Agri-environmental Soil Quality Indicator in the European Perspective

GERGELY TOTH

EUROPEAN COMMISSION
JOINT RESEARCH CENTRE
ISPRA, ITALY
Executive Summary

Soil quality is an account of the soil’s ability to provide ecosystem and social services through its capacities to perform its functions under changing conditions (after Tóth et al. 2007.) The concept of soil quality expressed by this definition allows practical applications with regards to targeted social and/or ecosystem services, including agri-environmental services.

The Thematic Strategy for Soil Protection of the European Union (COM 2006/231) identifies key soil functions of which the maintenance and improvement have to be considered in soil-related policies of the EU. Among the main soil functions several have agri-environmental relevance, which have to be taken into account when developing an Agri-environmental Soil Quality Indicator (AE-SQI).

For agronomic purposes the biomass production function of soil is of absolute importance. This function, however, can be performed under varying external influences. The two main factors conditioning the performance of biomass production of soil are climate and management. During the evaluation of production function, the reacting capacities of soil to these factors need to be considered.

Indication of soil quality from environmental point of view in the agricultural context can relate to off side environmental effects of soil functioning and land management practices. The soil’s capacity to store, filter and transform substances is crucial in this perspective (e.g. carbon storage and climate change; buffering capacity and diffuse contamination). Soil biodiversity can indicate local environmental quality.

Based on the above concept an agri-environmental soil quality indicator is being developed for application in the European Union. The agri-environmental soil quality is expressed by an index built up by four sub indicators:

- Productivity index (the capacity of soil to biomass production)
- Fertilizer response rate (input change / yield increase ratio)
- Production stability index (the soil-response to climatic variability)
- Soil environmental quality index (to express environmental aspects of SQ)

The four sub indicators cover both agronomic and environmental aspects of the goodness of soil (soil quality), therefore constitute to a comprehensive agri-environmental soil quality indicator, which might be applied on different spatial and temporal scales.

The proposed soil quality indicator can be used for policy development (including agricultural and soil protection policies) and monitoring; through its capacity to indicate:

- the effect of land use change (marginalization; soil sealing etc.) on the availability and functioning capacity of soil resources;
- the effect of land management (e.g. intensification) on the functioning capacity of soil resources;
- the effect of climatic variability on the production function of soil resources;
- the capacity of soil to mitigate environmental problems (climate change, water pollution etc.).

Based on the information provided by the AE-SQI and its sub-indicators, current levels of soil agri-environmental services can be assessed, monitored and future levels of such services can be projected.
Introduction: Background, scope objectives

Policy context to Agri-environmental Soil Quality Indicator

Environmental performance of agriculture in countries with advanced technologies is largely determined by the various rural and environmental policies. According to the OECD (2008) three main policy areas can act to intensify or reduce the pressure of agricultural activities on the environment, namely:

1. Agricultural policies
   Agricultural policies have production-related objectives, such as intensification. These policies are often accompanied by production constrains such as production quotas or set-aside land.

2. Agri-environmental policies
   These policies are specifically designed to enhance some environmental benefits associated with agriculture or offset the effects of production-linked support.

3. Environmental policies
   Environmental policies aimed at specific environmental issues (e.g. water pollution) but that can have an effect on agriculture, and which can be either national or international in scope.

To monitor the effect of these policies on soil quality – or measure the influence of soil quality on the potentials and effectiveness of these policies – an integrated approach is required. This approach has to consider both agricultural (production) and environmental aspects of the soil quality domain.

The European Union adapted its Thematic Strategy for Soil Protection (also referred as the Strategy; (CEC, 2006a) as the basic policy document for protecting the quality of soil resources in the EU. Detailed scientific background of the Strategy is provided in the documents prepared by working groups of scientist and different stakeholders from across Europe (Van Camp et al., 2004). An impact assessment accompanies the policy document (CEC, 2006b). With the publication of the Thematic Strategy for Soil Protection a framework has been put forward, which sets the way towards operational soil quality criteria in Europe.

