Concepts and indicators of soil quality – a review

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Concepts and indicators of soil quality – a review

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1. Purpose of this report

The project entitled "Interactive Soil Quality Assessment in Europe and China for Agricultural Productivity and Environmental Resilience" (iSQAPER) aims to develop an interactive tool for holistic in-field soil quality assessment and monitoring. To this end, the already existing soil quality related information is to be integrated with site-specific analytical and visual observations, so that the effects of agricultural management practices on ecosystem services can be accounted for.

The main purpose of this report is to critically review existing soil quality concepts and indicators. To this end, the relevant definitions and terminology are introduced in the beginning, followed by an overview over various national soil quality concepts based on quantitative laboratory measurements. Additionally, the most important approaches using visual soil evaluation in the field are presented. The choice of soil quality indicators is then discussed in-depth with respect to requirements of indicators, methods to select a minimum dataset, a compilation of the most frequently proposed indicators, and the interpretation of indicator values, including how to derive a soil quality index. This is followed by a section on potential novel biological soil quality indicators. Finally, conclusions are drawn with respect to development of a novel conceptual framework for soil quality assessment. In particular, the suitability of different indicators with respect to sensitivity to indicate soil threats and functions, while being reliable, simple and cost-effective, is evaluated, and a set of parameters proposed which can be used for soil quality assessment in various pedo-climatic zones in Europe and China.

2. Introduction

Soil quality as compared to air and water quality

Soil quality is one of the three components of environmental quality, besides water and air quality (Andrews et al., 2002). Water and air quality are defined mainly by their degree of pollution which impacts directly on human and animal consumption and health, or on natural ecosystems (Carter et al., 1997; Davidson, 2000). In contrast, soil quality is not limited to the degree of soil pollution, but is commonly defined much more broadly as “The capacity of a soil to function within ecosystem and land-use boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health“ (Doran & Parkin, 1994; Doran & Parkin, 1996). This definition reflects the great complexity and site specificity of soil ecosystems as well as the many linkages between soil functioning and soil-based ecosystem services. Indeed, soil quality is more complex than the quality of air and water not only because soil is a mixture of solid, liquid and gaseous phases, but also because soils can be used for a larger variety of purposes (Nortcliff, 2002). Soil quality therefore needs to be defined with respect to the desired function.

This complexity is also addressed when soil quality is defined from an environmental perspective as “the capacity of the soil to promote the growth of plants, protect watersheds by regulating the infiltration and partitioning of precipitation, and prevent water and air pollution by buffering potential pollutants such as agricultural chemicals, organic wastes, and industrial chemicals” (National Research Council (1993) as cited in Sims et al. (1997)). Soil quality can also be assessed for natural ecosystems in order to have baseline values which can be compared to future assessments (Karlen et al., 2001), whereas the identification of management effects is more relevant for agroecosystems.

Since soils often react slowly to changes in land use and management, it can be more difficult to detect changes in soil quality before non-reversible damage has occurred than for the quality of water and air (Nortcliff, 2002). Therefore, an important component of soil quality concepts is the identification of a set of sensitive indicators or attributes which reflect the capacity of a soil to fulfill its functions. This can be a combination of inherent properties such as texture and mineralogy which will not change during decades, and dynamic properties such as organic matter and pH which are affected by land use and management (Carter et al., 1997). Dynamic properties are therefore also referred to as manageable properties (Dominati et al., 2010). The distinction between these categories is, however, context-dependent (Schwilch et al., 2016). For example, stoniness as an inherent property is manageable by removal of stones from an area. In addition, extrinsic factors such as climate, topography and hydrology influence optimum values of soil properties to such a degree that it is impossible to establish universal target values, at least not in absolute terms.

The concept of soil quality as introduced by Larson and Pierce (1991) and Doran and Parkin (1994) was heavily criticized in a series of papers (Letey et al., 2003; Sojka & Upchurch, 1999; Sojka et al., 2003) for being subjective and ill-defined. A particular recommendation was to speak of soil use rather than soil functions, so that the responsibility to maintain the quality of the soil can be clearly assigned to the user of the soil. The main response by the proponents of the soil quality concept was to stress its educational mission. In particular, it was claimed to raise awareness and enhance communication between various stakeholders regarding the importance of soil resources (Karlen et al., 2001).

Soil quality vs. soil health vs. soil fertility

Assessments of the suitability of soil for crop growth may have been done even before the evidence of written records and certainly in ancient Chinese books such as "Yugong" and "Zhouli" written during the Xia and Zhou dynasty, respectively (Harrison et al., 2010) and by Roman authors such as Columella (Warkentin, 1995). Typically, the definition of "soil quality" goes beyond the productivity function of soils (Larson & Pierce, 1991; Parr et al., 1992) to explicitly include the interactions between humans and soil, and to encompass ecosystem sustainability as well as an intrinsic value of soil as being irreplaceable and unique (Carter et al., 1997). For example, the concept of Doran and Parkin (1994) aims at assessing whether the three main groups of ecosystem services (productivity, environmental quality, plant and animal health) are optimal within pedoclimatic constraints.

The term "soil quality" in this broader sense was first used by Warkentin and Fletcher (1977) and subsequently adopted for a symposium of the Canadian Society of Soil Science in 1979, resulting in three papers which used the term in the title without actually defining it (Ketcheson, 1980; Martel & Mackenzie, 1980; Saini & Grant, 1980). Measurements of soil quality in these studies were mainly related to soil organic matter, soil structural aspects and crop yield. A national program to assess and monitor soil quality in Canada was then started in 1988 (Acton & Gregorich, 1995), encompassing laboratory measurements of chemical and physical soil properties plus *in situ* measurements which included biopore, root and earthworm counts as biological indicators. In this program, the terms "soil health" and "soil quality" were used interchangeably and defined primarily from an agricultural perspective as "the soil's fitness to support crop growth without becoming degraded or otherwise harming the environment".

