SOIL QUALITY AND SUSTAINABILITY EVALUATION

AN INTEGRATED APPROACH TO SUPPORT SOIL-RELATED POLICIES OF THE EUROPEAN UNION

- A JRC POSITION PAPER -

Gergely Tóth, Vladimir Stolbovoy, Luca Montanarella

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EXECUTIVE SUMMARY

The optimization of soil resources use towards maximization of use-efficiency (increased competitiveness) and minimization of environmental degradation risk (sustainability) is a main challenge to European policies (COM(2006)231, COM(2006) 232).

The principles of sustainable soil use are well documented in the Thematic Strategy for Soil Protection, the basic soil-related document of the European Commission.

Soil quality and sustainability evaluation is a fundamental concept bridging between the utilization and protection aspects of soil-use planning.

A framework and definitions for evaluating the quality and sustainable use of soil resources is developed for applications in the European Union in the support of the Thematic Strategy for Soil Protection.

The method for evaluating soil quality is designed fully flexible in order to link it with the evaluation of degradation threats. Based on the evaluation procedure, three main indexes in the sustainable soil-use domain are calculated:

1) Soil Quality Index
   - to express the ability of soil to perform ecosystem and social services
2) Soil Threat Index
   - to express the level of risk on which the soil is exposed to degradation threats
3) Soil Sustainability Index
   - for the comparative measurement of soil quality across a gradient of stress or disturbance

Sustainability analysis of soil-use can be performed for any individual soil function or groups of soil functions in defined land use systems in a comparative manner, taking the potential effects of degradation into account.

The full applicability of the concept in supporting soil-related policies in the European Union is illustrated by the evaluation of biomass production and major soil threats (erosion, decline of organic matter).

ABBREVIATIONS

CDE: Cumulative Degradation Effect
DI: Degrading Impact
LFA: Less Favoured Areas
SC: Soil characteristics
SFA: Soil Functional Ability
SQ: Soil Quality
SQI: Soil Quality Index
SRP: Soil Response Properties
SSI: Soil Sustainability Index
STI: Soil Threat Index

1. BACKGROUND

Recognizing the extent of soil resources degradation and associated environmental and social risks in Europe, the European Commission proposed a Thematic Strategy for Soil Protection (EC 2006a). In the Strategy, human activities, such as inadequate agricultural and forestry practices, tourism, urban and industrial sprawl and construction works are named as the main impacting factors that prevent the soil from performing its services to society and ecosystems on required levels. These services rely on the key soil functions, which are identified as

- Biomass production
- Storing, filtering and transforming nutrients, substances and water
- Biodiversity pool such as habitats, species and genes
- Physical and cultural environment for humans and human activities
- Source of raw materials
- Acting as carbon pool
- Archive of geological and archaeological heritage

Direct degradation threats to soils are manifold, among which erosion, salinisation, compaction, loss of organic matter, landslides, contamination and sealing have major impact on soil in Europe, therefore are in the focus of the Strategy.

Decline of soil fertility, carbon and biodiversity; lower water retention capacity, disruption of gas and nutrient cycles and reduced degradation of contaminants are among the results of soil degradation processes. Soil degradation has a direct impact on the quality of water and air. Through its influences on food chains and climate change, soil degradation hinders biosphere functioning. It directly threatens food and feed safety as well.

To ensure sustainable use of soil is the main objective of the Strategy. This has to be done by integration of soil protection policy to other policies of the European Community on, inter alia, agriculture, regional development and energy.

In order to facilitate this integration, a common framework to assess soil functions, degradation threats and soil-use options in the perspective of sustainable development is discussed in this document.

2. INTRODUCTION

The long-term development of global socio-economic systems requires the sustainable use of natural resources. This paradigm is fundamental in the well established concept of sustainable development defined in the report of Bruntland (1987) which states that sustainable development is development that "meets the needs of the present without compromising the ability of future generations to meet their own needs". The International Institute for Sustainable Development (1996) proposed a Sample Policy Framework which includes a sustainability index that "would give decisionmakers tools to rate policies and programs against each other". In the last decades, with the progress of the sustainability paradigm, the formulation of metrics and indices of sustainability of systems (social economic and environmental systems) and sustainable development evolved and produced comprehensive indexing methods (Brown and Ulgiati 1999, Esty *et al.* 2005). During the same time, based on the results of corresponding scientific research and available information (Blum 2003, Heinecke *et al.* 1998, Jones *et al.* 2005, Le Bas and Jamagne 1996, Van-Camp *et al.* 2004) major development of soil conservation policy is taking place in the European Union (EC 2002, 2006a,b). These developments provided a framework to formulate sustainability perception applicable for soil-use and conservation planning.

The sustainable use of soil resources depends on three factors: soil characteristics, related environmental (climate, hydrologic etc.) conditions and land use. These factors interact on a systems-based principles, where the change in one factor causes alteration in the others. Therefore the sustainable use of soil resources is a dynamic category. It is important to assess our soil resources from this standpoint and consider soil as the prime object of sustainable use in relation to land management under given (changing) natural conditions. This approach needs to be an integral part of land use planning and decision making on different levels, ranging from the local to European scales.

In response to this issue, the need for understanding and management of soil resources in a sustainable manner is central to several pan-European environmental policies. The Sixth Environmental Action Programme required the European Commission to prepare a Thematic Strategy for Soil Protection. The supporting Communication (EC 2006a, adopted by the European Commission on 22.09.2006) sets the overall objective of the Strategy for Soil Protection through a proposal for a Framework Directive (EC 2006b) that establish common principles for protecting soil functions against a range of threats.

One of the key goals of the Strategy is to maintain and improve soil health. The Directive is supported by an Impact Assessment (EC 2006c and EC 2006d) that

contains an analysis of economic, social and environmental consequences of different options for soil protection.

To answer the challenge of soil resource degradation, there is an urgent need to develop a common, simple and transparent method to identify the possible changes of soil characteristics of the European Union together with the soil-use options adaptable in response to these potential changes.

The overall goal of this paper is to develop a framework and definitions for a systematized soil quality assessment that can be applied for the integrated assessment of sustainable soil-use. Besides an introduction of the concept of soil quality-sustainability system, examples illustrate the evaluation process.

3. THE CONCEPT OF SOIL QUALITY

Variety of landscapes, land use traditions, social environments, scientific schools, languages and many other factors has resulted in a diversity of definitions and understandings of the concept of 'soil quality' in Europe. Complex approaches to describe soil (and land) quality through the multifunctional nature of soil (and land) appeared in the second half of the 20th century worldwide, giving the frame for a possible common scientific understanding of the problem. One of the first widely accepted definitions was published by FAO (1976) describing land quality as „a complex attribute of land, which acts in a distinct manner in its influence on the suitability of land for a specific kind of use". As one replaces the word 'land' with 'soil' in this statement, an acceptable definition for soil quality appears[1]. However, this definition would be too broad to serve practical policy support.

In scientific literature as well as in policy supporting background documents 'soil quality' is often cited as a state indicator that describes the 'quality of the soil' (Bouma 1997, Karlen *et al.* 1997, Máté and Tóth 2003, Van Camp *et al.* 2004). However, neither in the soil science community nor among planners and land users does a

[1] There is an important need to distinguish between soil and land quality. Land comprises all elements of the physical environment, including climate, relief, soil, hydrology and vegetation, as well as includes the results of past and present human activity (FAO 1976). Soil is one compartment of the physical environment (land) and receives the influence of its other elements. In this respect, soil is examined as a subset of land and its characteristics are determined by other land forming factors. Meanwhile soil is also regulating environmental processes, thus influencing other elements of the physical environment. The present approach follows the perception of classical soil science and considers soil as a medium that integrates, transforms, stores and filters material (and energy) relevant to its environmental and management conditions in the spatial context. Soil, on the other hand, is a medium that is challenged by changing environmental and management conditions, therefore variable in time as well.

common agreement exist on the meaning of the term ‘soil quality’. Since the ‘quality’ of soil in the broadest sense means the ‘degree of excellence’, the diversity of interpretations originate from the specific viewpoint and motivations of the user of the term (“specific kind of use”). This phenomenon illustrates that ‘soil quality’ can not be the same for different purposes and only on a higher level of aggregation of different qualities may represent the sum of perceptions.

