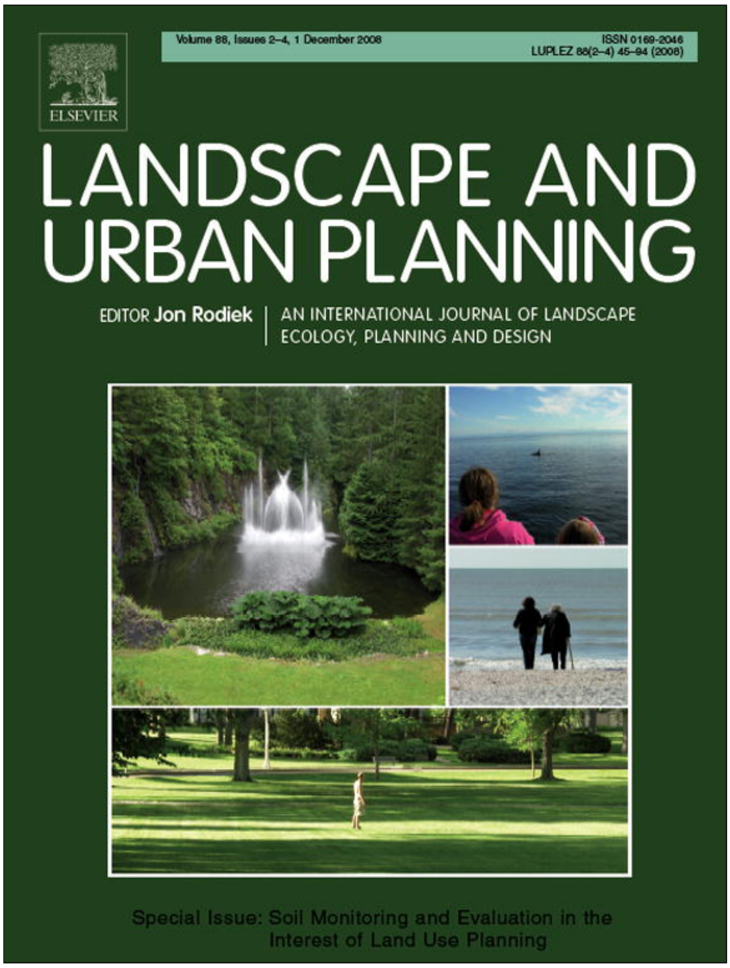
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A method for soil environmental quality evaluation for management and planning in urban areas

Borut Vrščaj[a,b,*], Laura Poggio[a], Franco Ajmone Marsan[a]

[a] Università di Torino, Dipartimento di Valorizzazione e Protezione delle Risorse Agroforestale, (DI.VA.P.R.A.), settore Chimica Agraria,
Via Leonardo da Vinci 44, 10095 Grugliasco, Torino, Italy
[b] Agricultural Institute of Slovenia, Centre for Soil and Environment, Hacquetova 17, SI1001 Ljubljana, Slovenia

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ABSTRACT

Soil represents a complex medium, which makes it difficult to evaluate its quality. In the past, soil quality evaluation was biased towards agricultural production rather than for purposes related to the broad range of functions and services that it performs. Soil function and soil quality in the urban environment differ due to the different needs and roles of soil within the diversity of urban land uses. The quality of urban soil should be evaluated to support public services for good environmental quality management. Planners should also adjust their decisions towards more sustainable urban design. Simple and applicable soil quality evaluation methods accompanied by an operations toolkit that could be used by laypeople are needed.

This paper discusses soil functions, soil quality indicators, pedotransfer functions, and urban soil quality. It presents an urban soil quality evaluation method for different land uses within one particular evaluation system. The calculation of three one-value measures of soil quality are introduced: index of soil quality (expresses soil quality/suitability for a particular land use), soil environmental quality index (environmental value of soil) in terms of performing the crucial ecological functions of soil, and land use change index (land use planning impact assessment on soil resources). The use of the method is described in two procedures: urban soil quality control and soil evaluation for urban planning.

1. Introduction

Soil is a vital natural resource which performs key environmental, economic, and social functions. It is non-renewable within human time-scales. It develops slowly and changes gradually over time, showing great spatial variability. Soil resources are under increasing pressure and its quality is decreasing. Erosion, a decline in organic matter content and biodiversity, contamination, sealing, compaction, salinisation, and landslides have been identified as the main threats to soil (Andrews and Carroll, 2002; Commission of the European Communities [EC], 2002). Of these threats, sealing and contamination predominate in urban and adjacent areas. Urban sprawl and land consumption is recognised as one of the major threats to soil in Europe.

Urban planning practices should integrate soil quality evaluation procedures to achieve rational urban planning with regards to soil consumption and to ensure less destructive methods with regards to the capacity of the soil to perform its environmental functions. To achieve effective management of the quality of the urban ecosystem, it is important to develop soil quality evaluation methods adapted for use by laypeople. The methods should facilitate effective soil evaluation, and enable planners to recognise the environmental quality of soil, its properties, spatial location, and extent in urban and suburban areas. The outputs of the methods should be developed to the level where they can be easily integrated in existing planning procedures and used in local communities with little adaptation by local experts. The application of the method should yield information applicable to actions that will be required by national and forthcoming European legislation.

The aim of this paper is to present a method for the evaluation of soil quality in city environments to achieve: (i) adequate performance of environmental functions of soil in cities, (ii) healthier environmental and pleasant living conditions for citizens; and (iii) more sustainable spatial planning and development of cities. An additional, but still important, goal is to contribute information that will help bridge the communication gap between soil scientists, urban planners, and decision makers.

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[*] Corresponding author at: Agricultural Institute of Slovenia, Centre for Soil and Environment, Hacquetova 17, SI1001 Ljubljana, Slovenia. Tel.: +386 1 2805290.
E-mail address: Borut.Vrscaj@kis.si (B. Vrščaj).

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2. Problems in soil evaluation

Soil is a multifunctional medium, and, as such, has the ability to provide several services and play several roles simultaneously (i.e., biomass production while buffering harmful substances and/or filtering water). Descriptions of the functions of soil reveal a broad range of perceptions of the role of soils (Herrick, 2000; Ditzler and Tugel, 2002; EC, 2002; Nortcliff, 2002; Hanks and Lewandowski, 2003; Karlen et al., 2003; Kibblewhite, 2003; U.S. Department of Agriculture - Small Quantity Generators [USDA SQG], 2004; Tzilivakis et al., 2005). In the last decade or two, the perception of the importance of soil has moved towards greater consideration of additional soil functions than had not been previously recognised. In developed industrialised countries the primary goal of agriculture (i.e., to provide food of adequate quality and quantity), appears to have been achieved. Societal concerns have changed from sheer productivity towards greater sustainability of agricultural production. The National Soil Resource Institute (NSRI, 2001) stressed the environmental importance of soil by defining soil functions in the following order: (i) environmental interaction; (ii) food and fibre production; (iii) provision of a platform for development and human activities; (iv) support for ecological habitat and biodiversity; (v) provision of raw materials; and (vi) protection of cultural and natural heritage.

Soil functions are the basis for soil quality interpretation. The multifunctional role of soil makes it difficult to conduct exhaustive and comprehensive evaluations. The main questions which must be answered regarding the quality assessment of a particular soil are:

- what function is the soil performing?
- what functions could it perform?
- are these the functions the ones that we want it to perform?
- is this the best use of this soil?

An approach to defining soil function that is similar to the ‘goods and services’ approach is suggested (NSRI, 2001). Soil functions and soil quality are assessed on the basis of what we require a particular soil to do. In this case, the soil is valued with regard to what it provides to society: tangible products (i.e., fibre and food production; raw material) as well as less concrete services (i.e., filtering and detoxification of water; carbon sequestration). These less tangible services are provided by environmental functions important for the proper functioning of the ecosystem(s).

The perception of what constitutes ‘good’ and ‘bad’ soil varies with respect to the functions performed by soil (Doran and Parkin, 1994). Different definitions of soil quality have been proposed (Larson and Pierce, 1991; Parr et al., 1992; Harris and Bezdicek, 1994; Herrick, 2000; Doran, 2002; Sojka et al., 2003; USDA-SQG, 2004), some of which are rather complex. The shortest definition of soil quality is simply ‘fitness for use’ (Pierce and Larson, 1993). A characteristic common to all definitions is that ‘soil quality is the long-term capacity of soil to perform its functions effectively.’