The term "soil health" originates in the observation that soil quality influences the health of animals and humans via the quality of crops (Warkentin, 1995). Soil health has thus also been illustrated via the analogy to the health of an organism or a community (Doran & Parkin, 1994; Larson & Pierce, 1991). Likewise, linkages to plant health can be established, as in the case of disease-suppressive soils (Almario et al., 2014). The website of the Natural Resources Conservation Service (http://www.nrcs.usda.gov/wps/portal/nrcs/main/soils/health/) states that "Soil health, also referred to as soil quality, is defined as the continued capacity of soil to function as a vital living ecosystem that sustains plants, animals, and humans." According to Moebius-Clune et al. (2016), a conceptual difference between the two terms may be that soil quality comprises both inherent and dynamic properties, whereas soil health is focused on the dynamic properties.

Importantly, the concepts of soil quality and soil health can go beyond the reductionist approach of measuring single indicators, which remains important from a practical point of view (Kibblewhite et al., 2008b). Such an integrated view would include the capacity for emerging system properties such as the self-organization of soils, i.e. bidirectional feedbacks between soil organisms and soil structure (Lavelle et al., 2006), and the adaptability to changing conditions. Since the concepts of soil health and soil quality are essentially similar, some authors use the composite term "soil quality and health" (Harris et al., 1996). While "soil quality" is the preferred term of researchers, the term "soil health" is often preferred by farmers (Romig et al., 1996).

Another frequently used concept is soil fertility. The term originates from the German literature on "Bodenfruchtbarkeit", in which it was predominantly aligned to yields (Patzel et al., 2000). According to Patzel et al. (2000), "soil fertility" is not applicable as a technical term in natural sciences as it describes a definite, but dispositional (concealed) soil feature and is also a phenomenon, not only a concept. Both "soil quality" (Reganold et al., 1993) and "soil fertility" (Mäder et al., 2002) made it into the title of papers in the journal "Science". Soil properties analyzed in these two studies were quite similar, encompassing physical properties such as bulk density and penetration resistance, chemical properties such as pH, total organic carbon and extractable P, and microbial activity indicators such as soil respiration and potential enzyme activities. This suggests that the term "soil fertility" is often used as a synonym to the term "soil quality". Indeed, the definition of Mäder et al. (2002) that a fertile soil "provides essential nutrients for crop plant growth, supports a diverse and active biotic community, exhibits a typical soil structure, and allows for an undisturbed decomposition" went beyond the provision of yields. In line with this, the maintenance of "natural soil fertility" is at the heart of organic farming (Rusch, 1985).

Soil quality assessment vs. land evaluation vs. soil monitoring

The term soil quality is sometimes used in the context of land quality and land evaluation (e.g. Eswaran et al., 1997). More precisely, soil quality is only one component of land quality, which integrates characteristics of soil, water, climate, topography and vegetation (Carter et al., 1997; Dumanski & Pieri, 2000). In this sense, land quality has a more permanent character than soil quality (Bouma, 2002). Whereas soil quality is more focused on the dynamic soil properties which can be strongly influenced by management and are mainly monitored in the top 20-30 cm of the soil, land quality addresses primarily the inherent soil properties which do not change easily and are often assessed for the entire profile (Karlen et al., 2003). Likewise, land evaluation is more focused on the inherent soil properties and less on the dynamic components.

Land evaluation has a long tradition, and an early comprehensive elaboration of the concept is the FAO Framework for Land Evaluation (FAO, 1976). Land evaluation aims to predict the use potential of land based on its attributes (Rossiter, 1996). While the process of land evaluation does not include the optimal allocation of land for various uses, it is the first step in sustainable land management. In contrast to soil monitoring, land evaluation or soil survey is done only once or with larger time intervals, and is limited to very few measured parameters (Huber et al., 2001). The number of surveyed sites, however, is typically much greater than in soil monitoring programs.

Typically, land evaluation or soil survey is mainly focused on productivity. In countries with low population densities, the main purpose of land evaluation in the past was to identify fertile land, whereas in more densely populated regions such as Europe it was more targeted at identifying deficient factors that could be remedied (van Diepen et al., 1991). Interestingly, the U.S. Soil Survey Staff used the term soil quality in the 1950s to indicate inferred soil properties such as fertility, tilth, and productivity, in contrast to soil characteristics which can be measured directly (van Diepen et al., 1991).

Recently, the schools of land evaluation and soil quality assessment seem to reconcile to some degree, because land evaluation procedures are now used in many different ways and for a range of purposes, including sustainable land management, environmental risk assessments and monitoring of environmental changes (Sonneveld et al., 2010). The provision of ecosystem services can be quantified, including in economic terms (Dominati et al., 2016). In a new land-potential knowledge system (LandPKS, www.landpotential.org), general management options are based on long-term land potential (depending on climate, topography and inherent soil properties) and can be modified according to weather conditions and dynamic soil properties (Herrick et al., 2016).

Linkages of soil quality to soil functions, soil-based ecosystem services, and soil threats

Ecosystem services are defined as "the benefits which humans derive from ecosystem functions" (Costanza et al., 1997), or "the direct and indirect (flux of) contributions of ecosystems to human well-being" (Braat & de Groot, 2012). Among soil scientists, the concept of ecosystem services is often used in connection with the concept of soil functions (Schwilch et al., 2016). The interpretation of the term "soil functions" is however quite variable, including the use as a synonym for 1) process, 2) functioning of a system, 3) role, and 4) service. According to Glenk et al. (2012), the best definition of soil functions would be "(bundles of) soil processes that are providing input into the delivery of (valued) final ecosystem services". The EU Soil Framework Directive defines seven soil functions: 1) biomass production, 2) storing, filtering, transforming nutrients, substances and water, 3) biodiversity pool, 4) physical and cultural environment for humans, 5) source of raw materials, 6) carbon pool, and 7) archive of geological and archaeological heritage (EuropeanCommission, 2006).