According to the Strategy soil delivers its services through its main functions: (1) food and other biomass production, (2) storing, filtering and transformation of materials, (3) habitat and gene pool of living organisms, (4) physical and cultural environment for humankind, (5) source of raw materials, (6) acting as a carbon pool, and (7) archive of geological and archaeological heritage.

The main objective of the Strategy is to ensure sustainable utilization of soil functions. This has to be done by integration of soil protection policy to other policies of the European Community on, inter alia, agriculture and environment. In order to facilitate this integration, a common framework has been worked out to assess soil functions in relation to soil use and degradation threats (Tóth et al., 2007). The framework for bridging between the utilization and protection aspects of soil-use planning includes evaluation procedure of soil functions and soil dynamic response properties (to external influences). By implementing the evaluation scheme a soil quality indicator can be derived. This indicator can be used to assess and monitor the effect of the land policies, whether agricultural, environmental or the combination of those.

Soil quality and sustainability of soil use

The sustainability of agricultural land-use can only be guaranteed if the processes of material and energy flow associated with crop production can be controlled and influenced. This means the management and maintenance of soil quality as well.

Among the factors influencing soil-use on the plot level (apart from social and economic factors) the ecological conditions of the plot, management practices and the existing connections to the surrounding areas (potential mutual effects) need to be emphasized. The connection to surface and underground water and the atmosphere is also important or might become important.

Long-lasting management effects on the ecological conditions, e.g. amelioration measures, as well as the seasonal changes of operations of soil cultivation, irrigation, nutrient management and plant protection,
alter the character of the processes of material and energy flow to smaller or greater extent. When these processes are traceable, controllable and should a feedback be necessary (even if indirectly) such feedback is possible, soil use remains sustainable in the long run, too.

Change in individual soil parameters can be a sign of positive or negative changes in the performance potential of soil functions. However, to assess the capacity of soil to perform its functions a number of soil parameters need to be considered in an integrated manner. Only a full assessment of soil functional capacities can comprehensively indicate the status and trends in soil quality. Policy planning and decision making can also be based only on clear information on the status of soil quality and on the possible effect of policies on soil quality. Therefore a new method of soil quality assessment is required which enables to integrate the effect of soil use and soil functioning in a system approach.

The soil quality concept

Soil quality is an account of the soil’s ability to provide ecosystem and social services through its capacities to perform its functions under changing conditions (Tóth et al. 2007.) The concept of soil quality expressed by this definition allows practical applications with regards to targeted social and/or ecosystem services. Targeted applications may be linked to special soil functions like soil productivity ranking, evaluation of carbon sequestration potential etc. The simplest case of soil quality evaluation therefore is to assess the performing potential of soil by a single soil function. On higher levels of aggregation soil quality can express the combination and sum of capacities.

The concept of soil quality recognizes that the comparative importance of soil functions may be spatially and temporally dynamic and it is up to the evaluator to define the conditions of evaluation in accordance with the goal of the assessment.

However, the evaluation scheme has to consider the two basic elements of soil quality: (1) functional ability and (2) response properties. (Figure 1.)

The two main elements corresponds to the

1) identification of existing potential to perform functions, and
2) indication of sensitivity/reaction to external influences.

With other words, these two elements reveal the (1) capacity to perform a function under given conditions and the (2) range of the functioning capacity under changing conditions.

![Figure 1. Constituents of soil quality](image)

Functional ability of soil is corresponding to well-defined (actual or desired) unique conditions. This prerequisite is necessary for the assessment. However the fact that conditions determining the performance of soils are in constant change in the nature is recognized and considered with the assessment of response properties. The functional ability of soil marks the ‘baseline’ information component of soil quality. Therefore the functional ability may be called as soil quality of stable (expected; average) external conditions.