With soil being such a complex medium, it is difficult to evaluate. In the agricultural context the evaluation of soil quality was integrated in different soil potential ratings and land capability/suitability classifications (Food and Agriculture Organization of United Nations [FAO], 1981; Rossiter, 1995; Young, 2000; Helms, 2006). Changes in the priorities of society in developed countries during the last decade of the 20th century, together with demands and pressures on soil resources, have redefined views of soil quality especially in terms of the needs of non-agricultural stakeholders. The quality of soil is largely defined by the priority of the environmental functions the soil performs and represents a composite of the chemical, physical, and biological properties of soil. The major issues or components defining soil quality are: (i) *environmental quality*—the ability of soil to attenuate environmental contaminants, pathogens, and offsite damage; (ii) *health*—the relationship between soil and plant, human and animal health; and (iii) *productivity*—the ability of soil to enhance plant and biological productivity. The principles of soil evaluation that come from the agricultural use of soil and the same evaluation concepts based on the same (or very similar) soil quality indicators are applicable for soil quality evaluation in all soil-associated ecosystems (NSRI, 2001) including the urban environment.

The term soil quality is often assigned to specific soil attributes (i.e., pH, soil structure stability, organic matter content, and nutrient supply). However, soil quality cannot be determined by the evaluation of a single measured parameter or measured by crop yield, water quality, or any other single factor. It is assessed through an evaluation of several *soil quality indicators* (SQI). Soil quality indicators are physical, chemical, biological, and functional soil and soil-related measured parameters and characteristics that can be expressed in terms of numeric values. Indicators, and the values assigned to them, may be determined by exact science (laboratory analysis) or expert opinion. The value of each indicator depends on the function it explains. The same indicator may have different optimal values for different functions, e.g. the optimal pH for a corn field is very different from the optimal pH for an ornamental garden with *Erica* species or a blueberry plantation; soils with high clay content can be evaluated better when planning chemical industry facilities compared with assessing the quality of an agricultural field for such use.

Several *soil quality indicator sets* have been developed for different purposes. Nortcliff (2002) suggested a general SQI set within standardised soil quality attributes. The National Soil Resources Institute (NSRI) developed a typical minimum dataset of physical, chemical and biological indicators for soil quality based largely on agricultural experience (NSRI, 2001). Tzilivakis et al. (2005) used the SQI set to assess the risk to soil functions in the context of general soil evaluation; Huinink (1998) did so for the calculation of the heavy metal concentration threshold values; Schipper and Sparling (2000) used the set to compare soil quality for different natural and semi-natural land uses; Larson and Pierce (1994) compared conventional and organic farming to assess soil quality in an agricultural context; Scheyer (2000) estimated dietary risk from soils in urban gardens; Hanks and Lewandowski (2003) determined the final topsoil condition for general urban soil; and Hanks and Lewandowski (2003) defined parameters required for the determination of the quality of compost and soil additives in the context of urban soil quality protection. Huninik (1998) discussed sets of measured soil parameters within the context of suitability for different types of urban soil use: public gardens, playing fields, ornamental planting, lawns, and herbaceous and recreational greens and road verges. *Pedotransfer functions* (PTF) are evaluation models or predictive algorithms of particular complex soil properties from other more easily available or cheaply measured soil parameters (Doran and Zeiss, 2000). A variety of different pedotransfer modules and functions was developed mostly for agricultural soil evaluation. Some of these are simple, while others require large datasets and complex evaluations. McBratney et al. (2002) presented a review of PTFs for predicting chemical, physical, and mechanical soil properties that have been published by several authors. For the purpose of developing an evaluation method for urban soil quality, it is important to be aware that a number of complex soil quality indicators may be estimated from easy-to-measure or already available data; and existing PTFs, developed mainly for agricultural purposes, may be used and/or adapted to evaluate soil quality for management and planning in urban areas.

Urbanisation and urban growth. The ratio between urban and non-urban populations began to change rapidly during the last two centuries. In 1800, only 3% of the world's population lived in cities, while by 2007 this ratio will exceed 50% and is expected to rise to 61% by 2030 (United Nations, Department of Economic and Social Affairs [UN-DESA], 2004). In Europe the urban ecosystem is becoming the main human living area (Bouma et al., 1998a,b). At present, 76% of people in developed countries live in cities (UN-DESA, 2004; Population Reference Bureau, 2005). The growth of cities has a vast impact on adjacent landscapes. Between 1990 and 2000, 2.8% of Europe's total land mass was affected by land use changes, including a significant increase in urbanized areas. The proportion of sealed surfaces varies significantly between Member States and regions, from 0.3% to 10% (EC, 2006). Cities are also becoming less compact (Kasanko et al., 2006). The SCATTER project (Gayda et al., 2004) lists negative environmental, economical and social effects of urban sprawl, including the consumption of land and the loss of high quality agricultural land and open space as well as the destruction of biotopes and the fragmentation of ecosystems. Agricultural soils are capable of performing the most complete list of soil functions (EC, 2002). Thus, urban expansion that consumes agricultural land is threatening not only food and fibre production, but many environmental and human functions related to well-being. In addition to the effects on neighbouring ecosystems, the expansion of urban areas also affects the inner urban ecosystem (Stroganova et al., 1995; Stroganova and Prokofyeva, 2006). For some authors, the spatial growth of urban areas is much less important than the effects of further urbanisation in terms of increased traffic, pollution, and energy consumption (Bouma et al., 1998a,b). Human activities affect and determine the quality of the urban environment, including soil which acts as a perfect trap; consequently ecological problems are distinctively reflected in polluted and otherwise degraded soil and surface and ground waters.

Urban ecosystems are complex habitats with extreme diversity. Each urban area is a juxtaposition of areas of very different ecosystems bordering on and influencing each other (i.e., traffic corridors border playgrounds and schools, blocks of houses border ornamental gardens, industrial areas border agricultural fields, etc.). A patchwork of different uses of land requires different *land use classifications* for planning, management and environmental activities in cities. The number of land use classes and class definitions can vary significantly from town to town, even for the same or similar land uses (City of Berlin, 2004; American Planning Association, 2006). For practical soil quality management, a manageable number of land use classes should be carefully defined. The main features that should be described for each land use include: (i) relevant soil functions; (ii) required/suggested/adequate soil quality; (iii) the main/most important soil quality indicators; and (iv) suggestions for soil quality management.

Urban soil develops under both natural zonal and anthropogenic soil-forming factors. It can differ significantly from adjacent soils under (semi)natural land uses. They play a principal role in biochemical transformations, cycling elements, filtering water, supporting plants and infrastructure, and supporting recreation (Stroganova et al., 1995). Urban green areas of adequate size are important for human well-being and the sustainability of the city (Chiesura, 2004). Semi-natural areas (parks, urban greens) contribute to the quality of life in cities, enrich human life, and provide social and psychological benefits. Soil forms the basis of these natural areas, thus it indirectly enables the fulfilment of important immaterial and non-consumptive human needs within the urban environment. A close look at the concepts of liveability, environmental quality, and the quality of life in the urban environment (van Kamp et al., 2003) leads to the conclusion that the functions performed by soil can be directly related to the quality of human life. Regarding the quality of life components (Fig. 1) the soil in an urban environment directly or indirectly contributes to the health, physical environment, scenic quality and housing, and natural resources. The definition of the needs of an urban population and the quality of life in an urban environment clearly encompasses the 'goods and services' approach.

The functions of soils in urban areas are particularly important because of their proximity to humans (Stroganova et al., 1995). The risk of dangerous substances passing through the human body through inhalation, ingestion, and dermal contact (Abrahams, 2002) is higher than in agricultural or natural settings. As soil is an important component of urban ecosystems, its quality must be recognised and integrated into environmental quality management and sustained at an appropriate level. Although other environmental factors have been largely recognised as essential components of city sustainability (Ravetz, 2000) and quality of life (van Kamp et al., 2003), soil quality information is generally overlooked at the time of land use planning. This is mainly due to the high social and economic pressure that makes soil only a consideration in terms of being a surface for buildings or a space for development. In part, however, it is also because of an existing inefficiency in transferring information to stakeholders (Brown, 2003). The priority of functions of soil in agricultural areas is only to a certain extent comparable with the priority of functions of soils in urban areas. Comparable agricultural soil quality evaluations are not suitable for application to an urban setting; they must be significantly adapted or developed anew. The most notable reasons, which require a special approach to soil evaluation in urban environments, are:

- The diversity of urban land uses and the specifics thereof;
- The significance of individual soil functions within different land uses;
- Extreme soil variability due to past and recent human activities;
- Immaterial and non-consumptive human needs.