To overcome the confusion and often controversial use of the term soil quality, a revision of comparative analyses made on the topic (Karlen *et al.* 2001; Letey *et al.* 2003; Nortcliff 2002; Sojka and Upchurch 1999; Tóth 2000) was carried out, including the purposes of soil quality assessment, definitions of the term soil quality, methodologies of soil quality assessment and applications of the concepts. A harmonization effort was than made to meet the requirements of the soil related policies of the European Union, which are summarized in the Thematic Strategy document (EC 2006a). In conclusion comprehensive terminology and definitions have been developed to meet the needs of policy development related to soil quality, degradation threats and sustainable soil-use in Europe. (For terminology and definitions see Table 1.)

Embodiment of the soil quality concept in the context of European Community policies offers an integrated approach which links soil functions and degradation threats with the perspective of sustainable soil-use.

In this approach, soil quality description is based on the performance (potential) of soil functions through an assessment of corresponding (primary, secondary etc.) land use goals. With the consideration of soil dynamics as responses to human or natural impacts soil quality can be comprehensively characterized. This characterization allows the sustainability of the soil-use system to be assessed.

3.1 SOIL FUNCTIONS

Soil, a non-renewable natural resource, has several functions in the biosphere and for humans. It is a reactor, transformer and integrator of material and energy from other natural resources (solar radiation, atmosphere, surface and subsurface waters, biological resources), a medium for biomass production; storage of water, nutrients and heat; natural filter and detoxication and buffering system; an important gene-reservoir; and a medium of past and present human activities (Blum 2005, Nortcliff 2002, Várallyay 1997).

Soil functions are general or specific capabilities of soil for various agricultural, environmental, landscape and urban applications. Specific soil functions are manifold and may be grouped according to the principal purposes

In the soil protection strategy (EC 2006a), the main functions are identified as

- biomass production
- storing, filtering and transforming nutrients and water
- hosting the biodiversity pool
- acting as a platform for most human activities
- providing raw materials
- acting as a carbon pool
- storing geological and archaeological heritage

These functions are performed on different levels and are determined by inherent soil characteristics (e.g. texture, organic matter content, pH, cation exchange capacity, porosity etc.) and external environmental (climate, terrain, hydrological, biological) and anthropogenic (soil-use and management) factors.

To assess the performance of soil functions, different purpose-specific measurement and modeling techniques can be applied. Land evaluation is one of the traditional tools. Early land evaluation methods (FAO 1975; Bouma and Bregt 1989) were associated mainly with the measurement of biomass production function (crop growing potential) of agricultural lands.
Although the basic FAO Framework for Land Evaluation (FAO 1976) - the initial for a number of land evaluation systems worldwide - provides guidelines for multicriteria "purpose oriented" evaluation, these guidelines are insufficient for the current needs of multicriteria multipurpose assessments.

With the evolvement of the paradigm of sustainable development recent applications of land evaluation tend to include a combination of different aspects and performance

characteristics of soil-use (Gaál *et al.* 2003, Vrscaj 2006), through the involvement of a number of specific functions in the evaluation process. These approaches attempt to provide a comprehensive answer to current needs of the society and represent state of the art scientific knowledge, which are supported by modern soil databases, soil inventories and monitoring at different scales and supplemented by the modern tools of information technology.

3.2 SOIL DEGRADATION THREATS

Soil is essentially a non-renewable resource with possible high rate of degradation and extremely slow rate of regeneration processes. Degradation deteriorates soil quality by partially or entirely damaging one or more of its functions (Blum 1988). Degradation processes occurring in Europe are widely studied (Batjes and Bridges 1993, EC 2006c, EEA 2000, Kirkby *et al.* 2004, van Lynden 1997, 2000) and incorporated to soil protection policies on national (Kraemer *et al.* 1999) and European levels (EC 2006a,b). The focus of policy actions is the reduction of risk of soil degradation. Risk of soil degradation depends on soil and terrain properties which make the soil inherently receptive of degradation. Van Camp *et al.* (2004) provide substantial knowledge towards identifying and describing hazards (threats) to soil. The work of Eckelman *et al.* (2006) summarizes the risk assessment methodologies applicable for soil degradation studies (Annex I.) and applies the concept of threats to represent the hazards endangering the functioning of soils.

The Thematic Strategy for Soil Protection (EC 2006a) declares that for sustainable development, soils (soil functions) need to be protected from degradation. The main threats to soil functioning abilities are identified as

(1) decline in organic matter	(2) soil erosion	
(3) compaction	(4) salinisation	(5) landslides
(6) floods	(7) contamination	(8) sealing

Threats 1-5 are area (and soil) specific in their appearance, therefore, they require additional spatial consideration during soil conservation planning.
Risk identification for these major soil threats – which have definite environmental and spatial dimensions – in the European Union is proposed by Eckelmann *et al.* (2006). For each area-dependent threat, the following conditions have been examined in order to define common criteria of risk identification throughout Europe:

- identification of factors/hazards related to threat (‘external’ factors),
- characterization of receptor (‘internal’ attributes),

- performance specification, model selection (with data requirements).

In order to identify and describe areas at risk to soil threats in the "Common Criteria" document, Eckelmann *et al.* (2006) proposes three types of approaches:

1) qualitative approach: land use in combination with "sensitive soils", or other political boundaries using other combined criteria, e.g. nitrate pollution, intensive cropping areas, urban areas, etc.;
2) quantitative approach: thresholds;
3) model approach: in the absence of monitoring data, the potential for soil degradation can be assessed [in the presence of monitoring data and in combination with 1): regionalization/upscaling of plot data].

For the application options the Common Criteria document provides explanations of the above approaches, articulating that thresholds initially require that reasonable values are available beyond which degradation of soil properties limits sustainable functioning of the soil. Data from soil inventories or monitoring must be available in a further step, in order to match observed values with thresholds. Even if thresholds, status and trends are based on models, soil inventory/monitoring data are still needed. The model approach needs to be eventually supplemented by a quantitative approach: not only for model validation and calibration, but also in order to detect the area where the degradation actually occurs, and to observe the trend after the implementation of measures. Models can also help in approach 1) and 2) to regionalize soil information, from the plot-level to the area/region.

On the bases of the overview of the conditions above cited Ecklemann *et al.* (2006) proposes a list of requirements that should be fulfilled in order to have a common bases for comparison the soil degradation risk in the member states of the European Union. These requirements are summarized in Annex II.

4. THE CONCEPT OF SOIL SUSTAINABILITY

Sustainable soil-use refers to "the use of soil as a natural resource on a way that does not exert any negative effects - that are irreparable under rational conditions - either on the soil itself or any other systems of the environment" (after Tóth 2003, 2004).
The sustainability of soil-use can be achieved by the practical methods of management and can only be guaranteed if the material and energy flow associated with soil processes are controlled and positively influenced. This means the management and maintenance of certain level of soil characteristics, which eventually embrace soil quality as well.