The specification of influential soil characteristics, their interrelations and their importance for functional ability requires a complex approach. Functioning ability of a soil is determined by the number and internal dynamics of soil characteristics. In addition, external conditions for individual functions and other factors are also influential and therefore need to be considered.
Optimal performance of soil functions often do not coincide. Soil conditions which favour filtering of substances might not be the most suitable for hosting high biodiversity; or soil conditions favouring biomass production might not be the best possible for organic carbon storage of the same soil (Figure 2).

The curve (on Figure 2.) illustrates that different carbon contents results in a different level of production (as shown by productivity indices) in the same soil type. The optimum for productivity does not coincide with the maximum of carbon content. This fact underlines that optimum status of soil properties can be different for different soil functions. Therefore a single soil property (e.g. organic carbon content) can not be used as a stand-alone indicator of soil quality.

Figure 2. Average wheat productivity indices of Haplic Luvisols with different organic matter content; based on (Tóth et al., 2008)

The example of Figure 2. underlines the fact that to select one individual soil function – or a soil parameter - to characterize the ‘general’ goodness of soil can be misleading. When setting policy targets one should always consider possible trade offs with respect to the soil’s performances of its varying functions. Soil properties need to be assessed according to their role in the performance of individual soil functions and the performance level of soil functions need to be compared and monitored.

Soil characteristics should be evaluated according to the conditions they provide for the specific function of interest. Actual characteristics might be in favour of or can limit the performance of the function (Figure 2.). In a detailed functional ability analysis the assessment of soil characteristics can be carried out to identify those soil characteristics (and/or clusters of characteristics) within the selected soil classes that are most important determinants of the level of performance. The same characteristics can be assessed to describe the soil-property-driven regulatory principles of material and energy exchange in soils.

The assessment of functional ability of soil requires the measurement of physical, chemical and biological soil characteristics and processes, together with the interaction between them; according to specific purpose of the evaluation.

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

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

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 or weights - like in any classical quantitative land evaluation processes - modify the mean index of the soil class.

The weights express the relative role of the characteristic in the functional ability of the soil class. These weights are the control parameters of the functional ability evaluation model. By knowing the (changeable) 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 functional ability of different soil varieties can be derived, which spans from the lowest to the highest value of the soil type. If required for different scales, on different level of the taxonomic hierarchy.
Soil response properties are particular characteristics that determine the soil’s reactions to environmental (or human) influences (Tóth et al., 2007). Soil response properties mark different potentials of soil functional ability by determining both the direction and magnitude how soil reacts to a disturbance or change. The above definition of soil response properties reveals the dynamic phenomena of soil. While the functional ability of soil indicate soil quality under stable (expected) external conditions, the consideration of response properties extends the meaning of soil quality by the information on possible changes under varying external conditions.

Response properties influence the soil quality by altering the functional ability of soil. The alteration may be either natural or human induced. Response properties are characterized by the direction, the degree and the speed of change. Since each soil type has a distinct path of reactions to any environmental change, response properties may also vary; thus influencing the stability of the performance (or adaptability to external impacts) to a great extent.

The meaning of a soil response property might also be read as an indicator of the diversities of soil functional abilities within widened boundary conditions. With the extension of soil quality perception by this dynamic component, scenario-based performance potentials may be calculated with associated probabilities.

Soil response properties influence soil quality by individual soil functions and can be used for various types of assessment, including agri-environmental.

The aim of the proposed agri-environmental soil quality indicator is to integrate the above criteria for agri-environmental applications, including monitoring and policy design.

### Structure and components of the Agri-environmental Soil Quality Indicator

The European Environmental Agency (EEA, 2005) has set criteria for indicators applicable in the agri-environmental context. Policy relevance, responsiveness, analytical soundness, measurability, ease of interpretation and cost effectiveness are among these criteria. Indicators based on, or linked to the above introduced general soil quality concept, including the agri-environmental soil quality indicator can fulfill these criteria. Validity of results depends on the scale/density of measurement.