Urban soil is moved, mixed, compacted, burned, and changed with mineral and chemical additives and shows extreme diversity (Schleu et al., 1998; Lorenz and Kandeler, 2005). The soils of building areas are completely destroyed or extremely disturbed while soils adjacent to construction sites are frequently altered and often compacted (Randrup and Dralle, 1997).

Probably the most significant urban soil characteristic is that it is polluted. When polluted, the soil acts as a source of pollution, and the risk of affecting human health is high. This is especially true in the case of heavy metal content (Kelly and Thornton, 1996; Biasioli et al., 2006). A significant number of comparative studies on the distribution, dispersion and chemical characteristics of toxic and potentially toxic heavy metals in the urban environment (Kelly and Thornton, 1996; Madrid et al., 2002; Cicchella et al., 2003; Imperato et al., 2003; Lu et al., 2003; Romic and Romic, 2003; Biasioli, 2006; Rodrigues et al., 2006; Wong et al., 2006) or in comparison to adjacent soils (Biasioli et al., 2006) have been carried out. Several authors have explored the distribution and concentrations of pollutants in relation to urban land uses (Xu and Thornton, 1985; Sutherland and Tolosa, 2000; Madrid et al., 2002; Ruiz-Cortes et al., 2005; Davidson et al., 2006). Pollutants may be transferred to human bodies in three main ways: ingestion, inhalation, and dermal contact (Abrahams, 2002), or they may potentially enter into the food chain through food produced on polluted soil (Xu and Thornton, 1985; Nicholson et al., 2003). The extent of the harmful effects depends on the age and structure of the population and the type and intensity of the contact with the soil. Children, as the most susceptible group of the population, may be affected greatly by heavy metal intake; they are also especially exposed to soil ingestion. This is the main reason why the soils of playgrounds,

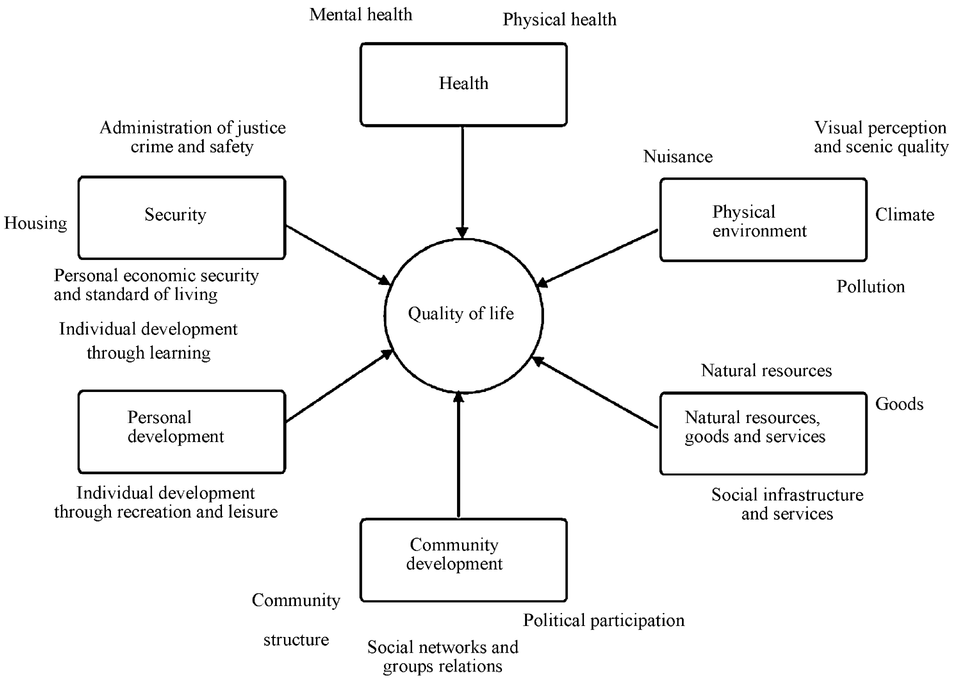

Fig. 1. Quality of life components (van Kamp et al., 2003).

kindergartens (De Miguel et al., 2006; Ljung et al., 2006a,b), parks (Lee et al., 2006), allotment gardens (Scheyer, 2000), and other urban land areas where people come into close contact with soil are investigated. The term 'soil quality' also comprises the level of soil pollution at which human health may be at risk or affected. One of the objectives of the Thematic Strategy on the Urban Environment is to ensure a high level of quality of life for citizens by ensuring an environment where the level of pollution does not cause harmful effects on human health and the environment.

Soil evaluation for urban planning. The expansion of urban areas and the resultant sealing of soil causes soil functions to be primarily ceased from the spatial aspect (e.g., during construction, the buffering and filtering capacity is not only decreased but completely eliminated within the area of the irreversible destruction of the soil covering). Soil sealing, accompanied by diffuse and local soil contamination and soil compaction have been recognised as two of the major European soil threats (Verheye, 1996; EC, 2002; Gayda et al., 2004). The proposal to establish a framework for the protection of soil (EC, 2006), among others matters, determines that "soil should be used in a sustainable manner, which preserves its capacity to deliver ecological, economic and social services, while maintaining its functions so that future generations can meet their needs" and "sealing is becoming significantly more intense in the Community as a result of urban sprawl and increasing demand for land from many sectors of the economy, and this calls for a more sustainable use of soil." To achieve sustainable city management it is important to recognise the importance of soil and its quality. Therefore, the planning process should be directed with due consideration to the following primary aspects:

- A healthy and pleasant environment for human life and efforts to minimise harmful impacts of human activities on groundwater and neighbouring ecosystems should represent the top priorities for urban ecosystem management and, equally, for the management of urban soils as part of the urban ecosystem.
- "Sustainable urban design (i.e., appropriate urban planning) can help to reduce urban sprawl, loss of natural habitats, and biodiversity. Integrated management of the urban environment should foster sustainable land use policies, which avoid urban sprawl and reduce soil sealing" (EC, 2002). In this sense, planning the expansion of cities in a manner that takes into consideration the selection of 'bad soils' for city expansion may be considered to be more sustainable or at least less destructive to the soil resource and the environment. This means that the sealing of soils of lower environmental quality should be encouraged and 'good' soils in the vicinity should be preserved.
- The planning of cities with as much preservation of soils as possible (e.g., the inclusion of green areas, minimising the spatial extent of impermeable artificial surfaces, etc.).
- Urban development must be planned in a way that causes as little damage as possible to adjoining areas (Doran and Parkin, 1994) or to ensure a more rational use of land to maintain as many soil functions as possible (EC, 2006). The effects of civil engineering projects on adjacent land must be assessed during the planning of the expansion and adequate protective measures must be implemented, which should be factored into the cost of the project.

3. The urban soil quality evaluation method

The method is based on the assumption of the relevance of different soil functions and, consequently, the soil quality definition varies within diverse urban land uses. For example, to evaluate the soil quality of children's playgrounds, a low concentration of pollutants and a high capacity of the soil to buffer and filter are more important than soil fertility. The buffering and filtering function is in this case more important than the food and fibre production function. On the other hand, when the quality of the soil within commercial centre areas (e.g., parking lots surrounded by grass-covered soils) is assessed, soil quality may be primarily defined by its function to absorb water, to support the growth of ornamental plants and grass, and to filter pollutants for groundwater protection.