There is possibly more agreement about the main soil threats than about the soil functions. The main threats that may lead to soil degradation have been defined in the European Soil Protection Strategy as erosion, decline in organic matter, contamination, sealing, compaction, decline in biodiversity, salinization, and floods and landslides (EuropeanCommission, 2002; Montanarella, 2002). Ultimately, soil degradation means a disturbance of soil quality (Bone et al., 2010), which can be reversible or not. Therefore, it is important to establish conceptual linkages between soil quality indicators and soil threats.

Different schemes how to link soil-based ecosystem services and soil functions have been developed (Haygarth & Ritz, 2009; Kibblewhite et al., 2008b; Tóth et al., 2013), but none of them includes soil threats. The scheme presented by Kibblewhite et al. (2008b) and modified by Brussaard (2012) is shown in Figure 1. It was adopted and further developed as a conceptual basis for the iSQAPER project during a workshop of work packages 2 (Spatial analysis of farming systems) and 3 (Analysis of existing soil quality indicator systems) at FiBL in Frick, Switzerland, October 12-14, 2015 (Figure 2). In this latter scheme, an attempt is made to also include soil threats, showing how they may affect the various soil functions. The soil functions in this scheme equate almost entirely to the “intermediate services” defined by Bennett et al. (2010), which are similar to the “soil processes” in the RECARE framework presented by Schwilch et al. (2016). Exceptions are that ion retention and exchange and gas cycling are not listed specifically in Figure 2, and that the scheme of Schwilch et al. (2016) summarizes the functions habit, decomposition and biological population regulation into the process “soil biological cycles”.

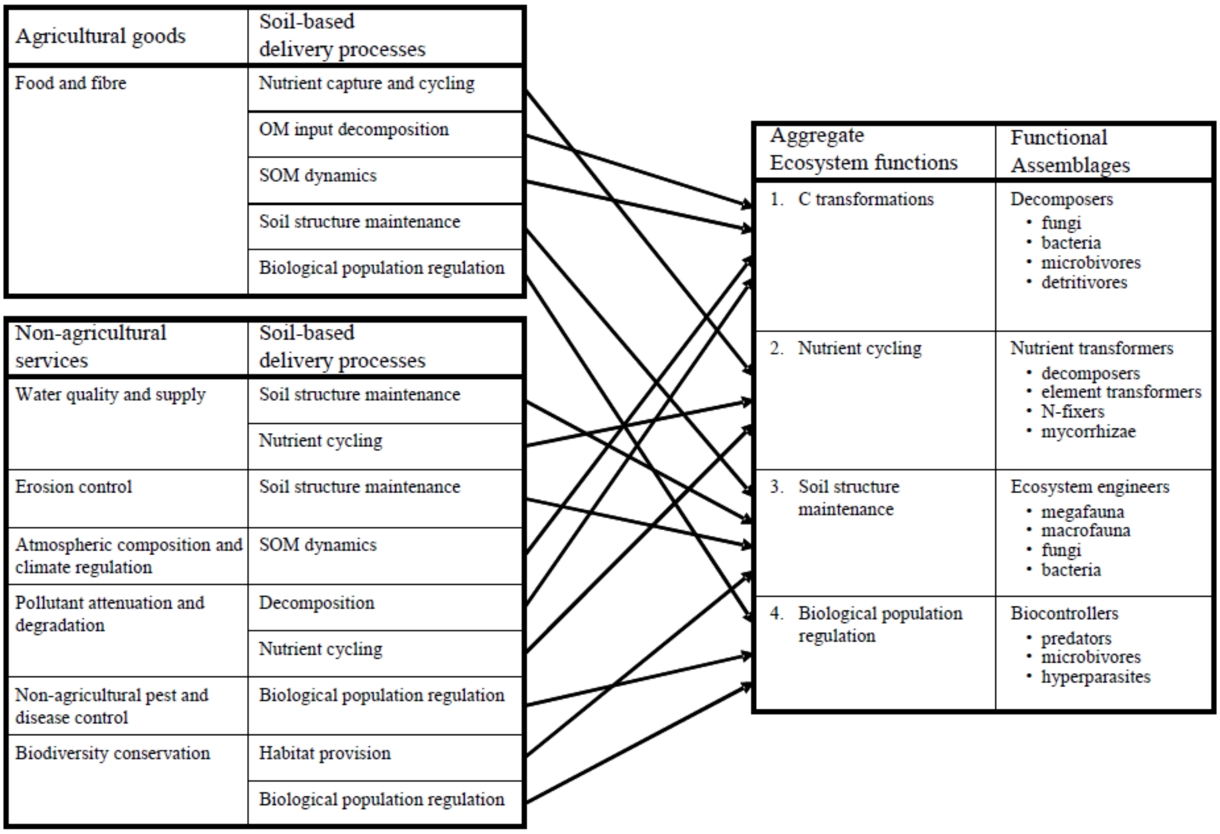


Figure 1: An example how ecosystem services can be linked with soil functions (Kibblewhite et al., 2008b)