A composite indicator of agri-environmental soil quality is proposed. The composite indicator consists of four sub-indicators (Table 1.) of similar weight which have relevance either to agricultural or to environmental performance of soil.

<table>
<thead>
<tr>
<th>Sub-Indicator</th>
<th>Relevant policy field</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>A) Productivity</td>
<td>Agricultural</td>
<td>The capacity of soil to biomass production</td>
</tr>
<tr>
<td>B) Production stability</td>
<td>Agri-environmental</td>
<td>The soil-response to climatic variability</td>
</tr>
<tr>
<td>C) Fertilizer response rate</td>
<td>Agri-environmental</td>
<td>The input-need to attain optimal productivity</td>
</tr>
<tr>
<td>D) Soil environmental quality</td>
<td>Environmental</td>
<td>Carbon storage; filtering; transforming; soil biodiversity</td>
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</table>

For example in soil bonitation the availability of water set the target of productivity. However, productivity can be altered by fertilization. The degree of yield change to fertilization is a distinct response property of each soil. Therefore during soil quality evaluation, both the functional ability (reference level) and response property (elasticity of ability) has to be considered to secure both agricultural and environmental applicability of the soil quality indicator.
A) Indication of productivity

The level of performance of the biomass production function of a given soil is computed on the basis of soil properties at prevailing climatic conditions. Since productivity is a result of the interaction of soil-, climatic-, terrain conditions and management, these factors need to be assessed in their complexity. Soil quality evaluation for biomass productivity is therefore performed in a spatially explicit manner, taking the impact of the climatic and topographic components of soil productivity into account. Land evaluation is the most widely used tool to assess soil and land productivity in practice (Bouma and Bregt, 1989). Functions of early land evaluation systems in Europe (FAO, 1975) were associated mainly with the assessment of crop growing potential of agricultural land. With the evolvement of the sustainability paradigm recent directions of land evaluation systems development include means to express environmental impacts of soil use, whether agricultural or other (Vrščaj et al., 2008).

During the productivity evaluation process, different soil attributes (texture, humus content, thickness of humus layer, pH, parent material etc.) can be characterized by numeric values (correction factors) according to their relative importance in the production potential of different soil types. A standard fertility index can be set for each soil type, which index corresponds to the relative fertility of the varieties of the soil type with average production potential. By applying the above correction factors according to soil variety, actual relative fertility of the soil variety can be characterized quantitatively. Fürizs et al. (1972), Shishov et al. (1992), Born and Vogel (1986), Vlad et al. (1996) and Han and Wu (1994) used similar approach in their productivity evaluation systems.

Productivity of soils can be expressed on a numeric scale (e.g. 1 to 10). Productivity index means the expected relative fertility of the given soil under actual material and energy input. Actual relative productivity of lands therefore can be expressed by taking land management conditions (fertilization, tillage method etc.) into account.

B) Indication of production stability

In the agri-environmental soil quality domain soil response properties are characterized by water and nutrient dynamics. Annual variations of yield depend on complex weather conditions, including precipitation and temperature regimes. The soil water element of productivity acts in interaction with the dynamics of nutrient availability. The water regime of soil types is reflected in the variability of yields over the years. This variety may differ to a great extent among soil classes. The variability of productivity indices due to climatic effects is illustrated by Figure 3. In the case of crop production the stability of yields is desirable; therefore soil characteristics responsible for higher variability should be considered as indicators of negative response property and consequently lower index of the production stability sub-indicator.

![Figure 3. The effect of climate variation on wheat productivity index of Haplic Luvisols (Debreczeni et al., 2003)](image)

The graph (on Figure 3.) 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.

Production stability of soils can be expressed on a numeric scale reflecting the proportional productivity change of given soils due to annual climatic variability.
C) Indication of fertilizer response rate

Nutrient reaction of the different soil types can vary to a great extent. This difference can be reflected in the soil quality indices. On soils where the effect of fertilization on yield formation is higher, this phenomenon should be considered as positive response property. To give a concrete example: as opposed to the strong nitrogen response of Haplic Luvisols, the reaction of Calcic Chernozems do not increase significantly with higher doses of nitrogen fertilizer under temperate sub-continental climate (Figure 4).