In this method the term PTF is used for the evaluation of algorithms, equations, Boolean logic or fuzzy logic rules, which grade

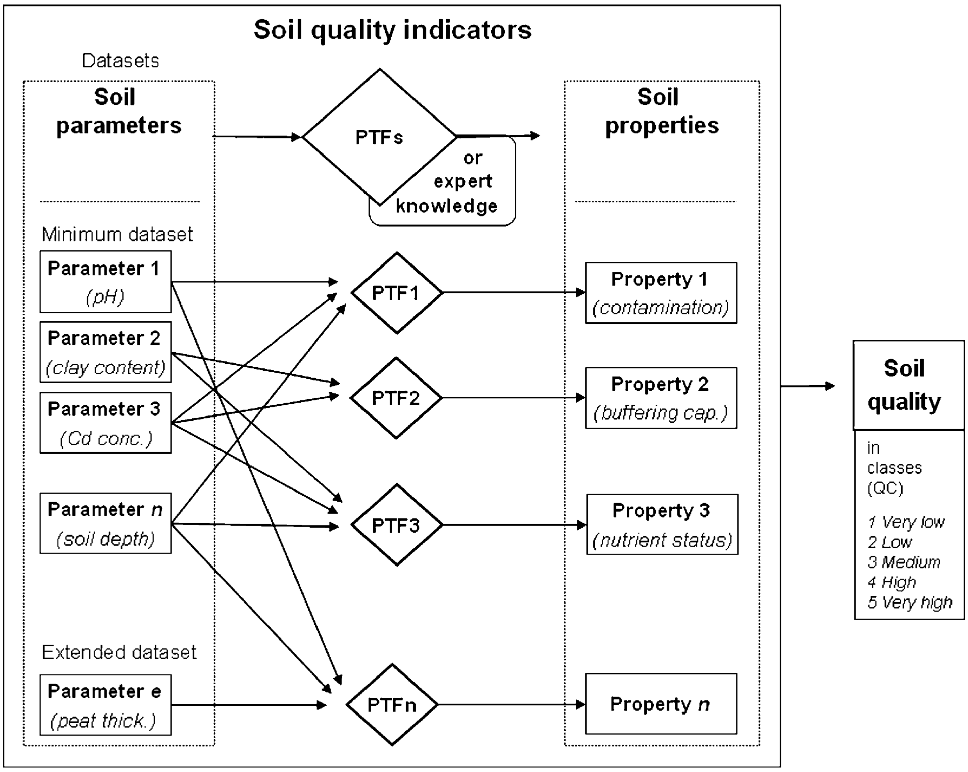

Fig. 2. Overview of the entire evaluation method.

the measured soil data values into simple or complex soil property quality classes. Both the measured soil parameters and the soil properties evaluated through PTF form the soil quality indicators (Fig. 2). Within this method new PTFs are not developed. As already discussed there are many available PTFs, which can be adapted for local use. In the event that suitable PTFs are not available, the evaluation and classification of soil data may be made using expert knowledge. The results of individual PTF evaluations are quality classes (QC). The quality of the data, the spatial accuracy of the input soil information, the number of measurements and the spatial variability of soil properties in cities usually do not justify the use of a large number of classes. In practical work, five classes offer an applicable and sufficiently detailed ranking of the quality of the individual indicators. The QC classes can be defined as presented in Appendix A for each individual SQI.

Not all soil quality indicators are equally important for soil quality evaluation for a certain purpose. More significant SQI for a selected land use has a greater influence on the determination of the soil quality, while less important indicators contribute less significantly to the final result. The level of significance of a separate SQI is expressed by the soil quality indicator weight (IW) values which are defined in a range from 1 to 3 where: 1—SQI is less significant, 2—SQI is normally evaluated, and 3—SQI is very important. The same SQI can have a different weight when evaluated for different land uses.

Effective urban soil evaluation can be carried out within an operative system composed of data, procedures, work steps, documentation and IT support. Various urban-ecosystem related data are collected and stored in information systems where the soil information should become a standard component, which is maintained as a continuously growing data source. The measured and observed soil parameters and other relevant parameters should be continuously collected from different sources. The items in Appendix B represent an ideal framework that is complex and not easy to establish; it grows slowly and is fully operational within a certain time period. Nevertheless, soil quality evaluation can be carried out when the essential components are available (underlined in Appendix B). The methodology describes four consecutive steps: (1) evaluation of individual soil quality indicators; (2) evaluation of overall soil quality; (3) assessment of environmental soil quality; and (4) evaluation of the impact of land use change (Fig. 3).

4. The core mechanism of soil quality evaluation

The soil quality evaluation is based on the *predefined information* which is described for each land use (or land use group) by local soil/environmental experts. Appropriate/applicable SQI are selected and QC values are defined for each individual SQI (Appendix C). Further on, for each land use, the classes of required SQI quality and SQI weights are defined (Appendix D). Predefined information is elaborated once and supplemented when needed. It represents standard soil information and is used in a local community for soil evaluations in planning or environmental management case studies.

The soil quality evaluation itself is carried out within an area of uniform land use in two steps:

Step 1: *Evaluation of individual soil quality indicators.* The SQI relevant for a present or planned land use are selected. They are separately evaluated using PTF to assess the quality of each. Evaluation results are expressed as quality class (QC) values (Fig. 2). In the event that suitable PTFs are not available, the evaluation of the soil measured data and the classification of soil properties may be made using expert knowledge.

Step 2: *Evaluation of overall soil quality.* The soil quality for a considered land use is calculated by using QC values of individual SQIs and predefined SQI weights by applying two equations. First, the qualities of separate indicators are compared to

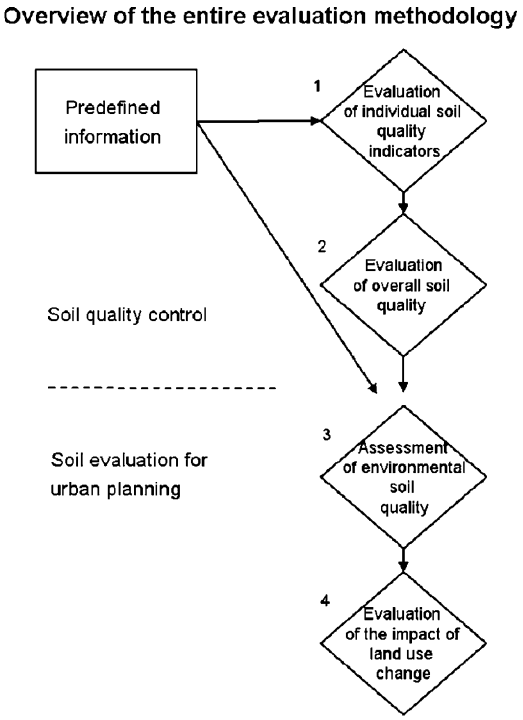

Fig. 3. Evaluation of separate soil quality indicators using pedotransfer functions or expert knowledge.

the required quality predefined for the selected land use. The *quality difference* (QD) is calculated for each SQI using Eq. (1). Quality difference values express to what extent the individual soil quality indicators meet the required quality criteria for the land use in question. The value and the magnitude of QD values indicate how the evaluated soil quality indicator differs from that required for the evaluated land use:

- $-1 > \mathrm{QD} \geq -4$: the SQI quality is lower than required.
  - o When the $\mathrm{QD} \approx -1$ the quality is slightly below that required, soil remediation measures should be carried out to improve the evaluated soil property.
  - o When $\mathrm{QD} \ll 1$ (e.g., it is close to -4) the quality is well below that required. Soil remediation or, when not feasible, land use change should be reconsidered.
- $\mathrm{QD} \approx 0$: the evaluated quality of the indicator matches that required.
- $1 < \mathrm{QD} \leq 4$: the evaluated indicator quality exceeds that required; the quality is better than needed.

$$\mathrm{QD} = (\mathrm{QC}_{\mathrm{identified}} - \mathrm{QC}_{\mathrm{required}}) \qquad (1)$$

where QD is the difference in the quality of individual SQI between the identified (evaluated) ($\mathrm{QC}_{\mathrm{identified}}$) and required/predefined ($\mathrm{QC}_{\mathrm{required}}$) SQI quality class.

$$\mathrm{ISQ} = \sum_{i=1}^{n} \frac{[\mathrm{QD}_i * (\mathrm{IW}_i/2)]}{6n} \qquad (2)$$

where ISQ is the index of soil quality, n is the number of evaluated SQI; QD_i is the deviation of soil quality expressed in classes for each individual i (soil quality indicator); IW_i is the SQI weight for each individual i; 2 is a factor to normalise the IW_i values, and 6 is the factor used to distribute the output ISQ values in a range from -1 to 1.