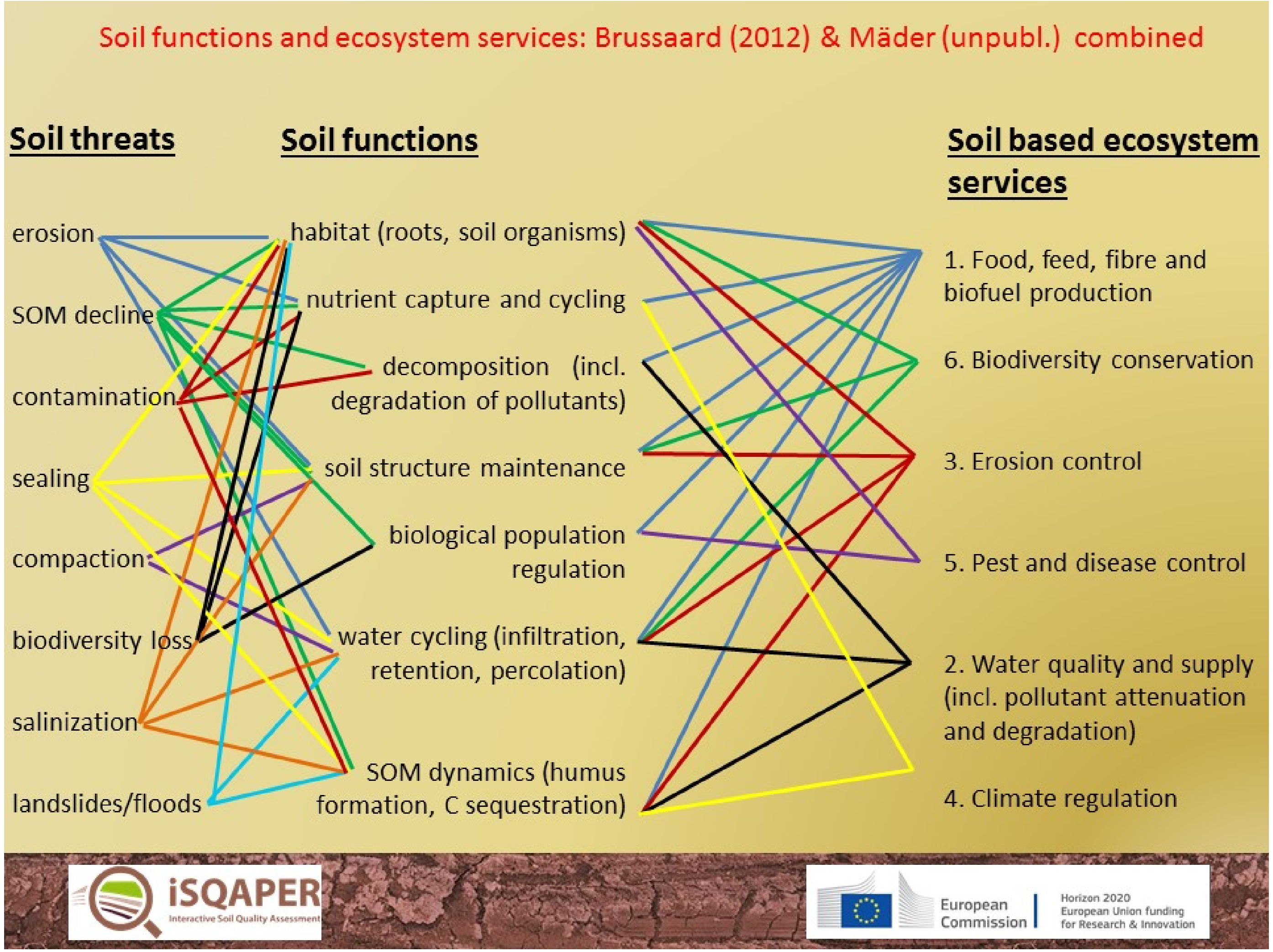


Figure 2: Conceptual presentation of linkages between soil functions, soil-based ecosystem services and soil threats developed during the iSQAPER workshop at FiBL, Frick (October 2015).

Already early on, soil health or quality was addressing not only one function such as productivity, but trying to represent and balance the multiple functions of soil (Doran & Safley, 1997). More recently, this multifunctionality has been emphasized even more strongly (Bone et al., 2010). In particular, soil quality indicators should be applicable to multiple soil functions. This requires the inclusion of ecological indicators (Bennett et al., 2010). An important requirement is that soil-based ecosystem services can be quantified (Schulte et al., 2014) and directly related to soil properties (Adhikari & Hartemink, 2016). An example for such an approach of quantifying ecosystem services was presented by Rutgers et al. (2012). Using Best Professional Judgement (a consultation of experts), soil parameters which could serve as proxies for ecosystem services were identified. The most universal parameter was soil organic matter content which was thought to reflect nine out of ten ecosystem services. In this report, we aim to further strengthen the conceptual linkages between soil quality indicators and the multiple functions of soil.

Linkages of soil quality to resilience and resistance

Seybold et al. (1999) related the concepts of resilience (the capacity to recover to functional and structural integrity after disturbance) and resistance (the capacity to continue to function without change throughout a disturbance) to the concept of soil quality. During a disturbance, soil quality is a function of resistance, while after a disturbance, soil quality is a function of resilience. Disturbances include pathogen and pest attacks, to which disease-suppressive soils would be resistant, and natural or human-induced soil threats such as erosion or acidification. Because disturbances are frequent, especially in agricultural soils, resistance and resilience are integral components of soil quality. For both resistance and resilience, threshold values of soil properties can be established below which the soil is not able to resist disturbance or recover from it, i.e. soil quality is permanently deteriorated. Typically, soil quality and resilience are positively related in that a high quality soil will also be highly resilient (Bouma, 2002). Resilience may indeed be applicable as a main criterion for health in agriculture in general, not only with respect to soils (Döring et al., 2015).