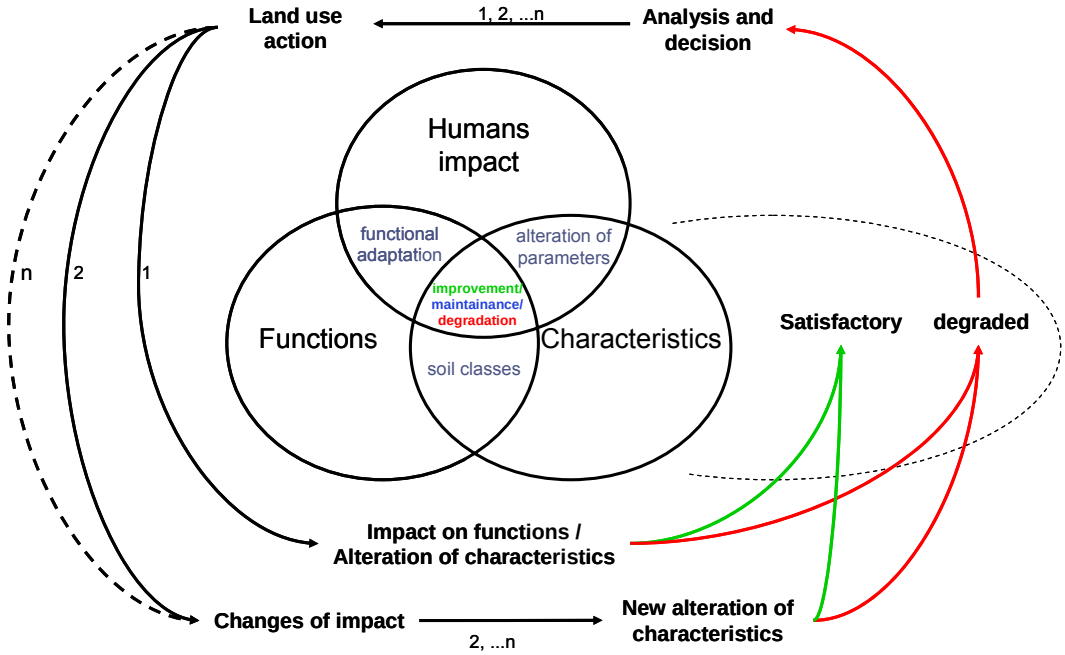

Figure 1. The soil quality loop. *Humans affect soil functions and characteristics (their adaptation or alteration). Soil functions together with soil characteristics are aggregated in soil classes. Land use yields satisfactory or degraded soil functions/characteristics. In the case of satisfaction the human's task is limited to the maintenance of the status quo. In the case of degradation the decision should be taken to modify land use in order to improve soil functions and properties. The loop indicates the necessity of adjustment of land use practices appropriate to the optimal and sustainable utilization of soil functions. Optimal and sustainable soil-use aims to maximize satisfactory and minimize degraded parameters of soil characteristics. Alteration of soil characteristics by human impact may change functional ability of the soil. The maintained, improved or degraded quality thus depends on the human impact and soil characteristics from the perspective of the soil function of interest.*

Among the factors influencing soil-use at the local level (cadastral scale) - apart from social and economic factors - the ecological conditions of the plot, the effects arising due to soil-use and management and the existing associations to the surrounding areas (potential mutual effects) need to be emphasized. The link to surface and underground water and the atmosphere is important or might become significant. The later

components need a special accent since the approach summarized in Figure 1. can support *inter-alia* climate change analysis and mitigation planning as well.

Long-term influence of human impact (by land use change; amelioration/restoration measures; degradation effects) on the ecological conditions of soil as well as the seasonal soil-use operations (drainage, cultivation, irrigation, nutrient management etc.) modify material and energy flows, resulting in the transformation of the pedogenic processes at smaller or greater extent. When these processes are traceable, controllable, soil-use and soil quality remains sustainable in the long run (Figure 1).

The society needs simple measurements to compare the options for utilizing soil functions and measuring the risk of that particular utilization to soil degradation processes. Soil quality assessment can serve as a basis of this comparison and shoul be one of the main criteria for planning and practicing sustainable soil-use.

Although, not the sole basis of decision-making, soil quality can have an important input to various policy development considerations. The most important questions of soil-use related decision-making (Várallyay 2002) can be answered on the bases of soil quality assessment:

- What are the potential land use alternatives under the given conditions, taking into consideration the requirements (biomass production for food, fodder, industry, energy; meaningful work for the local rural population; exploitation of mineral resources; place for building construction and infrastructure; drinking water supply; place for recreation, sport; aesthetic landscape; conservation of biodiversity, etc.) and the natural conditions (elements of the ecological potential: climate-weather, relief, water resources, soil, biota, vegetation)?
- What are the potential and actual efficiencies of the various alternatives (based on a comprehensive and realistic cost/benefit analysis)?
- What are the predictable ecological and economical risks (risk analysis) and environmental consequences and potential side effects (impact analysis)?

The answers to the above questioned complicated problems are complex. The comparability of different alternatives requires a new integrated approach in which the synthesis of the results of soil quality evaluation is recommended.

5. EVALUATION OF SOIL QUALITY, SOIL THREATS AND SOIL SUSTAINABILITY

Relationships among the components of the soil quality/sustainability system are quite complex. In order to arrive at an applicable framework, before parameterization of the soil quality and sustainability concept this relationships had to be clarified and described (Figure 2.). To achieve a clarification, there was a need for clear terminology supported by concise and comprehensive definitions. The terminology and definitions suggested in this document have been designed to the specific needs of the EU's Thematic Strategy for Soil Protection, taking into account the corresponding state-of-the-art scientific literature. (Table 1.)

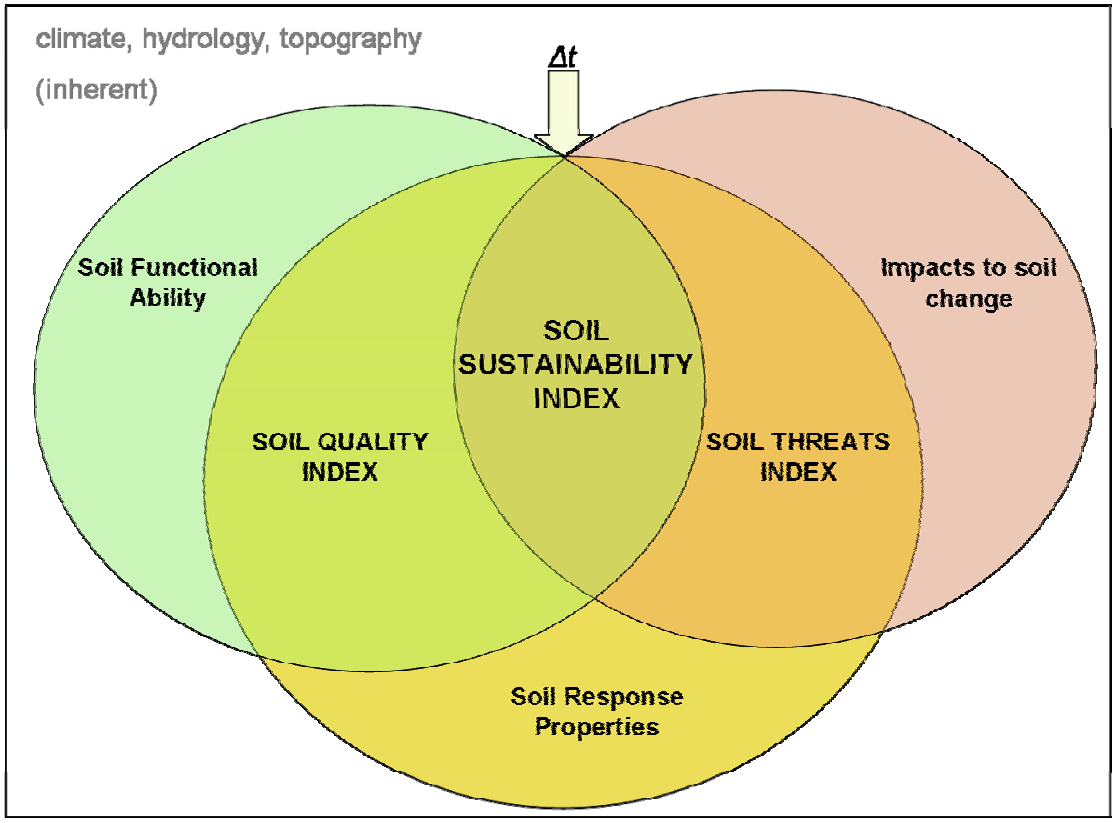

Figure 2. Clusters of soil sustainability. *Soil sustainability (valued by Soil Sustainability Index) reflects on the interactions of soil functions and the impacts on them, taking soil response properties and time into account.*

Table 1. Glossary of the soil quality/ sustainability system

Soil Functional Ability (SFA)
The SFA refers to the number and composition of functions a given soil is able to provide and the level on which functions are provided.
Soil functional ability covers a wide range of scales. On the highest level of aggregation it is related to the seven major soil functions outlined in the Thematic Strategy for Soil Protection of the European Union.

Soil Response Properties (SRP)
The SRP are particular characteristics that determine the soil's responses to environmental (or human) influences and thus mark different potentials of Soil Functional Ability.
SRP determine both the direction and magnitude how soil responds to a disturbance or change.
Soil types can be grouped according to their functional response properties (of known mechanisms) for land use planning applications.

Soil Quality (SQ)
Soil quality is an account of the ability of soil to provide ecosystem and social services through its capacities to perform its functions and respond to external influences.
The term soil quality encompasses a broad spectrum of features and considers → functional ability together with the → response properties of the soil. SQ is therefore provides a complex information on the sum of different soil characteristics, with regards to the level of ecosystem services a soil can provide.