Second, the QD and the IW values are used to calculate a single-value *index of soil quality* (ISQ) (Fig. 4) by using Eq. (2). The ISQ is a one-value numerical representation of the soil quality determined for the evaluated uniform land use. Then Eq. (2) is calibrated to give results between -1 and 1; i.e., whatever number of SQI is used in the evaluation. The ISQ should be interpreted as follows:

- $\mathrm{ISQ} < 0$: The soil quality is low or unsatisfactory:
  - o When ISQ is a little below 0, the soil quality marginally deviates from that required
  - o When the $\mathrm{ISQ} \approx -0.5$, the soil quality is considered to be unsatisfactory. Soil remediation is recommended
  - o When the ISQ value is below -0.5 or approaching -1, the soil is not suitable for the selected land use and remediation measures are needed. If the remediation is not feasible there is a need to change the land use towards a less demanding use in terms of soil quality. $\mathrm{ISQ} \approx 0$: the soil quality meets the required quality
- ISQ value > 0: the soil quality exceeds the requirements for the evaluated land use.
  - o $\mathrm{ISQ} \approx 0$: the SQ marginally exceeds the required quality.
  - o $\mathrm{ISQ} \approx 0.5$: land use with higher soil quality requirements should be considered.
  - o $\mathrm{ISQ} \approx 1$: the soil is ‘too good.’ The evaluated/planned land use can be interpreted as wasteful with regards to the potential of the soil resource.

The ISQ represents the soil quality as assessed on the basis of a ‘goods and services’ approach; i.e., the soil is evaluated on the basis of what we need the soil to do/to produce or on the basis of the services/functions we need it to perform.

5. Application of the soil quality evaluation method

The soil environmental quality evaluation is applied for:

1. Management of the soil quality with regard to present urban land uses. The soil is evaluated to determine the quality/suitability of the soil for a certain purpose. Typical questions which must be answered within the evaluation process are: is the soil suitable for a present land use? How suitable is it? Which soil quality indicators/parameters are not satisfied? Is soil remediation needed? Is the soil too good for its present use?
2. Soil quality evaluation for planning purposes and assessment of the impact of land use change on the soil resource. In this case, soil is evaluated following the ‘environmental–natural resource protection’ approach. Questions which must be answered are: What is the environmental quality of the soil in the area? How will it be affected by the land use change? Will the capacity of soil to perform its main environmental functions decrease? If yes, by how much? Which planned land use will have lower/higher negative impacts?

The core mechanism of the soil quality evaluation is embedded in two procedures: Soil quality control (Procedure A) and Soil evaluation for urban planning (Procedure B) (Fig. 5).

Procedure A is carried out for control and soil quality monitoring. The quality of soil of an existing area of the uniform land use is verified. The land use is not changed. Land use relevant SQIs are selected for the evaluation. Step 1 and Step 2 of the core mechanism of soil quality evaluation are carried out. For easier evaluation a form may be used (Appendix E). Quality difference (QD) and ISQ

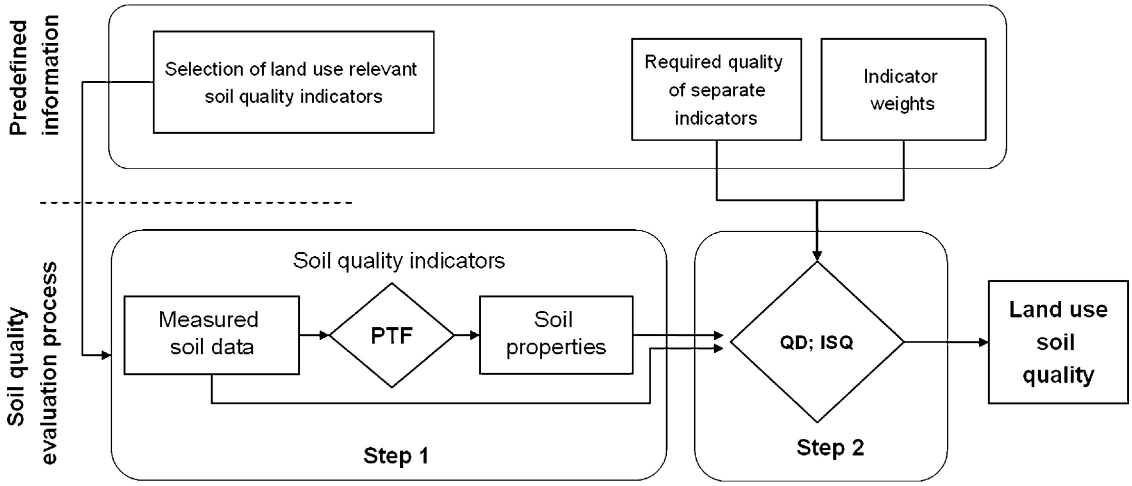

Fig. 4. The overview of the urban soil quality evaluation method.

values are interpreted as already described.

$$\mathrm{SEQ} = 100 \times \left(\sum_{i=1}^{n} \frac{\mathrm{QC}_i}{5n} \right) \quad (3)$$

where SEQ is the soil environmental quality index, QC_i is the quality class of each i (separate soil quality indicators); n is the number of SQI evaluated in the equation; 5 is the factor used to normalise QC_i values expressed in 5 classes.

Procedure B is carried out to estimate the environmental quality of the soil and to assess the impacts of a land use change on the soil resource. The main impacts are the destruction of soil by sealing (and consequently the termination of the environmental functions the soil performs) and a change in the soil quality in the area. The quality can decrease (e.g., mixing, compacting, topsoil removal, etc.) or improve (e.g., remediation, increase in organic matter, etc.) This procedure enables a comparison of the soil capacity with regards to present land use and the estimated capacity of the soil after the land use change. The evaluation is performed using a form (Appendix F). Procedure B is carried out in two parts. In the first part, the suitability of the soil for the planned land use(s) is verified by applying Step 1 and Step 2 using the planned land use relevant SQI. Additionally, the impact of planned land use change to the soil is assessed by applying Steps 3–5.

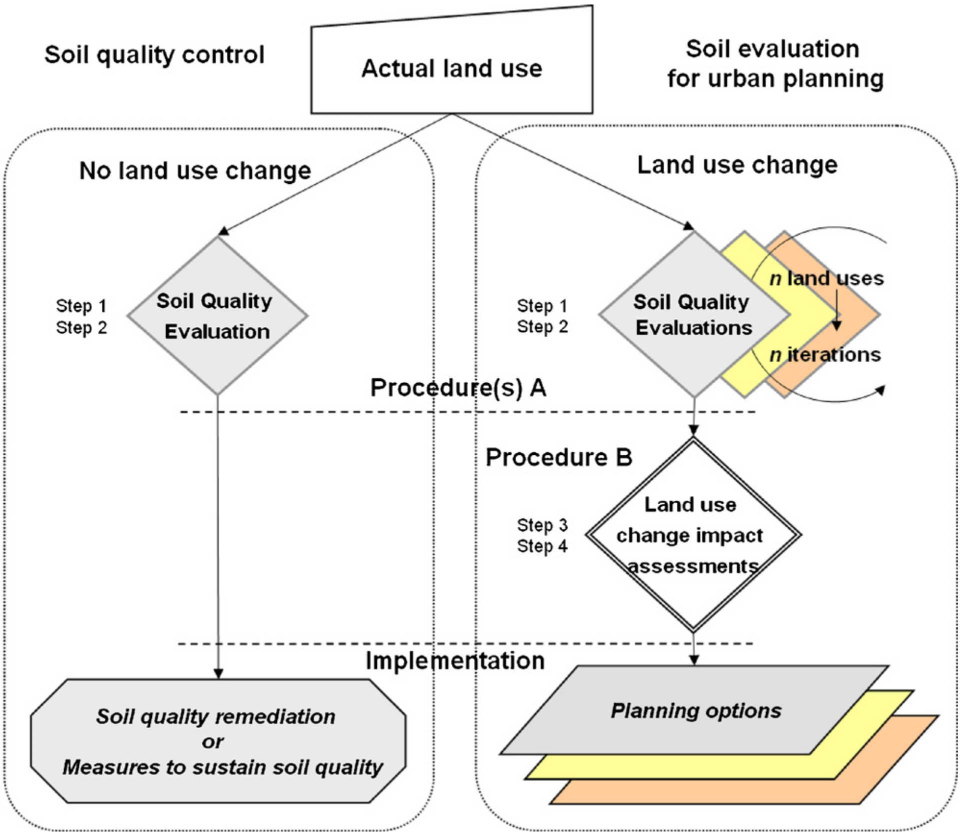

Fig. 5. Application of the soil quality evaluation method in two procedures.