Recent developments in soil biology methods

Although recommendations to include biological indicators into soil quality assessments were made early on (Visser & Parkinson, 1992), the recent rapid developments in soil biology, especially in molecular methods, make it timely to review potential soil biological indicators more in-depth and to assess strengths and weaknesses of these for a potential inclusion in soil quality concepts.

Objectives of this review

The main objective of this review is to compare existing soil quality concepts, especially with respect to indicator selection, and to discuss the potential inclusion of new soil biological indicators into soil quality assessment. The focus of this review is on analytical measurements, since visual soil evaluation has been reviewed recently (Emmet-Booth et al., 2016). Nevertheless, a short presentation of visual approaches is included. Based on our review, we will identify strengths and weaknesses of current soil quality concepts and try to outline a novel framework for a soil quality assessment tool.

3. Existing soil quality concepts

Overview on various national soil quality concepts

A national soil quality monitoring program using benchmark sites was established in Canada between 1989 and 1993, with the aim to assess changes in soil quality over time, especially in relation to the soil threats erosion, compaction, organic matter loss and acidification and salinization (Wang et al., 1997). In total, 23 sites under arable land-use in representative agroecological zones were selected. A total of 22 measurements were proposed, which were grouped into i) sensitive properties such as pH, total organic carbon, bulk density, penetration resistance and earthworm counts which should be measured annually to every few years, ii) moderately sensitive properties such as cation exchange capacity and water retention which should be measured every ten years, and iii) non-sensitive properties such as particle-size distribution which should be obtained only once to establish baseline data. In addition to soil properties, crop yields and management data were collected every year, and climatic data obtained continuously. At a much broader scale, a GIS-based approach to characterize both inherent and dynamic soil quality was presented by Macdonald et al. (1998).

While the Canadian soil quality monitoring program as such was not consistently continued, the data is still partly used in the assessment of agri-environmental indicators, which include soil, water and air quality (Clearwater et al., 2016). The soil quality compound index is a weighted average of indicators for soil erosion, organic carbon losses, salinization and contamination with trace elements. Mainly due to reductions in tillage intensities in the Prairies and associated reductions in soil erosion and increases in organic carbon, the compound index shows improving soil quality since 1981. In contrast, the water quality is decreasing due to continued inputs of nutrients and pesticides.

In the USA, the Soil Quality Institute which was created during the reorganization of the USDA Soil Conservation Service in 1994 has the mission to develop, acquire and disseminate information on soil quality and related technology aimed at conserving and sustaining natural resources and the environment (Karlen et al., 2001). The Soil Management Assessment Framework (SMAF), which is based on indicator selection, interpretation and integration into a soil quality index, was developed here (Andrews et al., 2004; Wienhold et al., 2009). Importantly, the soil quality concept developed at the Soil Quality Institute is seen as an educational as well as an assessment tool (Wienhold et al., 2004). Consequently, the website (http://www.soilquality.org) offers a lot of information on soil quality. Another soil quality concept developed in the USA resulted in the Cornell Soil Health Test (Idowu et al., 2008; Moebius-Clune et al., 2016), which offers various soil health testing packages for farmers, landscape managers and others (http://soilhealth.cals.cornell.edu).

A comprehensive concept for soil quality monitoring in New Zealand was developed by Schipper and Sparling and co-workers (Lilburne et al., 2004; Schipper & Sparling, 2000; Sparling et al., 2004). A nationwide survey of soil quality in the topsoil (0-10 cm) at over 200 sites was evaluated to identify seven indicators which explained 87% of the variation (Sparling & Schipper, 2002). These seven indicators were then measured in 511 sites across 12 soil orders and all major land-uses in order to establish benchmark values against which to assess future changes (Sparling & Schipper, 2004). This work resulted in a computer tool called "Sindi" (soil indicator assessment) which was first presented by Lilburne et al. (2002) and is available on-line (https://sindi.landcareresearch.co.nz).

In Europe, many national soil quality concepts were developed. For example, the French national soil quality observatory was started in 1986 and includes 11 sites of about 1 ha each (Martin et al., 1998). In the UK, a concept for soil quality monitoring was first presented by Loveland and Thompson (2002), with a special focus on forestry and semi-natural soils. The concept was then further elaborated and the indicators tested, resulting in the proposition of a minimum dataset of only seven measurements (Merrington, 2006). In the Netherlands, an indicator system for soil ecosystem services has been developed by RIVM (National Institute for Public Health and the Environment). Soil ecosystem services are measured with a comprehensive set of indicators in 200 sites representing 70% of the land-use activities in The Netherlands. The set is composed of soil biological indicators, abiotic indicators and system-oriented indicators. The set has been used in two five-year measurement cycles of the national soil quality monitoring network (Wattel-Koekkoek et al., 2012). Target values and ranges for agronomic land use are based on median values of the monitoring network and on expertise of a group of soil experts. The indicators are also to be used for assessing the natural capital of soils and for developing practical indicator sets to support local soil and landscape management. Also in The Netherlands, a large Public Private Partnership 'Sustainable Soil' is developing a soil quality system in which a set of soil chemical, physical and biological indicators is related to target values and ranges and integral advice on soil management (www.beterbodembeheer.nl).

A first proposal for a common European soil monitoring framework based as much as possible on existing national monitoring activities was presented by Huber et al. (2001). Subsequently, the ENVASSO project (ENVironmental ASsessment of Soil for mOnitoring) aimed at defining and documenting a soil monitoring system for implementation in support of a European Soil Framework Directive (Kibblewhite et al., 2008a). One of the most important outcomes of this project was the identification of three priority indicators for each soil threat (Huber et al., 2008). This list was further revised and amended by the project RECARE (Preventing and Remediating Degradation of Soils in Europe through Land Care). An overview of indicators for soil threats suggested by these two projects can be found in Table 1.