The graph (on Figure 4.) illustrates that nutrient reaction of different soil types can be different, and this difference is reflected in the productivity indices by various fertilizer inputs. As opposed to the strong nitrogen response of Luvisols, the reactions 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.

Figure 4. The effect of N fertilization on wheat productivity of two soil types (Tóth et al., 2005)

Fertilizer response properties of soils can be expressed on a numeric scale reflecting the proportional productivity change of given soils as a result of increased fertilizer doses. Differences between the effect of fertilizer doses at low input and at yield saturation points should be considered for the calculations.

D) Indication of soil environmental quality

The evaluation of productivity-independent environmental services of the soil is an important need. From the agricultural production perspective one should always consider, whether soil functions other than biomass production can be related to the production potential or they have to be analyzed separately. Nevertheless, all analyses should be based on the same integrated dataset because this can secure the most accurate information in the most economical way.

There are a number of soil functions – as defined by the Soil Thematic Strategy – that contribute to the environmental quality of soil. Four of these functions are recommended to be evaluated in relation to agri-environmental measures:

- **Organic carbon storage**
  - Organic carbon storage is computed on the basis of (1) the actual organic carbon content and (2) the organic carbon saturation relative to the maximum amount a soil is able to absorb in the given bioclimatic region. This component of environmental quality is valued higher for soils with high level of organic carbon accumulation, both in relative and absolute terms.

- **Substances filtering**
  - Substances filtering capacity of any porous media is a function of the textural and colloid properties (Lapidus and Amundson, 1952). There are a number of models available to quantitatively estimate filtering capacity of European soils (e.g. EuroPEARL for pesticides, 2008). These models can bee applied for the assessment.
- **Substances transforming**
  - Several patterns of material transformation exist in soil. Aerobic and anaerobic biological decomposition plays a major role in these processes. Further redox processes, such as stabilization of humus etc. may also bear great importance for specific functions. Material exchange between soil components as well as between soil and non-soil components is another major process of which the magnitude is determined by the substances transforming capacity of soil. Soils need to be assessed by the availability and strength of these processes.

- **Biodiversity and biological activity**
  - In order to answer agri-environmental policy questions the role of soil biodiversity needs to be addressed – among others - in terms of threshold values of influences from impacts and interpretation of the functioning of soil biodiversity (Francaviglia and Parris, 2003).

The evaluation of the performance of the above listed comprehensive functions is not an easy task. A decision has to be taken on the relative importance of each element. The individual elements might also have reverse importance if examined against different criteria. For example a high capacity to filter contaminated water might be an advantage for preventing hazards of chemical contamination exposure to underground water while might be a harmful feature from the viewpoint of biological hazards to soil biota. Nevertheless, for applications on the European scale, soils can be ranked according to the performing capacity of the individual soil functions. In other words, a soil with high filtering, storing and transforming capacity will be ranked higher than one with low capacity.

Evaluation of soil environmental quality can be carried out through the quantification of its component on a relative scale and with equal weights.

**Data need**

Data availability is one of the most important conditions to operationalize the proposed agri-environmental soil quality indicator. Conclusions for complex soil characteristics could only be drawn on the bases of appropriate information. The practice of indicator development as well as the evaluation process could only be carried out by using information that is available in soil maps, databases of soil monitoring, other soil information registries and related land use, climate etc. information sources.

The European Soil Data Centre in the Joint Research Centre of the European Commission has elaborated an inventory of data demand and availability specific for European scale assessment. Data need and source of information is for each sub-indicator is provided in Table 2.