Soil Threat Index (STI)
The STI is a composite indicator of degradation-related Soil Response Properties and external factors (climate, land use) expressing the level of risk on which the soil is exposed to the main degradation threats.
For applications in the EU, STI refers to the (comparative risk of) five major threats (erosion, salinization, compaction, loss of organic matter, landslides).

Cumulative Degradation Effect (CDE)
CDE is the result of cumulative stress. Cumulative stress marks the gradient of degradation.
CDE represents the extension of Soil Threat Index with the time factor (Δt).

Soil Sustainability Index (SSI)
Comparative measure of Soil Quality across a gradient of stress or disturbance.
The expression also contains the stability of soil characteristics in time and the internal and/or external environmental interactions of soil, thus it also relates to the degradation threats.
Within the context of the Soil Protection Strategy of the EU, Soil Sustainability Index is proposed as an indicator of soil functional ability and degradation-related hazards with a time perspective.

5.1 SOIL QUALITY AND SUSTAINABILITY APPRAISAL

Soil quality is an account of the ability of soil to provide ecosystem and society services through its capacities to perform its functions and respond to external influences.

The ability of soil to perform any of the identified functions (on given levels) depends on its physical, biological and chemical characteristics also referred to as „internal" characteristics. The realization of the performance is conditioned by natural (e.g. slope steepness) and/or anthropogenic (e.g. artificial drainage) factors referred to as 'external' factors. Both internal characteristics and external factors are time dependant. Humans, amongst the most influential players, directly or indirectly transform the performance characteristics of soil thus limiting or enhancing the capacity of the soil to function.
The status of the soil parameters and the risk of negative effects on them are central to the concept of applied soil quality approach (Figure 1). The suggested method of assessment of soil quality recognizes that the relative importance of soil functions is both spatially and temporally dynamic.

In order to evaluate soil quality, soil functions and response properties must be assessed taking into account major influencing factors (climate, hydrology etc.). The Soil Functional Ability (SFA) describes the number of different functions that a soil can perform together with the level of performance, while recognizing the fact that all functions are not equal. (Weighting of the importance of distinguished soil functions in special cases may be a valid option, taken local preferences or potentials into account.)

Soil Response Properties (SRP) condition the potentials of SFA, and complete the description of SQ.

Equations 1-3 below present the formulas to define terms in the soil quality domain.

Soil Functional Ability (SFA) can be defined as:

$$SFA = (F_{i,n} X\ E_{Fi,n})/n \qquad (1)$$

Where:
$F_{i,n}$ are the considered functions from i to n,
E is the efficiency (level) of how functions from i to n are performed individually,
n is the number of functions included in the evaluation.

Soil Response Properties (SRT) can be defined as:

$$SRP = \Sigma f_{i,n} (\Sigma SC) \quad (2)$$

Where:
f is a (non linear) function describing the response (both its direction and magnitude) to an impact, determined by,
ΣSC that represents soil characteristics.

Soil Quality Index (SQI) can be defined as:

$$SQI = SFA \text{ X } SRP \quad (3)$$

Where:
SFA and SRP as defined in eq. 1 and eq. 2 respectively.
Soil Quality Index can be used as an indicator of the 'goodness' of soil with regards to functions and responses.

To define Soil Threat Index (STI) major degradation threats originating from the combination of soil-use, environmental conditions and soil characteristics are matched. The indicator of degradation risk of soil can be defined:

$$STI = SRP \text{ X } DI_{i,n} \quad (4)$$

Where:
SRP as described in eq. 2
$DI_{i,n}$ is the Degrading Impacts, the external factors of degradation (e.g. soil management, climate change) from i to n.

DI can be events of occasional, repetitive or continuous occurrence and represent stress to the receptor (soil). An example for occasional stress is heavy rainfall causing landslide. For repetitive stress, repeated parallel tillage inducing erosion and for continuous stress, atmospheric deposition of contaminants (eg. by motorways). Exposure of soil to DI over a defined period of time result cumulative stress. The impact of cumulative stress on soil depends on the SRPs and eventually on soil characteristics.

The effect of cumulative stress - that might cause a process which may be described with a gradient of degradation – can be described by Cumulative Degradation Effect (CDE), which represents the extension of STI with the time factor (Δt).

Cumulative Degradation Effect is defined as:

$$CDE = STI \times \Delta t \quad (5)$$

Where:
STI as described in eq.4
Δt is the time period of observation

The sustainability of soil-use and preservation of soil resources depends (i) on the ability of soil to perform and maintain its function and (ii) the capacity of soil to respond to impacts over time (iii) under changing pressure of soil degradation threats. Therefore matching soil quality and degradation characteristics with a time horizon helps to evaluate soil sustainability. The result of the evaluation is the Soil sustainability Index (SSI), which can be defined as:

$$SSI = SQI \times (100 - CDE) \quad (6)$$

Where:
SQI is the Soil Quality Index,
CDE is the Cumulative Degradation Effect (the gradient of the degradation processes), which is scaled adversely, on a proposed 100 score scale. Adverse scaling in this equation helps to identify the effect of degradation on the function, and provide a realistic SSI.

5.2 EVALUATION OF SOIL QUALITY AND SUSTAINABILITY

The assessment of soil resources requires the measurement of physical, chemical and biological soil characteristics and processes, followed by the evaluation of the interaction between them, according to specific purposes.

The specification of soil characteristics, their interrelations and their importance for SFA is a complex approach in itself. This approach can be based on soil classifications (Figure 1). However, different classification schemes group soil differently and none of the schemes can meet all purposes. A fundamental soil science considers soil classes matching the processes and mechanisms driving soil formation and geographical distribution; environmental science uses soil grouping according their ecological functioning, biological activity, buffering and water filtering capabilities; technical applications need soil groups according to different building carrying capacities, roads construction, swelling and shrinking properties while agriculture wishes to have information on crop suitability, responses to various chemicals and management practices. The selection of the appropriate soil classification scheme becomes an

important duty for the sustainability framework because by this operation a link between the evaluation and knowledge about the soils related to a specific purpose will be established.

The SFA of a soil is determined by the number and dynamics of soil characteristics In addition, external conditions for individual functions and other factors are also influential and therefore need to be considered. Soil characteristics should be evaluated according to the conditions they provide for the specific function in interest. Actual characteristics might be in favor of or can limit the performance of the function.

In a detailed SFA analysis the assessment of soil characteristics can be carried out to identify the soil characteristics (and/or clusters of characteristics) within the selected soil classes that are most important determinants of the level of performance and to describe the soil-property-driven regulatory principles of material and energy exchange in soils. (See figure 1.)

Soil characteristics are ranked according to their diagnostic role in the different soil classes performance. Soil parameters should also be examined from the viewpoint whether their effect on SFA could be expressed through some other, more easily measurable characteristics (pedotransfer rules) or, if their importance is increasing, in combination with another soil property.

Naturally, the evaluation process could only be carried out by using information that is available in soil maps, databases of soil monitoring and other soil information registries. Therefore, conclusions for complex soil characteristics could only be drawn on the bases of this information.

Relevant soil classifications may apply purpose-oriented methods concerning the soil functional characteristics (e.g. water and nutrient dynamics). Such soil classification schemes should provide a good basis for estimating the ecological behavior of soil.

The degree of loss in functional capacity due to soil degradation (of different kinds) is an interim reaction of different soil types. On the basis of quantitative soil quality evaluation and assessment of the effects of various kinds of soil degradation (erosion, acidification, compaction, etc.) measurements, an integrated method becomes available to express the soil quality - soil threat relationship, thus, soil sustainability.

According to the role of different soil characteristics in the quality of soil classes, correction factors (weighting factors that accent the importance of the characteristics for the evaluated property) can be assigned to each soil parameter during the detailed

evaluation process. These correction factors modify the mean index of the soil class. The correction values of the same soil parameter may vary in the case of different soil classes. 'Average' soil characteristics, can be assigned a correction value of "1" (no correction to the expected quality of the soil class). Characteristics that limit functioning capacity have lower correction values (0.97; 0.88 etc.), favorable soil parameters have correction values higher than 1 (1.02, 1.20, etc). Other scaling methods may be applied as well.