The history of soil quality monitoring in China has been reviewed for an international readership by Teng et al. (2014). Chinese researchers have defined soil quality as a comprehensive concept encompassing 1) soil fertility which provides biomass growth for food, fiber and energy, 2) soil environmental quality which maintains clean water bodies and air, and 3) soil health which is related to maintenance of animal and human health and therefore to concentrations of organic and inorganic pollutants below safety threshold values (Cao & Meng, 2008; Zhao et al., 1997). Accordingly, a minimum dataset should reflect each of these three components (Xu et al., 2008). Indicators for soil fertility include pH, soil organic matter, clay, available P and K, bulk density and cation exchange capacity. Indicators for soil environmental quality are compound indicators of different measurements, include storage of carbon and nitrogen vs. their emission to the atmosphere, and storage of P and N vs. their release to water bodies. Indicators for soil health include pH, soil organic matter, texture, heavy metals, and total and available potentially toxic elements (Zn, Cd, Pb, Cr, Hg, As, Se, Ni, F) and organic pollutants.

Table 1: Key indicators for soil threats identified by the projects ENVASSO and RECARE (Huber et al., 2008; Stolte et al., 2016)

Soil threat	**ENVASSO**	**RECARE**
Soil erosion	Estimated soil loss by	
	- water erosion (rill, inter-rill, and sheet erosion)	Area affected by soil erosion (km^2); magnitude of soil erosion/deposition or sediment delivery (tons)
	- wind erosion	Measured soil loss by wind ($t\ ha^{-1}\ yr^{-1}$); estimates of wind erosion; susceptibility to wind erosion; various proxy indicators
	- tillage erosion	Not specified.
Decline in soil organic matter	Topsoil organic carbon content (measured)	Clay/SOC; topsoil organic carbon content
	Soil organic carbon stocks (measured)	Total carbon stocks to 1 m depth
	Peat stocks (calculated or measured)	Peat stocks
Soil contamination	Heavy metal contents in soils	
	Critical load exceedance by sulphur and nitrogen	
	Progress in management of contaminated sites	
Soil sealing	Sealed area	Sealed area
	Land take (Corine Land Cover)	Transition index (TI)
	New settlement area established on previously developed land	Sealed to green areas ratio
Soil compaction	Density (bulk density, packing density, total porosity)	Relative normalized density
	Air-filled pore volume at a specified suction	Air-filled pore volume
	Vulerability to compaction (estimated)	Penetration resistance
Soil biodiversity loss	Earthworms diversity and fresh biomass	
	Collembola diversity (enchytraeids diversity if no earthworms)	
	Microbial respiration	
Soil salinization	Salt profile (total salt content or electrical conductivity)	
	Exchangeable sodium percentage	
	Potential salt sources (groundwater or irrigation water) and vulnerability of soils to salinization/sodification	
Landslides	Occurrence of landslide activity	
	Volume/weight of displaced material	
	Landslide hazard assessment	
Flooding	Not addressed	Seasonality, magnitude, frequency of precipitation/rainfall intensity; extent of inundated area; flood frequency; loss of crops due to inundation of fields
Desertification	Land area at risk of desertification	
	Land area burnt by wildfires	
	Soil organic carbon content in desertified land	

Due to increasing pressure to maintain and improve soil quality in China, the Chinese government in 2008 established the China Soil Quality Standardisation & Technology Committee (SAC/TC 404). The committee has been responsible for formulating and modifying soil quality standards in China, including terminology, indicators, criteria, soil sampling methods, analytical methods, standards for soil quality assessment, and remediation of contaminated soils (Chen et al., 2011). By April 2010, 141 soil quality related standards had been set up, with part of the standards adopted from ISO. The Chinese framework of soil standards is shown in Figure 3.