Step 3: *Assessment of environmental soil quality*. To evaluate the environmental soil quality, the SQI, which reveals the capacity of the soil to perform the basic environmental soil functions (i.e., filtering, buffering, and decomposition of pollutants, water filtering, food and fibre production capacity) are selected as input information. The Basic set of SQI (Appendix G) comprises elementary soil analytical parameters, which are commonly measured and soil properties, which are generally assessed. The set can serve to distinguish between 'good' and 'bad' soil in the most general sense of the word and reflect the potential of the soil to perform the main environmentally important functions and services. It can be used to evaluate the environmental quality of a particular soil and to estimate the loss of the soil resource and the decline in the performance of soil functions in the event of soil sealing. The QD values from the Basic SQI set are used to calculate the soil environmental quality index (SEQ) by applying Eq. (3). The SEQ equation yields values in a range from 0 to 100. They can be used for a qualitative description of the soil quality and for quantifying the terms 'good' and 'bad' soil in a general meaning of the word. The SEQ values can be rated as follows:

- $\text{SEQ} < 20$: soil of marginal quality.
- $\text{SEQ} \approx 20$: low quality.
- $\text{SEQ} \approx 40$: low to medium quality.
- $\text{SEQ} \approx 60$: medium quality.
- $\text{SEQ} \approx 80$: good to medium good quality.
- $\text{SEQ} \approx 85$: good to very good quality.
- $\text{SEQ} > 90$: high capacity soil.

Step 4: *Evaluation of the impact of the land use change*. First the area performance index (API) is calculated. The API quantifies the potential of the area to perform the main environmental soil functions. The API is calculated on the basis of the SEQ and active soil area (ASA) value and by using Eq. (4). The ASA is an area of unsealed soil within the planning area expressed as a percentage. The resulting API value includes the spatial and quality dimensions of the soil. In the evaluation procedures and corresponding forms, two API values are present. The APIe value is the area performance index assessed for the evaluated area under the present land use. The APIp value is the area performance index estimated for the potential/planned land use after the land use change. The APIe and APIp values are calculated using Eq. (4).

$$\text{API} = \text{SEQ} \times \frac{\text{ASA}}{100} \tag{4}$$

where API is the area performance index, ASA is the active soil area (in%) and SEQ is the soil environmental quality index.

$$I = \text{APIp} - \text{APIe} \tag{5}$$

where I is the impact of the land use change, APIp is the area performance index of the present land use, and APIe stands for the area performance index of the potential land use.

In continuation, the impact of the land use change (I) value is calculated by using Eq. (5). The relative value of I indicates the estimated impact of the planned land use change on the soil resource or, in other words, how the capacity of soil to perform the main environmental functions will change after land use alterations in comparison to the present situation. The results of the equation theoretically range between 0 and 100. Since the I value is calculated by a comparison of the API values of the existing and planned land uses, it may represent a measure of change. The I value is used for the estimation of how much the capacity/quality of the soil resource in the area will decrease (increase in the event of soil remediation). It can be used to support more sustainable planning decisions or to trigger soil/environmental protection measures. A negative I value indicates that the planned land use will reduce the soil capacity/quality in the area in qualitative and quantitative ways. Positive I values indicate soil quality improvement in the area.

6. Discussion

The soil scientific community is aware of the complexity of soil quality evaluation. Many methods have been developed for different purposes, where a significant number of them are technical and require expert knowledge in order for them to be applied. In view of the highly varied types of end-users to which soil quality evaluation is directed, an applicable method for soil quality evaluation in urban areas must be flexible and easy to implement and upgrade. It should produce sensitive, effective, and clear results.

Soil quality evaluation. The selection of soil quality indicators should be made carefully. The involvement of complex indicators could significantly improve the accuracy of the soil quality evaluation but it is likely that the procedure would then be much less applicable. It could also become costly, making unfeasible demands on time and knowledge. From the extensive list of possible soil parameters and measured soil data, a selection of the most important, generally applicable, and frequently measured SQI should be made, where these can be evaluated by using simple evaluation modules or pedotransfer functions.

Several soil quality indicators used in the evaluation may be mutually dependent. The high quality of many SQI can, to a certain extent, compensate for the low quality of one SQI. In situations when numerous SQI are evaluated and the quality is high for all of them but one, the resulting index value can still be relatively high (e.g., >0.5) in spite of the very low quality (low QD value) of only one indicator. Consequently, the soil should be interpreted as 'quality soil' and the significance of the single low quality SQI evaluated should be judged according to its importance or it should be determined by the legislated threshold values or by an additional risk-assessment procedure. Such situations often occur in urban areas when heavy metal soil pollution is defined in terms of threshold values. In reality, the quality of other important soil properties with high evaluations (e.g., organic matter, clay content, etc.) to a certain extent compensates for the single parameter with a low evaluation; thus, the high ISQ values indicate the lower potential for heavy metals to be released into the environment. In such cases the risk of soil pollution should be further assessed using additional risk evaluation procedures.

Many different soil quality classes may be used. During practical work, the ten-class rating was found to be too detailed regarding the spatial resolution of data and the spatial variability of the soil parameters, while three classes were found to be less suitable for the evaluation. It is justifiable to define the quality classes more precisely in cases when accurate and quality input about soil and land information is available, the spatial resolution of data enables/justifies the numerical precision of the evaluation, and separate SQI evaluation procedures are used, which give results of required precision. In this case, real values between 1 and 5, respectively (e.g., 3.5) can be used. Soil quality indictor weights (IW values) may be integers (1, 2 or 3) or real. An adequate definition of the soil quality class and indicator weight values for local environments and land uses primarily depends on local expert knowledge.

Evaluation of the impact of land use change on the planning process. The soil resource is affected during urban expansion of the city by the physical destruction of the soil (the spatial decrease in the active soil surface—soil sealing), and by the negative impacts caused by construction activities on the soils adjacent to the construction sites. Urban planning practices oriented towards more sustainable urban planning should take into consideration the evaluation of the loss of the soil resource and the assessment of the negative effects on the performance of the environmental soil functions resulting from urban expansion. The main purpose of Procedure B is to obtain a notion of: (i) how the active soil area will decrease as a result of the land use change; i.e., what the loss of the soil resource will be; and (ii) how the performance of soil functions will decrease (or increase in the event of remediation) with the land use change.

Building activities often degrade the soil adjacent to the actual construction site (e.g., the soil is mixed and/or compacted, and topsoil may be removed, polluted, or the quality lowered in some other way). This degradation is taken into consideration by adapting the ASAe to ASAp values in the evaluation procedure. For the final evaluation of the land use change impact on the soil, the ASAp value is used.

The assessment of two or more different planning areas at the same time enables a comparison of the API and I values. The I values calculated for different optional land uses may be used in scenario modelling. This information derived from the soil quality indicators can be useful in guiding planners in the selection of a planning option which, from a soil protection point of view, would result in a lower negative impact on the soil resource and a lower decrease in soil function performance within the planning area.

High ISQ values can be used to detect the irrational use of soil (e.g., soil with high environmental value is environmentally too good to be sealed by extensive shopping centres). A comparison of the quantified results of Procedure B can be used to reconsider or adjust planning decisions towards more "sustainable urban design" (i.e., appropriate urban planning) and to "foster land use policies, which avoid urban sprawl and reduce soil sealing" (EC, 2002).

The applicability of the method is facilitated and promoted also by means of the careful preparation of a set of instructive documents adapted to end-user needs and knowledge. In any case, the general pre-defined input parameters presented in this evaluation method should be included in the introductory stage of the method supplemented by local experts to best meet the specific needs of the local conditions.

In developing an end-user oriented method, a typical trade-off situation is frequently encountered: the simplicity of the method used might entail a loss of scientific accuracy regarding the method, but this is compensated for by greater applicability and, above all, acceptability. If the method is recognised and accepted by planners it might contribute to better soil quality management in urban areas and more sustainable urban planning.

The diversity of cities and local conditions do not facilitate the elaboration of an evaluation method based on inflexible set of fixed parameters (i.e., threshold values of soil quality parameters), or the determination of a universally applicable PTF. The concept of the method itself is applicable within different cities but users are encouraged to supplement and tailor the method to meet the national/local legislation requirements, analytical procedures and interpretation, data availability, local planning practices, and other special circumstances. Local expert knowledge is indispensable to improving the evaluation accuracy, applicability, and feasibility of the soil quality evaluation. The selection of the appropriate PTF depends mainly on data availability and data suitability for local use.