The weights express the relative role of the characteristic in the SFA of the soil class. These weights (or factors) are the control parameters of the SFA evaluation model. By knowing the dynamic properties of soil class, these factors can be used to evaluate the complexity of the soil sustainability system. With this classical land evaluation method, a continuous scale of SFA of different soil varieties can be derived, which spans the lowest to the highest value of the soil type. If required for different scales, on different level of the taxonomic hierarchy.

There are various ways to structure this soil quality evaluation system. However, it is worth structuring the model in such a way that the different aspects of soil quality could be expressed within the same categorization framework, in a clear and comprehensive manner.

The quality of various soil functions should be evaluated on a scale between 1-100 points. The evaluation could be carried out for soil of various (energy and material) input levels. The basic input level - which could be used as a standard for further comparisons - should be defined by a clearly described soil-use system.

SFA of representatives of soil taxonomic class can be graded by correcting the mean index of the class. An additional standard factor has to be applied in all cases in order to achieve the 100-grade scale. These indices express the 'natural' inherent Functional Ability. SQ indices need to be weighted by landform and climatic factors in order to achieve a Land Quality Index. SFA and SQ factors have to be calculated on a basis of both continental and regional comparisons. Continental comparison is needed to establish a common platform for European applications (e.g. yield level, sealing density, degree of erosion) while regional comparisons are needed to assess qualities within similar climatic conditions.

Actual relative Functional Ability of soils can be expressed by taking SRP (and eventually soil management conditions) into account. The actual SQI in certain circumstances may exceed the 100-point value of the inherent index as this index is based on the 'natural' conditions of soils, under 'average' environmental impact.

With the same method, the effect of degradation factors can be incorporated to calculate the STI. By applying the gradient of degradation stress, CDE can be computed.

Since complex systems regulate the material and energy exchange in soil, neither individual soil quality/sustainability components can be characterized by the measurement of a single attribute (Figure 1.).
Taking the example of biomass production, although the size of the nutrient stock of a soil is an important determinant of fertility, the dynamics of the nutrients is even more important.

Within the frame of SFA and Soil Threats, soil characteristics might have specific meanings as well. They might provide information on the interaction with other environmental media (air, water) and influence the quality[2] of these media. Quality- or risk assessment with regards to atmosphere and water can be linked to soil quality directly. In assessment for different purposes soil characteristics might be weighted differently. High humus content, for example, can limit fertility, while benefiting buffering capacity.

Therefore, one should always consider whether the examined soil functions can be related to each other or they have to be analyzed separately.

the diversity of content, meaning and measure of the elements in the soil use domain categorical interpretation of soil sustainability is often a more feasible option.

Categories for SSI are proposed to be classified on the basis of SQ and the changes of the quality due to CDE over a defined time period and land use system (Figure 3.)

Evaluation of sustainable soil use can be performed by interpreting SQI and STI. In certain cases this interpretation may be done through mathematical indexing. Considering

Scenario analysis can be performed for different land use and soil management systems on the basis of quantified Soil Sustainability Categories and economic evaluation should supplement the evaluation process.

Soil sustainability analysis is performed on the basis of numerical indices of SQ and CDE and is demonstrated on a working example in chapter 6.1.

[2] Qualities of the soil-atmosphere-water system might indicate environmental sensitivity or other categories and can be analyzed in the context of interactions between soil and other environmental media (e.g. surface or underground water).

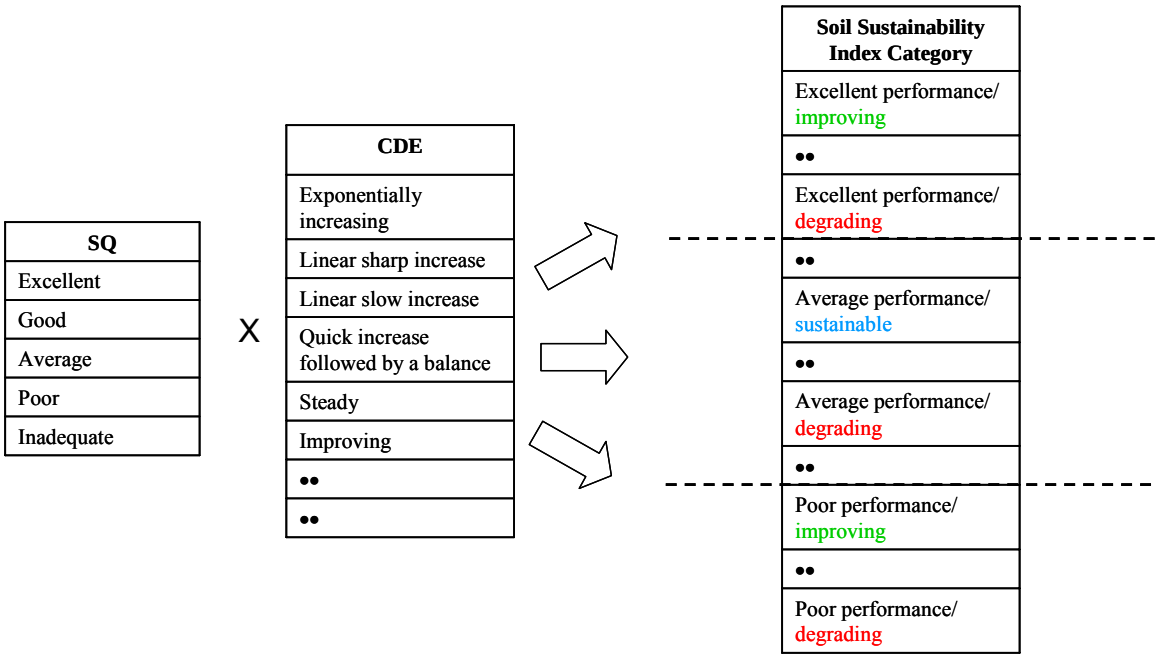

Figure 3. Components and categories of Soil Sustainability Index. *Categories of SSI are based on principles of numerical classification and indicate the level of performance of one or more soil functions and the dynamics of the performance under defined soil-use. Dynamics of the system (as introduced in Figure 1.) allows soil types to change category with (i) time or (ii) changed soil-use.*

6. APPLICATION OF THE FRAMEWORK

The status of soil characteristics and the risk of negative effect on them are the central concept of the applied soil quality approach in Europe (Figure 1). This approach is expressed in the document of Thematic Strategy for Soil Protection. Assessment of soil quality in this approach recognizes that the relative role of soil functions is both spatially and temporally variable. Consequently, rather than a single universal expression of soil quality that characterizes the 'goodness' of soil, the above introduced conceptual approach allows for the implication of different quality perceptions for a wide range of applications (including economic analyses on a common bases of measurable parameters).

Thus, the evaluation of soil quality can support the synergies between local soil-use options and regulative (eg. the Common Agricultural Policy of the European Union, international conventions) conditions.

For example, the thickness of humus layer – in certain cases - can indicate the level of erosion, while by knowing the soil taxonomic class, its parent material, texture, humus content and other properties together with terrain and climate information one can assess the risk of further erosion. In this case different aspects of soil functional abilities can be linked by soil characteristics that are important in both aspects and the soil quality (or the potential change in quality) can be expressed through biomass productivity evaluation measurements.

Similarly, the evaluation of buffering and functions for providing raw materials or any other functions are possible. Aggregation of the developed indices can be performed if complex situations arise.

6.1 A WORKING EXAMPLE

In most decision making dilemmas, planners generally need to consider a limited number of conflicting factors. In those situations evaluation by specific soil functions and threats is a feasible option.

In the purpose-oriented evaluation, the considered individual Soil Functional Abilities can be seen from the viewpoint of alternative land use options and the evaluation of SFA can be supplemented by evaluation of the STI of the relevant degradation threats.

This is achieved by the first step process of specification of evaluation (land use) criteria of soil quality and sustainability.

A good example is the possible determination of Less Favoured Areas (LFA) for agricultural production. The main question in the context of LFA is: What is the valuable land, that with the higher productivity but greater sensitivity to degradation (less sustainable on site and off site effects) or that with the lower productivity but strong resistance against degradation? To answer this question, a soil sustainability evaluation based on the soil quality/soil threat matching approach can help.

6.1.1 Matching agricultural production and soil degradation / environmental effects in the soil sustainability perspective (evaluation for less favoured areas designation)

There is a wide range of perceptions and consequently policy applications in the European Union regarding areas less favourable for agricultural productions.
In order to have a comparable measure, which takes sustainable use of soil resource into account throughout Member States, both (1) productivity and (2) degradation threats need to be assessed.
Loss of soil organic carbon and erosion are among the main degradation processes having an impact both on-site (loss of fertility and other functional abilities) and off-site (greenhouse effect, eutrophication of water resources etc.). Therefore these two degradation threats are considered in our working example.