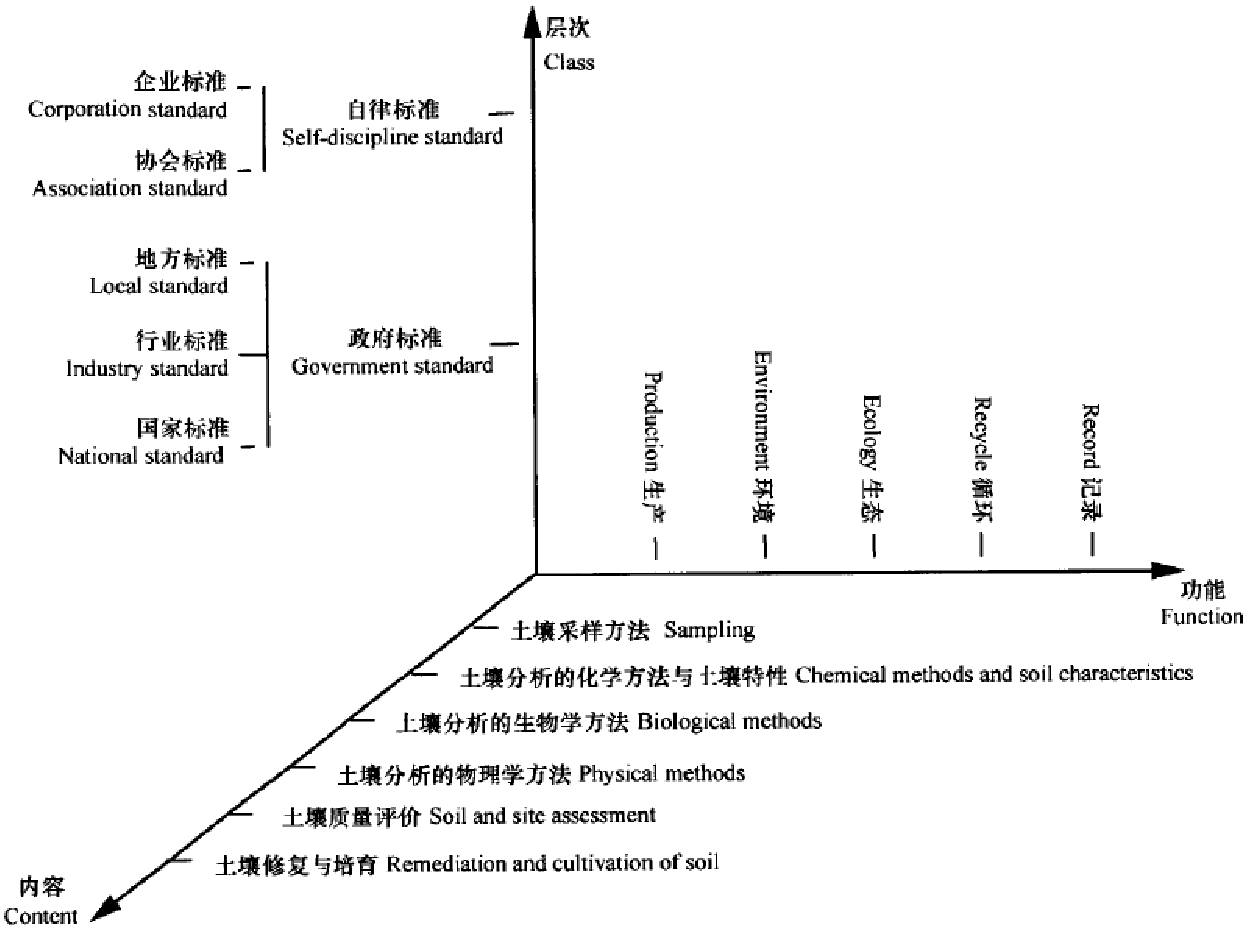


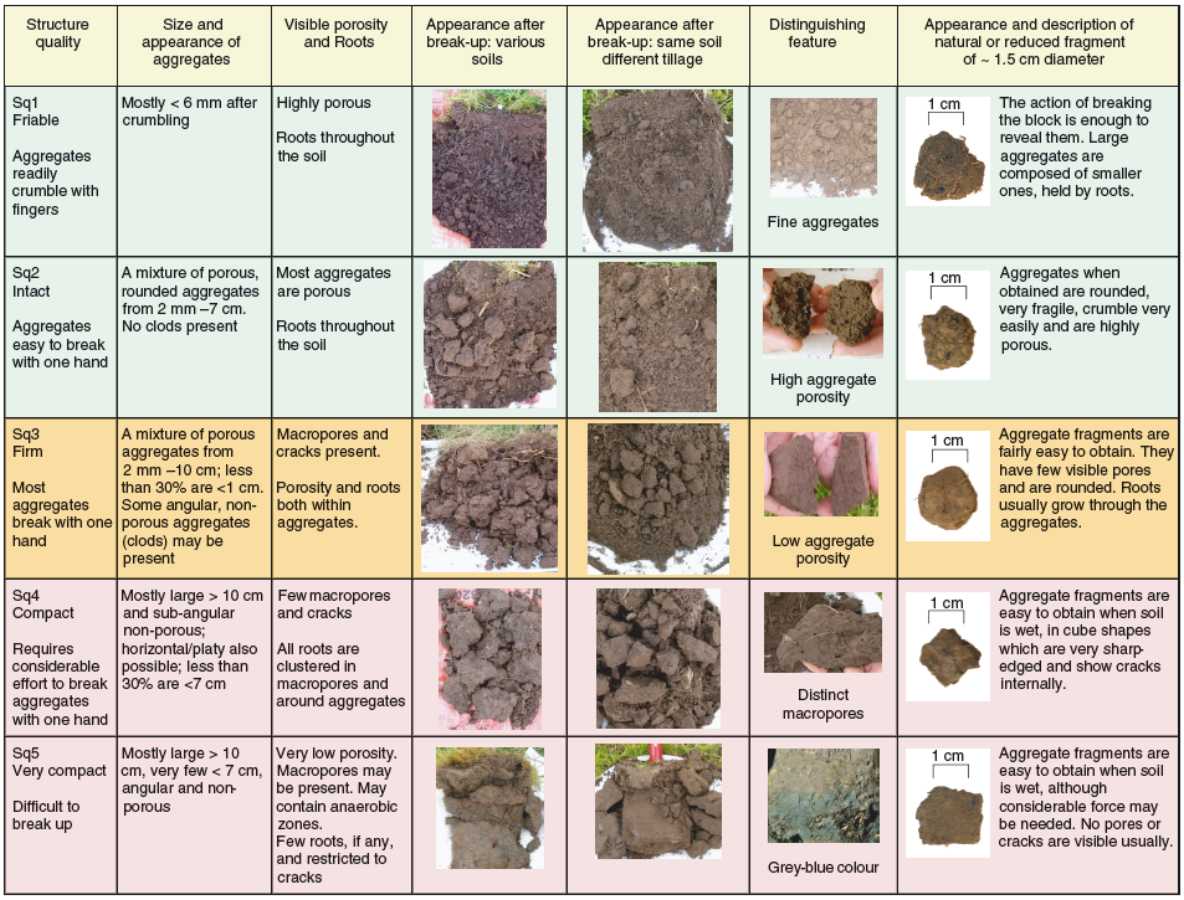
Figure 3: Framework of soil standards in China (Chen et al., 2011)

Visual soil assessment approaches

The national soil quality concepts described so far, which focus primarily on knowledge gathering about the state of soils on a regional or national scale, are mainly based on quantitative indicators and thus require analytical laboratory facilities. Concepts targeting farmers and stressing the educational aspect need more empirical, qualitative indicators that can be easily assessed in the field and interpreted by both farmers and scientists (Beare et al., 1997). An important advantage is that results are immediately available, in contrast to laboratory analyses.