The method was developed in the second part of the Interreg IIIb Alpine Space TUSEC-IP project and tested in the city of Grugliasco (Torino, Italy). To simplify computations and use, the method was accompanied by a simple-to-use Excel® tool and was implemented in a GIS environment using ArcGIS®. The applicability and the first end-user opinions enabled conclusions about the method that represented a suitable basis for further improvements. Future activities should be concentrated on the development of suitable pedotransfer functions, rigorous testing and fine-tuning of the method.

7. Conclusions

The method combines two aspects of soil quality evaluation: the 'goods and services' approach and the environmental protection aspect. It represents a novel approach to soil evaluation for urban planning and soil quality and environmental management purposes in cities.

The presented method is land-use based. In contrast to the existing land capability and soil quality indexing systems developed for one (predominantly agricultural) land use, it combines soil quality evaluations for different land uses within one particular evaluation system.

The method introduces two one-value measures of soil quality:

- The index of soil quality expresses soil quality/soil suitability for a particular land use;
- The soil environmental quality index expresses the environmental value of soil in terms of performing the crucial ecological functions of soil.

Additionally, the impact of the land use change is introduced—an index that takes into consideration the land use planning impact assessment on the soil resource.

The presented method of soil quality evaluation offers the possibility of more extensive use of soil information in municipalities in planning and soil quality management procedures. It is suitable for non-expert use and can be used to adjust planning decisions towards more sustainable urban design and to foster land use policies that avoid urban sprawl and reduce soil sealing.

A better understanding of the functions of soil in urban ecosystems combined with an understandable and easy to use soil evaluation method designed specially for urban environments should lead to better environmental management of cities, to urban planning oriented to the rational use of land, better soil protection, and, consequently, to more sustainable development of cities.

Acknowledgments

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Appendix A. Description of soil quality indicator classes

SQ Class 1	Description of classes
1	Very low/very bad/not suitable
2	Low/bad/marginally to less suitable
3	Medium high/medium/medium suitable
4	High/good/suitable
5	Very high/very good/very suitable

Appendix B. Components of the soil quality evaluation framework

- Soil information:
  - o Soil data sets: geo-referenced soil measured and observed soil data on the urban and sub-urban area
  - o Predefined data on required soil quality for urban land uses
  - o Predefined minimum and specific SQI data sets
  - o Predefined SQI weights related to land use
  - o The set of pedotransfer functions
- Documentation, look-up tables and guidance:
  - o The soil sampling form and sampling guidance
  - o Description of the analytical methods
  - o Land use description and definition
  - o Step-by-step procedures for soil evaluation
  - o Legislation threshold tables
  - o Soil evaluation interpretation guidance
- Soil information systems and computer tools:
  - o A computer application: a helpful tool which performs calculation faster; it is used for the soil quality evaluation of individual locations (e.g. Excel® application)

A system composed of GIS geo-referenced data, software, hardware, and GIS procedures. It is used for the spatial implementation of the soil quality evaluation which includes scenario modelling, data visualisation, and map production.

Appendix C. An example of SQI set. Definition of soil quality classes (QC values)

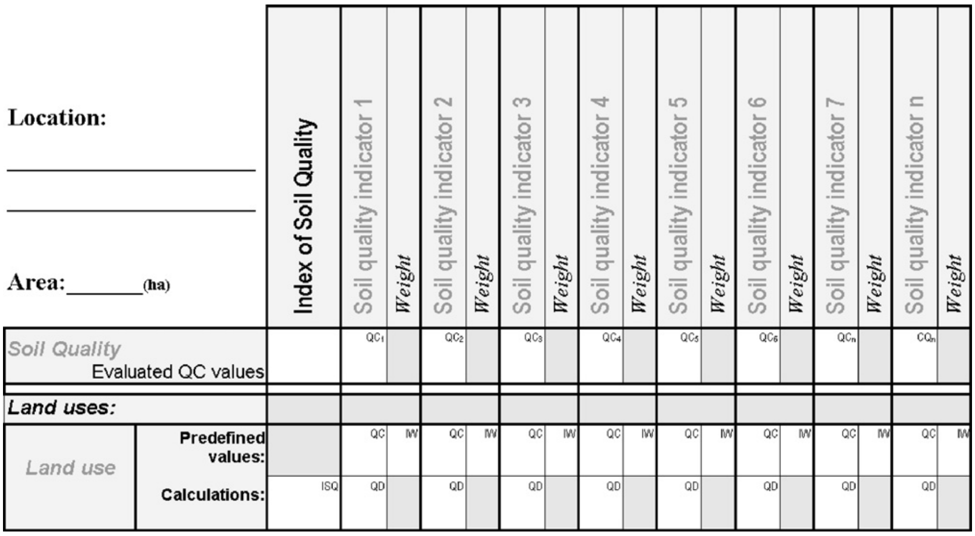
Soil quality indicator	Low/bad		Medium	Good/high		Method	Input data
	1	2	3	4	5		
Heavy metal contamination	Highly HM polluted	Medium HM polluted	Low HM polluted	Not polluted-increased HM conc.	Not polluted-very low HM conc.	PTF; mathematical model classification	HM concentration analytical values
Contamination with organic pollutants	Highly OC polluted	Medium OC polluted	Low OC polluted	Not polluted – increased OC conc.	Not polluted – very low OC conc.	PTF; mathematical model classification	OP concentrations OM, pH. CEC, texture analytical values
Soil pH (general)	Very strong acidity (pH <4,5) or Very Strong alkalinity (pH > 9,5)	Strong acidity (pH 4.5–5} or Strong alkalinity (pH 8.5–9.5)	Moderate acidity (pH 5-5.5) Moderate alkalinity (pH 7.5–8.5)	Sligt acidity (pH 5 5–6) or Neutral (pH 7–7.5)	Slightly acid (pH 6–7)	Classes adapted from USDA Field Book for describing soils, V1.1	pH analytical value
Soil organic matter content	Very low/mineral (OM<	Low (OM 1–2%)	Low to medium (OM 2–4%)	Medium (OM 4–6%)	High (OM >6%)	General values – arable land (USDA)	OM analytical value
Soil texture	Clay, Sand	Loamy Sand, Sandy Clay	Sandy Loam, Loam, Silt, Silty clay	Silt Loam, Silty Clay Loam, Sandy clay Loam	Loam; Clay loam, Silt loam	USDA Field Book for describing soils, V1.1	Particle size distribution
Buffering, filtering and decomposing capacity	Very low buffering	Low buffering	Medium buffering	Medium/high buffering	High buffering	PTF; mathematical model classification	OM, texture, pH, CEC analytical values
General soil fertility/productivity	Very low fertile	Low fertile	Medium fertile	Fertile	Very fertile	Expert opinion	OM, pH, exch. P, K, N
Soil permeability	Impermeable; very slow permeability (<0.15 cm/h)	Slow and moderately slow permeability (0.15–<1.5 cm/h)	Moderate permeability (1.5–<5 cm/h)	Moderately rapid permeability (5–<15 cm/h)	Rapid and very rapid permeability (>15 cm/h)	USDA Field Book for describing soils, V1.1	Texture, depth of impermeable layer
Ground water recharge	No groundwater recharge	Stow GW recharge or Not significant for GW recharge	Medium important for GW recharge	Importing GW recharge area	Protected GW recharge area	USDA Field Book for describing soils, V1.1	Texture, depth of impermeable layer
Infiltration capacity	Very low infiltration	Low infiltration	Medium infiltration	Good infiltration	Highly absorbing	Expert opinion	Porosity, texture
P, K nutrient status	Very poor on nutrients	Low nutrient content	Medium nutrient content	Good nutrient content	Optimal nutrient status	Expert opinion	Exch. P, K, N analytical values
Soil structure	Structureless	Platy, Cloddy, Columnar	Wedge, Prismatic	Angular blocky	Granular, Fine Blocky	USDA Field Book for describing soils, V1.1	Field observation
Ground water level (depth of gleyic properties)	Highly hydromorphic	Medium hydromorphic	Hydromorphic	Low hydromorphic	Non-hydromorphic	PTF: expert opinion	Field observation
Soil surface condition	Surface very disturbed and polluted	Surface disturbed and polluted	Surface disturbed	Surface not polluted	Surface in natural condition	Expert opinion	Field observation
Soil permeability (ground water protection risk)	Rapid and very rapid permeability (>15 cm/h)	Moderately rapid permeability (5–<15 cm/h)	Moderate permeability (1.5–<5 cm/h)	Slow and moderately slow permeability (0.15–<1.5 cm/h)	Impermeable Very stow permeability (<0.15 cm/h)	USDA Field Book for describing soils, V1.1	Texture, depth of impermeable layer
Soil pH (Ornamental gardens – Calluna (Ericacea) species)	(pH > 6.5)	(pH < 3) or (pH 5.5–6)	(pH 3–3.5) or (pH 5–5.5)	(pH 3.5–4) or (pH 4.5–5)	Slightly acid (pH 4–4.5)	Huinink (1998). Classes adapted from USDA Field Book for describing soils, V1.1	pH analytical value