Method

To assess soil-use options with regards to Less Favoured Areas the soil sustainability evaluation framework is applied following the procedure below:

Step 1. To assess SQ, the productivity function and related response properties need to be considered:

SFA = productivity
SRP = water, nutrient reaction

Step 2. To assess CDE, STI of special degradation indicators have to be applied with the time dimension (eg. a, and b, with consideration of c):

a) Degradation related SRP = organic carbon dynamics
   External factors of degradation = land use (, climate)
b) Degradation related SRP = sensitivity to erosion

External factors of degradation = land use (terrain, climate)

c) Δt to express temporal dynamics of a) and b)

Step 3. SSI is developed as a composite of (1) and (2a,b) with the consideration of temporal dynamics (Δt).

The evaluation procedure of soil taxonomic classes may follow different methods, However, within the sustainability evaluation framework, these methods need to be quantitative and to be scaled on a common dimensionless numeric scale (without a unit).

Procedure and results

(1) **The productivity (SFA) evaluation** designates the relative productivity index of the given soil taxonomic class. We consider Haplic Luvisols (n > 3000) with 1% organic matter content in agricultural use in Hungary (Figure 4). On a scale from 1 to 100 points, the productivity (SFA) index of this soil is 57,

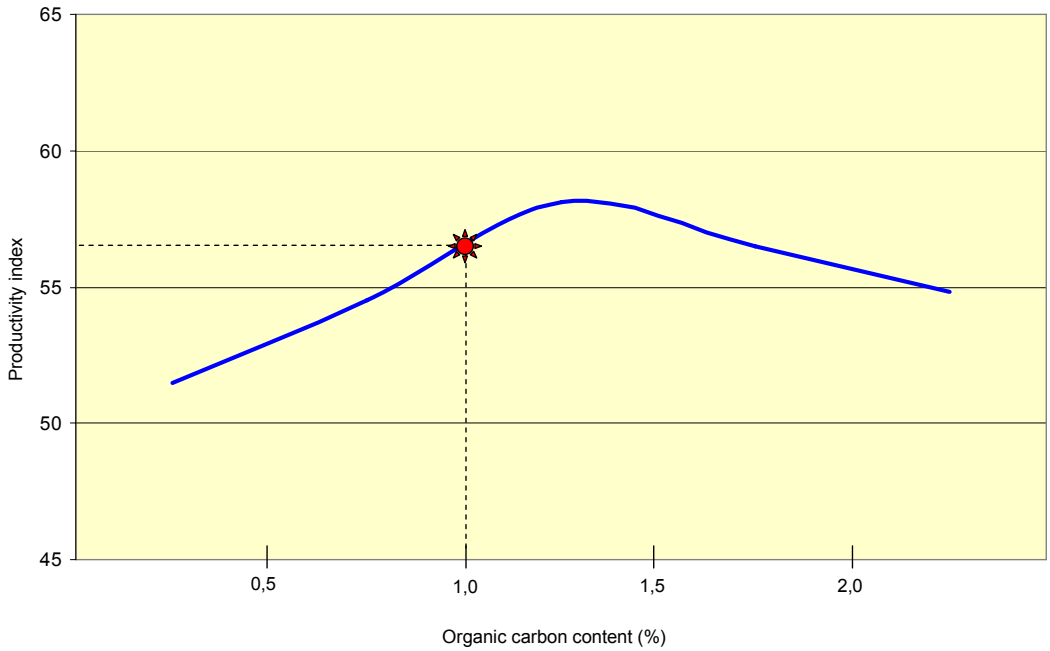

Figure 4. Average wheat productivity indices of Haplic Luvisols with different organic matter content (Tóth et al. 2007). *The curve illustrates that different carbon contents results in a different production function (as shown by productivity indices) in the same soil type. The optimum for productivity does not coincide with the maximum of carbon content. For other soil functions the optimum can be different. The productivity index of 1% organic carbon content is highlighted for the working example in the text.*

SRP in the productivity function domain are characteristics of water and nutrient dynamics. As Figure 5 illustrates (with the example of nitrogen reaction) the effect of fertilization is rather positive on Luvisols, therefore the index of response properties for nutrients is also high: (85).

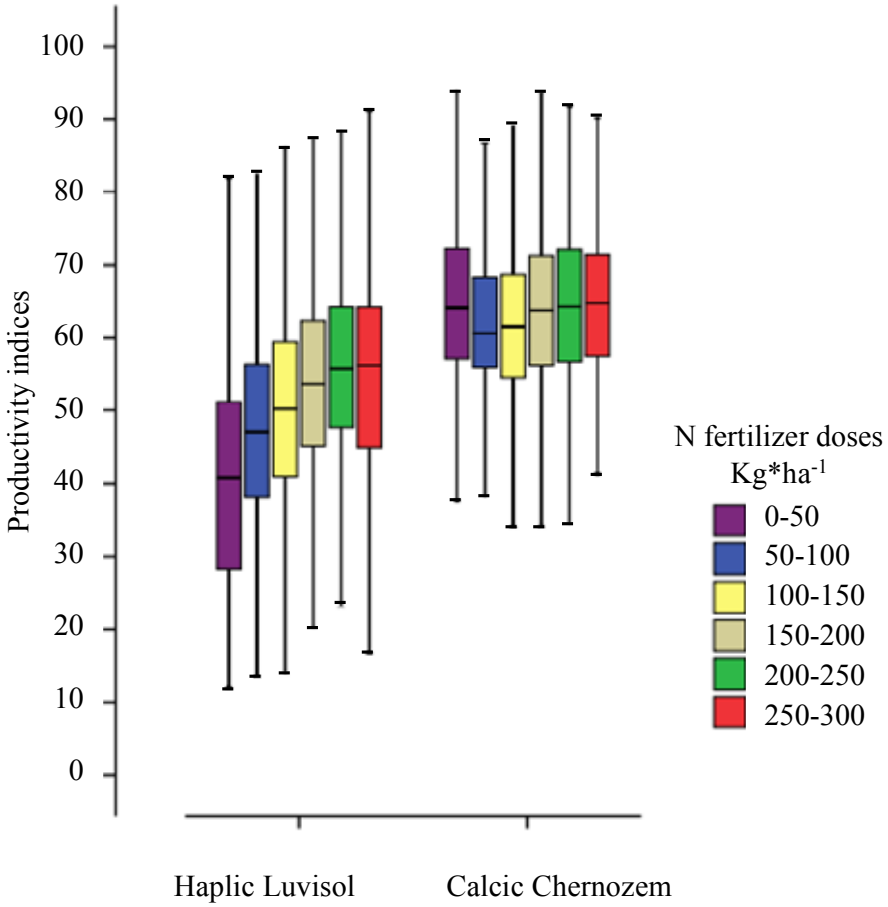

Figure 5. The effect of N fertilization on wheat productivity of Luvisols (Tóth et al. 2005). *The graph illustrates that nutrient reaction of different soil types can be different, and this difference is reflected in the productivity indices. As opposed to the strong nitrogen response of Luvisols, the reaction of Chernozems do not increase significantly with higher doses of nitrogen fertilization. The productivity indices of the figure are based on measurements of several thousand plots in Hungary.*

Annual variations of yield depend on complex climatic phenomena, including precipitation and temperature regimes. The soil water element of productivity acts in interaction with the dynamics of nutrient availability. However, from the annual variability of yields one can deduce the effect of water regime by applying climate-productivity models (eg. Szász *et al.* 2002). The water regime of soil taxonomic classes is reflected in the variability of yields over the years (which may differ to a great extent

among soil classes). Figure 6 illustrates the variability of productivity indices due to climatic effects. In this case there is no extreme variability, which is a positive characteristic (however the stability of productivity is lower than in the case of 'more stable' soils like chernozems), therefore the Soil Response Property of water reaction is ranked with an index (60) close to and somewhat higher than average (50).

