical use of results in many fields of science, including in soil science and, as the main objective of this paper, in erosion and compaction studies. Nevertheless, much is till to be done in order to get all that could be obtained using these procedures. Moreover, best results should not mean renunciation to many of the previous techniques, but just a correct of both of them.

Figure 1.

Relationships between databases and data processing (simulation modelling, maps) frequently used in soil science

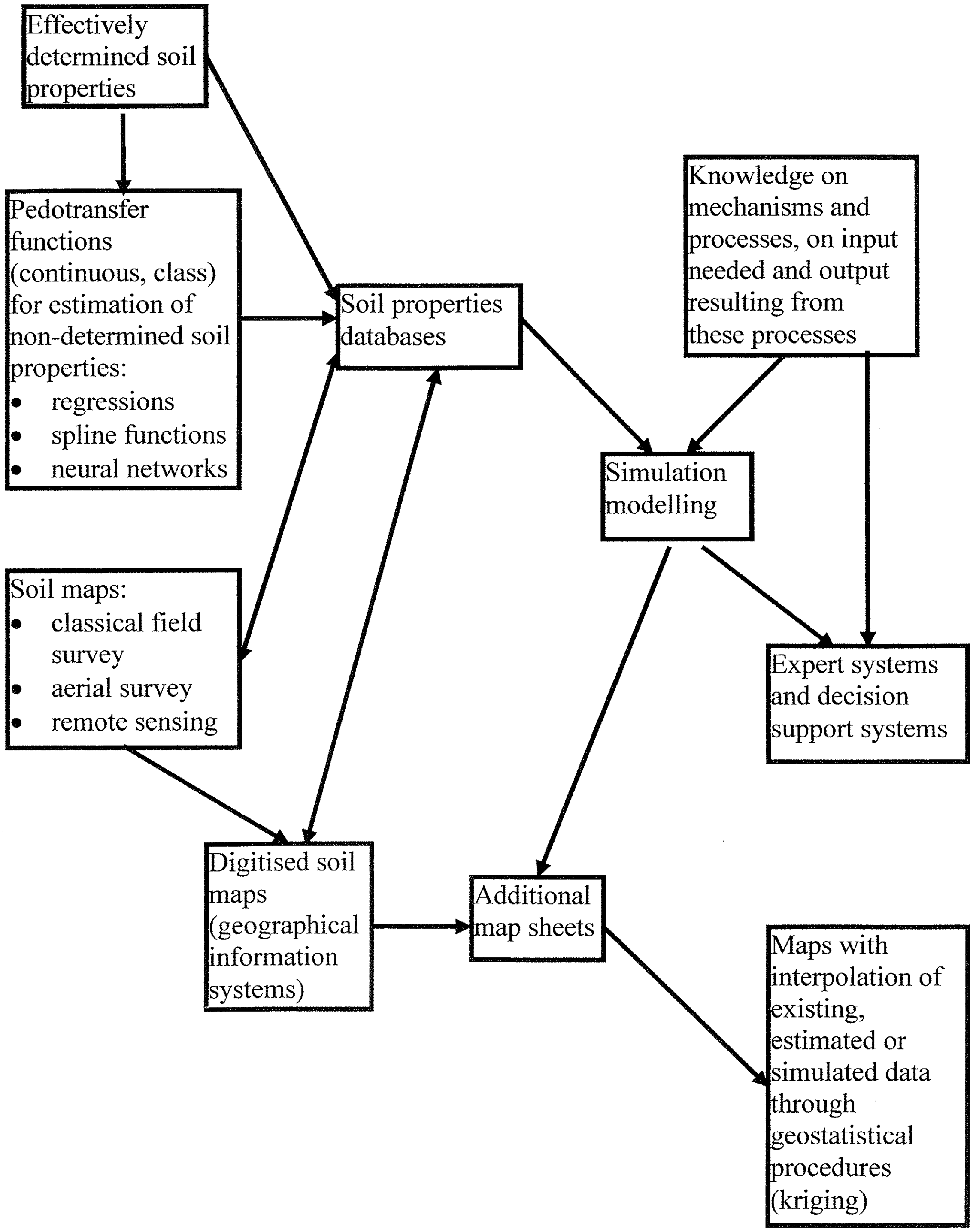
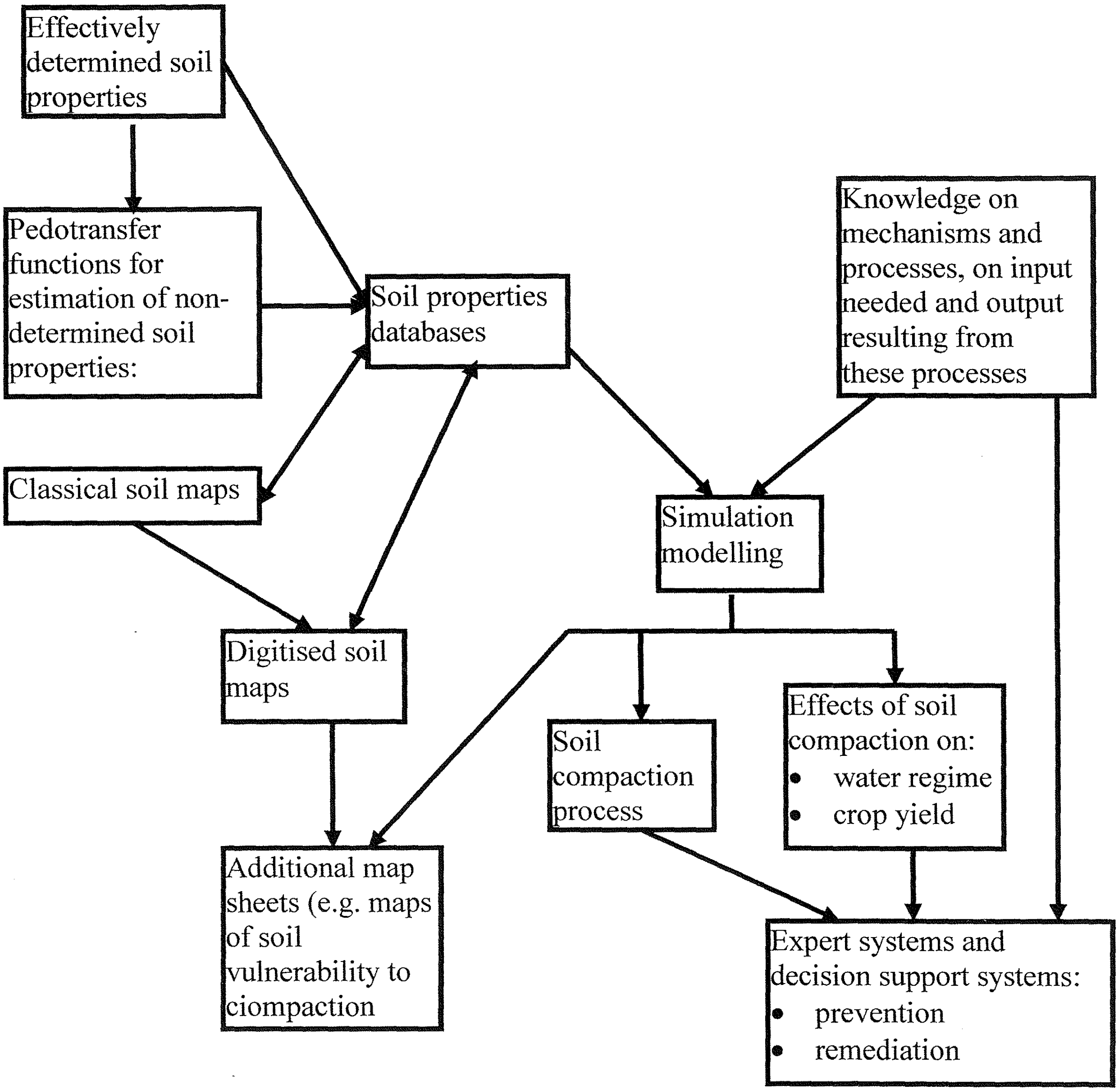


Figure 2.

Relationships between databases and data processing (simulation modelling, maps) frequently used in soil compaction research



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