Appendix D. Predefined set of required SQI quality class values and IW values for different urban land uses (an example)

Land use	SQI1 Heavy metal contamination	IW1 Weight: Heavy metal contamination	SQI2 Contamination with organic	IW2 Weight: Contamination with organic pollutants	SQI3 Soil pH	IW3 Weight: Soil pH	SQI4 Soil organic matter content	IW4 Weight: Soil organic matter content	SQI5 Soil texture	IW5 Weight: Soil texture	SQI6 Buffering, filtering and
Residential areas	3	2	3	2	3	2	4	3	3	2	4
Family house areas	4	2	3	2	3	2	4	3	3	2	4
Children's playgrounds	5	3	5	3	4	3	5	3	4	3	5
Sport and leisure areas	4	3	4	3	3	2	4	3	4	3	4
Urban agriculture, allotment gardens	5	3	5	3	4	3	5	3	4	3	5
Parks	3	2	3	2	3	2	3	2	3	2	4
Ornamental gardens	2	2	2	2	3	3	4	3	3	3	4
Commercial areas	2	2	2	2	4	3	4	3	4	3	3
Shopping centres	2	2	2	2	4	3	4	3	3	2	3
Low emission industry	2	2	2	2	4	3	3	2	3	2	4
High emission industry	1	1	1	1	3	2	3	2	2	3	5
Roadsides, crossroads	1	1	1	1	3	3	4	3	3	1	4
General agriculture	4	2	4	2	4	2	4	3	4	3	4
Good agricultural area	5	3	5	3	5	2	5	3	5	3	5
Medium quality agricultural area	4	3	4	3	4	2	4	3	4	3	4
Low quality agricultural area	3	3	3	3	3	2	3	3	4	3	3
Meadows/grassland area	3	3	3	3	3	2	3	2	3	2	3

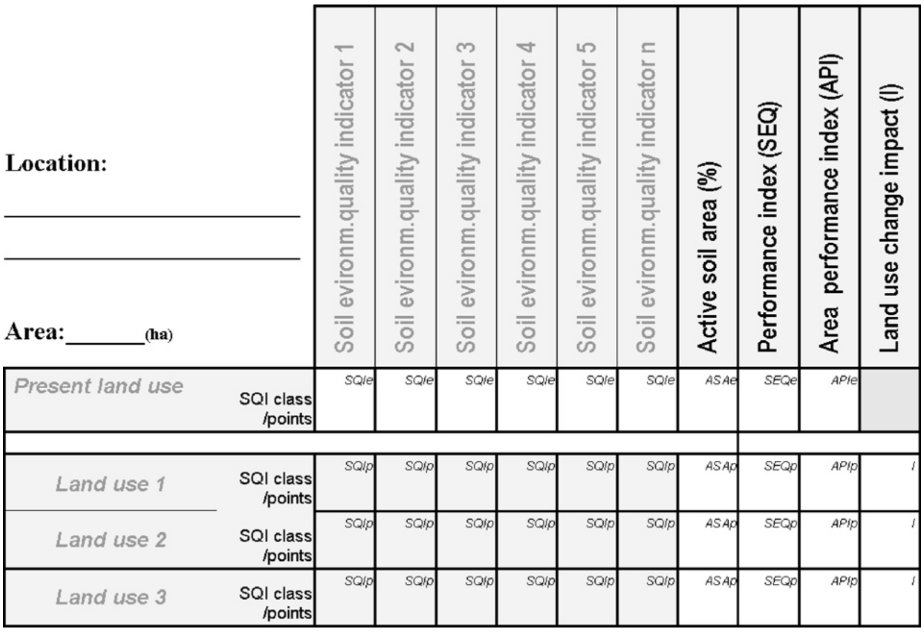
Land use	IW6 Weight: Buffering, filtering and decomposing capacity	SQI7 General soil fertility/productivity	IW7 Weight: General soil fertility/productivity	SQI8 Soil permeability	IW8 Weight: Soil permeability	SQI9 Infiltration capacity	IW9 Weight: Infiltration capacity	SQI10 P, K nutrient status	IW10 Weight: P, K nutrient status	SQI11 Ground water recharge	IW12 Weight: Ground water recharge
Residential areas	3	3	2	4	3	4	3	4	3	4	2
Family house areas	3	3	2	3	2	3	2	3	2	4	2
Children's playgrounds	3	3	2	3	3	3	3	3	3	5	2
Sport and leisure areas	3	3	2	4	3	4	3	4	3	5	2
Urban agriculture, allotment gardens	3	4	2	4	2	4	2	4	2	4	2
Parks	3	3	2	3	2	3	2	3	2	3	2
Ornamental gardens	3	3	3	3	3	3	3	3	3	3	2
Commercial areas	2	2	2	4	2	4	2	4	2	3	2
Shopping centres	3	3	2	4	3	4	3	4	3	3	2
Low emission industry	3	2	1	2	3	2	3	2	3	2	2
High emission industry	3	1	1	1	3	1	3	1	3	1	3
Roadsides, crossroads	3	3	2	2	2	2	2	2	2	2	1
General agriculture	3	4	3	5	2	4	2	4	2	4	2
Good agricultural area	3	5	3	5	2	4	2	5	2	5	2
Medium quality agricultural area	3	4	3	4	2	4	2	4	2	4	2
Low quality agricultural area	3	3	3	4	2	4	2	4	2	3	2
Meadows/grassland area	2	3	3	4	2	3	2	3	2	3	2

Appendix E. Form for soil quality evaluation



Location: ____________________ ____________________ Area:________(ha)		Index of Soil Quality	Soil quality indicator 1	Weight	Soil quality indicator 2	Weight	Soil quality indicator 3	Weight	Soil quality indicator 4	Weight	Soil quality indicator 5	Weight	Soil quality indicator 6	Weight	Soil quality indicator 7	Weight	Soil quality indicator n	Weight
Soil Quality Evaluated QC values			QC_1		QC_2		QC_3		QC_4		QC_5		QC_6		QC_n		CQ_n	
Land uses:																		
Land use	Predefined values:		QC	IW	QC	IW	QC	IW	QC	IW	QC	IW	QC	IW	QC	IW	QC	IW
	Calculations:	ISQ	QD		QD		QD		QD		QD		QD		QD		QD	

Appendix F. Form for land use change impact assessment for three optional land uses



Location: ____________________ ____________________ Area:________(ha)		Soil evironm.quality indicator 1	Soil evironm.quality indicator 2	Soil evironm.quality indicator 3	Soil evironm.quality indicator 4	Soil evironm.quality indicator 5	Soil evironm.quality indicator n	Active soil area (%)	Performance index (SEQ)	Area performance index (API)	Land use change impact (I)
Present land use	SQI class /points	SQIe	SQIe	SQIe	SQIe	SQIe	SQIe	ASAe	SEQe	APIe	
Land use 1	SQI class /points	SQIp	SQIp	SQIp	SQIp	SQIp	SQIp	ASAp	SEQp	APIp	I
Land use 2	SQI class /points	SQIp	SQIp	SQIp	SQIp	SQIp	SQIp	ASAp	SEQp	APIp	I
Land use 3	SQI class /points	SQIp	SQIp	SQIp	SQIp	SQIp	SQIp	ASAp	SEQp	APIp	I

Appendix G. An example of a basic soil quality indicator set

Soil quality indicator:

- Soil organic matter content
- Soil texture
- Soil pH
- Soil depth
- Soil structure
- Heavy metal contamination
- Contamination with organic pollutants
- Buffering, filtering and decomposing capacity

General soil fertility/productivity

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