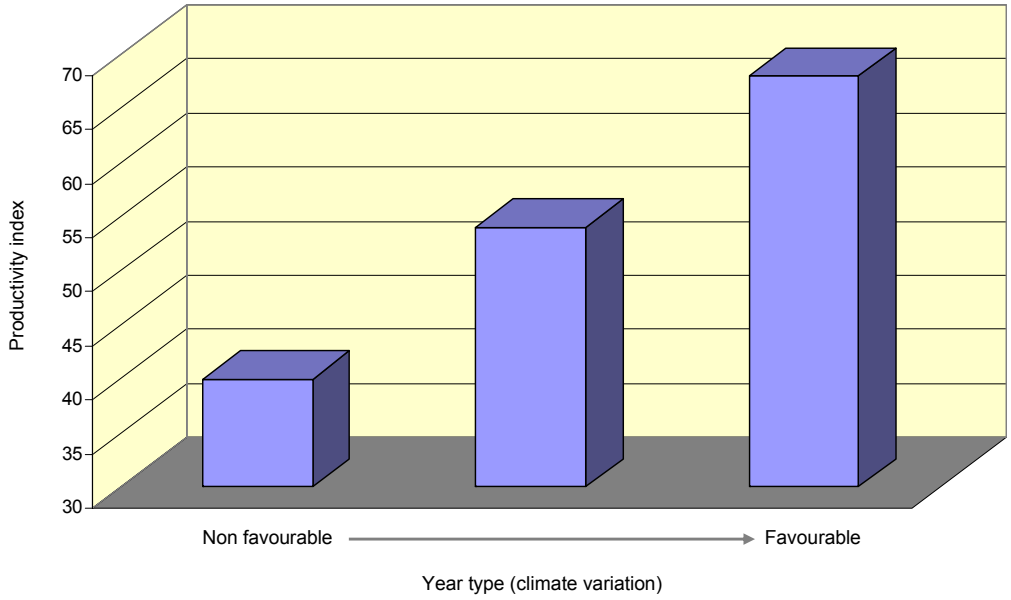

Figure 6. The effect of climate variation on wheat productivity index of Haplic Luvisols (Debreczeni *et al.* 2003). *The graph illustrates the temporal variability of functional abilities (productivity function expressed through productivity indices). The magnitude of temporal variability is determined by the response properties of different soil types.*

SQ of the selected soil taxonomic class is based on calculations of productivity, nutrient reaction and water reaction as a function of climatic variability; and it is computed as 57*85*60 (meaning that productivity is above the average SQ), it can be improved by good nutrient management and has an above-the-average stability throughout the years. Therefore the SQ index for the individual function of productivity is 67.

(2) **CDE** is calculated on the basis of STI including SRP, the prevailing terrain, land use and climate conditions and time. In the example the (a) erodibility and (b) stability of organic carbon is accounted.

(a) Erodibility of Luvisols with 1% organic carbon and wheat as a crop is mainly the function of slope, texture and climate. In our example a non-eroded clayey loam haplic Luvisol with a slope of 5%. (With a climate characteristic to the region of the location). The erodibility of this soil has an STI of 78, a rather high value on the 100 point scale, mainly due to land use and slope. The progress of

soil loss in time follows a linear trend (based on the soil vertical characteristics) consequently has a rather sharp gradient and corresponding high CDE value (74).

(b) Loss of organic carbon in the example is originating from two sources: (i) with the erosional loss of topsoil the humus rich layer is washed away (the current land use – cropland – gives limited option for erosion control) and (ii) a lower level of equilibrium of organic carbon content is a result of the intensive soil cultivation The calculation of loss of organic matter compared with alternative land use (eg. extensive cower crop cultivation) indicates a 40% decrease; a considerably high amount. Taking the effect of erosion as a process in time also into account, the gradient of degradation is even sharper. Therefore, the CDE for organic carbon loss is higher (80).

To visualize the concept, the loss of productivity due to loss of organic matter and erosion in the case of the selected Haplic Luvisol is indicated with a process shown by Figure 7.

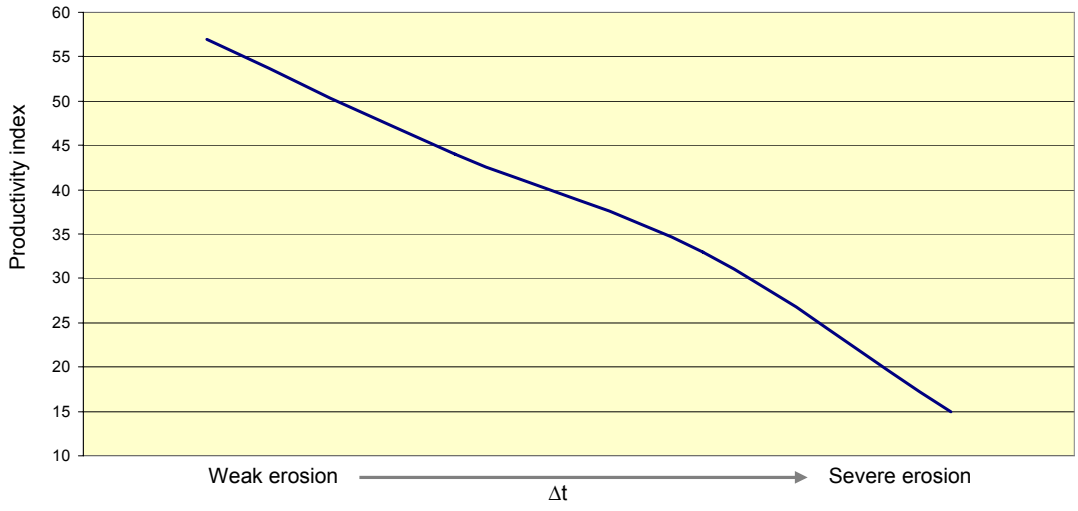

Figure 7. Soil productivity decline of a Haplic Luvisol due to erosion and loss of organic carbon (1% OC content in the original topsoil) (based on Tóth 1996). *The graph illustrates the change in SFA (productivity function expressed by productivity index) due to CDE (erosion and accompanying loss of organic matter)*

SSI can be calculated on the basis of SQ and CDE. In a value-neutral approach, where no preset priority of soil function is defined (the importance of production and soil conservation is the same), a simple compilation of the values are used to calculate the SSI. Applying eq. 6. in our sample case: 67 X {100- (74X80)} = 45

Although SQ and CDE indices have individual meaning, within the SSI evaluation an integration of the separate meanings allow detailed sustainability analyses for decision support. In order to provide full information on the performance and sustainability of the system, SSI has to be supplemented with the corresponding SQ and CDE.

Therefore the proposed SSI for our sample case is: 45 [67 ‘ 77]

With the application of the SSI categories this index is interpreted as:

SQ		CDE		Soil Sustainability Index Category
Good	X	Linear slow increase	⇨	Good performance/ slowly degrading

This composite indicator means a rather good performance of soil under the current land use, however, with a high risk of depletion. Therefore under current practices the soil is fertile, but to keep its fertility conservation measures (erosion control and good management of organic matter) are essential.

As SSI has two components which may interact, it is worth performing a scenario analysis taking this interaction into account. (In the case of areas with high degradation risk, the exposure to degradation will result decline in the productivity.)

Message of the LFA application

Soil sustainability evaluation was demonstrated to be a viable tool to assess areas from different perspectives (soil function and threat) and draw conclusions based on multi-criteria analysis.

In the case of the Less Favoured Areas of agricultural production, decision makers should draw threshold values for different programs. However, as Figure 4 very clearly illustrates (by showing that productivity and organic matter content are not always in linear function), the multiple criteria optimization needs the comparison of different functions.

To perform a multiple criteria soil sustainability evaluation, different functions have to be assessed. After calculating the SSI, possibly for different functions, or groups of functions, a scenario analysis can be carried out to calculate the index for different land use options. Land use planning decision can be based on weighting the importance of

SQ according to different functions, the CDE (considering both on side and off side effects) and eventually economic and social factors.

7. CONCLUSIONS

Site-specific optimization of soil performance with the consideration of the criteria of sustainable soil-use is in the forefront of policies in the European Union, framed by the Thematic Strategy for Soil Protection.

In order to harmonize efforts of soil resources utilization and environmental resources conservation, integration of soil quality measures to policy planning is essential. Soil quality in this context is an account of the ability of soil to provide ecosystem and social services through its capacities to perform key functions and respond to external influences.