Table 2. Data needs and sources of European scale agri-environmental soil quality indicator*

<table>
<thead>
<tr>
<th>Input data</th>
<th>Data source</th>
<th>Productivity</th>
<th>Fertilizer response rate</th>
<th>Production stability</th>
<th>Soil environmental quality</th>
<th>Biodiversity and biological activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate</td>
<td>JRC</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Climate areas of Europe</td>
<td>JRC</td>
<td>-</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>Precipitation; potential evapotranspiration; aridity index</td>
<td>JRC</td>
<td>+</td>
<td>-</td>
<td>+</td>
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<td>+</td>
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Table 2. continued

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<tr>
<th>sub-indicator</th>
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<td></td>
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<tr>
<td>Soil</td>
<td>JRC (SGDBE)</td>
</tr>
<tr>
<td>Texture</td>
<td>JRC (SGDBE); LUCAS Soil (Eurostat, DG ENV, JRC)</td>
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<tr>
<td>Water capacity</td>
<td>JRC (SGDBE)</td>
</tr>
<tr>
<td>Depth</td>
<td>JRC (SGDBE); LUCAS Soil (Eurostat, DG ENV, JRC)</td>
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<tr>
<td>OM</td>
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<tr>
<td>Mineralogy</td>
<td></td>
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<tr>
<td>Biological activity</td>
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Land use/ management

| Land use type | CORINE Land cover; SGDBE | + + + + + + + |
| Mineral fertilizer consumption (N and P2O5) | EUROSTAT | + + - - - - - |
| Pesticide use | EUROSTAT | - - - - - - + |
| Yield statistics | Eurostat; JRC | + + + - - - |
| Topography | SRTM90 | + - - - - - + |

* Abbreviations: JRC - Joint Research Centre; SGDBE – Soil Geographical Database of Eurasia; LUCAS – Land Use and Cover Area frame statistical Survey; DG ENV – Directorate General Environment; CORINE - Coordination of information on the environment; SRTM - Shuttle Radar Topography Mission; CEC – Cation Exchange Capacity.

Concluding remarks

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. Soil-related policies of the EU are 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.

For the realization of complex agricultural, rural development, food safety and environmental objectives decision-makers of agricultural policy have to implement measures that ensure increased or maintained production by rational and sustainable use of resources. The double criterion of sustainability and productivity increase underlines the necessity of complex information on soil quality. Sustainability in this context is considered for the environmental quality in general and soil use in particular.

Decision-makers must have information on soil resources both with regards to agricultural and environmental issues on a comparable way according to a unified system of criteria. The applied soil
The quality concept can be one of the operational tools to design agri-environmental programs and to implement them for mutual socio-environmental benefits.

The scheme of agri-environmental soil quality indicator development for European applications corresponds to the recommendations of the OECD Expert Meeting (Francaviglia and Parris, 2003) as it takes a spatially and temporally comprehensive ecosystem approach for the integrated assessment of soil functions, land use and related ecosystem services.

Agriculture that takes landscape and environmental management into account can operate harmoniously in a wide range of activities; from most intensively to extensive farming. The harmony and comparability of the social appropriation of added value of agricultural land use and environmental conservation can be guaranteed with the integration of soil quality criteria to socio-environmental context. Soil quality evaluation processes, however, cannot be the sole bases of decision-making, but may play an important role in them.

The proposed soil quality indicator can be used for policy development (including agricultural and soil protection policies) and monitoring through its capacity to indicate:

- the effect of land use change (e.g. marginalization) on the availability and functioning capacity of soil resources;
- the effect of land management (e.g. intensification) on the functioning capacity of soil resources;
- the effect of climatic variability on the production function of soil resources;
- the capacity of soil to mitigate environmental problems (climate change, water pollution etc.).

Based on the information provided by the proposed agri-environmental soil quality indicator and its sub-indicators, current levels of soil agri-environmental services can be assessed, monitored and future levels of such services can be projected.

Current work at the Joint Research Centre focuses on the parameterization of soil attribute components of the soil quality model by individual soil functions with the aim to provide on a mid-term an operational agri-environmental soil quality indicator.

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