The status of soil parameters and the risk of negative effects on them are in the central concept of the applied soil quality/ sustainability evaluation approach presented in this report. Based on this methodology parameterization of soil quality, soil degradation threats and sustainable soil-use can be performed in an integrated manner.

This report illustrates how sustainability analysis of soil-use systems can be performed for any function and degradation threat. A case study of one function (biomass production) and two major threats (erosion, decline of organic matter) has been presented.

An advantage of the conceptual approach designed for application in the European Union (as presented in this report) is that rather than a single universal expression of soil quality that characterizes the ’goodness’ of soil, the implication of different quality perceptions for a wide range of applications is allowed including economic analyses on the common bases of measurable parameters.

Thus, the evaluation of Soil Quality and soil-use sustainability can support the synergies between local soil-use practices and regulative (CAP, international conventions etc.) conditions, land use and policy planning.

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Annex I: Definitions and terms in risk assessment

(After Eckelmann *et al.* 2006)

1 Hazard

"*Inherent property of an agent or situation having the potential to cause adverse effects when an organism, system or (sub) population is exposed to that agent*" (OECD 2003).
"*A property or situation that in particular circumstances could lead to harm*" (EEA, 1999).

2 Risk

"*The probability of an adverse effect in an organism, system or (sub) population caused under specified circumstances by exposure to an agent*" (OECD 2003).

"*The combination of the probability, or frequency, of occurrence of a defined hazard and the magnitude of the consequences of the occurrence*" (EEA 1999).

3 Risk Assessment

"*A process intended to calculate or estimate the risk to a given target organism, system or (sub)population, including the identification of attendant uncertainties, following exposure to a particular agent, taking into account the inherent characteristics of the agent of concern as well as the characteristics of the specific target system* " (OECD, 2003).
The Risk Assessment process includes four steps:

1. hazard identification
2. hazard characterisation (related term: dose-response assessment)
3. exposure assessment
4. risk characterization.

Risk assessment is the first component in a risk analysis process" (OECD, 2003).

"Procedure in which the risks posed by inherent hazards involved in processes or situations are estimated either quantitatively or qualitatively" (EEA 1999).

3.1 Hazard Identification

"*The identification of the type and nature of adverse effects that an agent has as inherent capacity to cause in an organism, system or (sub) population*" (OECD 2003). Hazard identification is the first stage in hazard assessment and the first step in the process of Risk Assessment.

3.2 Hazard Characterization

"*The qualitative and, wherever possible, quantitative description of the inherent properties of an agent or situation having the potential to cause adverse effects*" (OECD

2003). This should, where possible, include a dose-response assessment and its attendant uncertainties.
[related terms: dose-Effect relationship, effect assessment, dose-response relationship, concentration-effect relationship**]**

3.3 Exposure Assessment

"*Evaluation of the exposure of an organism, system or (sub) population to an agent (and its derivatives)"* (OECD 2003).

3.4 Risk Characterization

"*The qualitative and, wherever possible, quantitative determination, including attendant uncertainties, of the probability of occurrence of known and potential adverse effects of an agent in a given organism, system or (sub) population, under defined exposure conditions*" (OECD 2003).

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Annex II: Summary Table: Common Criteria for Risk Area Identification for Major Soil Treats

(After Eckelmann *et al.* 2006)

SOM Decline

common criteria	data source/type of information	minimum data quality /resolution	
		Tier 1	Tier 2
soil typological unit (soil type)	soil type	1:1,000,000 (1:250,000)	1:250,000 or larger
soil texture/clay content	standard textural analysis; textural classes according to official classification	*not required for Tier 1*	national profile data base; soil inventory/monitoring
soil organic carbon (concentration)	analysis: dry combustion, [g/kg], or pedo-transfer function	*not required for Tier 1*	forest floor, peaty layers, 0-30 cm
soil organic carbon (stock)	[kg/m^2], [t/ha]; - stone content - bulk density	*not required for Tier 1*	forest floor, peaty layers, 0-30 cm
climate	annual average precipitation; annual average temperature	10 km grid climatic data	1 km raster size (modelled from national weather station network)
slope, exposition, position in relief	digital elevation model	250 m	*same or higher*
land cover/land use	CORINE; LUCAS SSU extended by soil type; management statistics	250 m NUTS* III	*same or higher*

*NUTS (Nomenclature des Units Territoriales Statistiques) is a system for referencing the administrative division of countries for statistical purposes in the European Union. There are three levels of NUTS defined where NUTS III refers to counties/departments/ districts in the Member States.

Erosion

Common criteria	Data source/type of information	Data Quality /Resolution	
		Tier 1	Tier 2
soil typological unit (STU) (soil type)	Soil type European/national soil databases	national level	regional level
soil texture (STU level)	sand, silt, clay content	texture class	particle size
soil density, hydraulic properties (STU level)	bulk density, packing density, water retention art field capacity and wilting point	pedo-transfer-rules (PTR) or functions	measured data
topography	gradient (slope), length	250 m (SRTM)	90 m
land cover	land cover type	250 m	100 m
land use	land use, agricultural statistics	NUTS3	NUTS4
climate	Precipitation (rainfall, snowfall) number of rain days, storm events, PET, temperature	10 km daily average 50km daily average	1 km raster (modelled from national
hydrological conditions	catchments information system, digital elevation model	10 km	1 km
agro-ecological zone	based on soil, climate, landscape	50 km	1 km

Compaction

Common criteria	Data source/type of information	Data Quality /Resolution	
		Tier 1	Tier 2
SMU/STU delineation	National soil databases	national	regional
STU topsoil and subsoil texture	texture class or mean silt, clay and sand content	texture class	particle size
STU description	bulk density, water retention, organic matter content, structure, mechanical properties	pedotransfer functions or rules	measurements
climate	rainfall, potential evapotranspiration	average year with monthly or 10-day data NUTS 3 or 50 km	20 to 30 years with one day data 10 km
land use	statistical data on agriculture and forestry: crop types and forest areas, types of farming systems (annual crops, vineyards, animal breeding, etc.), type of forests	NUTS 3	NUTS 4
farming and forest systems	typology of farming systems or forestry systems in relation to land use data	expert knowledge	survey data
land cover	localisation of agricultural areas, forest areas, etc. using data like CORINE land cover	250 m	100 m
slope	Digital Elevation Model	250 m	90 m

Salinization

Common criteria	Data source/type of information	Data Quality /Resolution	
		Tier 1	Tier 2
soil typological unit	European Soil Database; National soil databases	1:1,000,000 (1:250,000)	national
soil texture	texture class; sand, silt, clay content	texture class	particle size
soil hydraulic properties	hydraulic conductivity, water retention, drainage	*not required for in Tier 1*	national profile data base; soil inventory / monitoring
irrigation areas and chemical properties of irrigated water	irrigated area, irrigation intensity, salt content, sodicity, alkalinity of irrigation water	national registries	regional registry
groundwater information	depth, salt content, sodicity, alkalinity	European Groundwater Database (salt concentration, type of salt)	regional database
climate	annual rainfall, annual potential evapotranspiration	1 km raster size (modelled from national weather station network)	*same or higher*

Landslides

Common criteria	Data source/type of information	Data Quality /Resolution	
		Tier 1	Tier 2
occurrence/density of existing landslides	statistics	NUTS III	larger-scale regional/local assessments
bedrock	nature of material + presence of fissures and pores Sensitive bedrocks can be Gault Clay and Flish	Map of Geology 1:1,000,000	higher resolution maps
soil properties	texture, structure, permeability	*not required for in Tier 1*	classification/grouping according to?
slope	classes: 0-10°; 10°-30°; >30°	250 m	*same or higher*
land cover/land use	infrastructure; cultivation density/pressure, mining	*Non relevant for Tier 1*	100 m
climate	likelihood of heavy rainfall events	daily events (e.g. < 10, 10-70, >70 mm/day of precipitation)	*same or higher*
seismic risk		threshold	threshold

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Abstract

This report presents an integrated approach of soil quality and sustainability evaluation. Interactions of the soil and land use systems are summarized from the perspective of the implication of soil related policies in the European Union. The approach introduced in this report has been design in support of the EU Thematic Strategy for soil Protection, aiming soil quality preservation by sustainable soil-use practices. Following the methodology explained in this report, soil quality evaluation and sustainability analysis of soil-use systems can be performed for any function and degradation threat. A case study of one function (biomass production) and two major threats (erosion, decline of organic matter) has been presented.

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