In the Wisconsin Soil Health Program, for example, a soil health score card was developed which collects farmers' observations on the soil and the plants, and includes even a few questions on animal health and water quality (Romig et al., 1996). A soil quality test kit that allows determining soil pH, electrical conductivity, nitrate and water content as well as soil respiration was tested by Liebig et al. (1996), and recommendations on when and how often to sample were given by Sarrantonio et al. (1996). A more comprehensive kit is available as the USDA test kit which was developed for assessing the effect of agricultural management on soil quality (Seybold et al., 2001). It includes tools to assess soil respiration, infiltration, bulk density, salinity (EC), pH, nitrate, aggregate stability, earthworms, compaction, soil structure, soil texture and water quality. It can be useful for comparative analysis, either between management options or over time. A disadvantage is that this kit frequently needs replacement material such as batteries and test strips.

More recently, several tools for visual soil assessment (VSA) have been developed which have a particular focus on soil structural aspects. Ten such methods were compared in the field during an expert meeting in France (Boizard et al., 2005). Generally, all methods ranked the soil structural quality of the investigated sites in the same order. It was found that methods based on observations of the whole soil profile from a trench are more sensitive, especially to assess compaction, but require more time. Faster methods based on a spadeful of soil can be replicated more easily. Only three out of the ten methods were clearly suitable for farmers. It was concluded that one of the fastest methods which was developed by Peerlkamp and used in the Netherlands for 40 years needed some improvement, e.g. a simplified scoring scheme, and this task was subsequently performed by Ball et al. (2007). In particular, the inclusion of a visual key was considered an important improvement over the original protocol, and this key (Figure 4) was subsequently modified by Guimaraes et al. (2011).



Structure quality	Size and appearance of aggregates	Visible porosity and Roots	Appearance after break-up: various soils	Appearance after break-up: same soil different tillage	Distinguishing feature	Appearance and description of natural or reduced fragment of ~ 1.5 cm diameter
Sq1 Friable Aggregates readily crumble with fingers	Mostly < 6 mm after crumbling	Highly porous Roots throughout the soil			Fine aggregates	1 cm The action of breaking the block is enough to reveal them. Large aggregates are composed of smaller ones, held by roots.
Sq2 Intact Aggregates easy to break with one hand	A mixture of porous, rounded aggregates from 2 mm –7 cm. No clods present	Most aggregates are porous Roots throughout the soil			High aggregate porosity	1 cm Aggregates when obtained are rounded, very fragile, crumble very easily and are highly porous.
Sq3 Firm Most aggregates break with one hand	A mixture of porous aggregates from 2 mm –10 cm; less than 30% are <1 cm. Some angular, non-porous aggregates (clods) may be present	Macropores and cracks present. Porosity and roots both within aggregates.			Low aggregate porosity	1 cm Aggregate fragments are fairly easy to obtain. They have few visible pores and are rounded. Roots usually grow through the aggregates.
Sq4 Compact Requires considerable effort to break aggregates with one hand	Mostly large > 10 cm and sub-angular non-porous; horizontal/platy also possible; less than 30% are <7 cm	Few macropores and cracks All roots are clustered in macropores and around aggregates			Distinct macropores	1 cm Aggregate fragments are easy to obtain when soil is wet, in cube shapes which are very sharp-edged and show cracks internally.
Sq5 Very compact Difficult to break up	Mostly large > 10 cm, very few < 7 cm, angular and non-porous	Very low porosity. Macropores may be present. May contain anaerobic zones. Few roots, if any, and restricted to cracks			Grey-blue colour	1 cm Aggregate fragments are easy to obtain when soil is wet, although considerable force may be needed. No pores or cracks are visible usually.

Figure 4: Visual key to soil structure assessment according to the revised Peerlkamp test (Guimaraes et al., 2011)

A comparison of the most widespread methods of visual soil assessment (Table 2) shows that most of these methods target mainly soil structure, sometimes in relation to productivity. Only the VSA approach (Shepherd et al., 2008) claims to assess soil quality in general, which is however questionable since no chemical soil properties are assessed. In this respect, the VS-Fast method (McGarry, 2006) targeting land degradation is more comprehensive. The methods vary in material and time requirements, with spade methods being generally faster to perform than profile methods. Importantly, visual soil evaluation can provide different information than laboratory approaches (Emmet-Booth et al., 2016).

Visual soil evaluation is currently moving beyond soil structure to include also other soil properties (Ball et al., 2013). An example of such a comprehensive visual assessment of soil quality is the Muencheberg Soil Quality Rating (M-SQR) presented by Mueller et al. (2014), which has been shown to reflect potential or relative yields (Abdollahi et al., 2015; Mueller et al., 2013). Ultimately, the increased use of visual soil assessment is believed to be important in yield gap analysis and land management programs (McKenzie et al., 2015).

Table 2: Comparison of major visual soil assessment methods

Country	Australia	France	Australia	UK	New Zealand	Brazil/UK	Germany
Reference	**McKenzie (2001)**	**Roger-Estrade et al. (2004)**	**McGarry (2006)**	**Ball et al. (2007)**	**Shepherd et al. (2008)**	**Guimaraes et al. (2011)**	**Mueller et al. (2014)**
Stated objectives (assessment of …)	soil structure, suitability for root growth	soil structure	land degradation	soil structure	soil quality	soil structure	soil properties with respect to yield potential
Method name	SOILpak	Profil cultural	VS-Fast	Peerlkamp	VSA	VESS[1]	M-SQR[2]
Principle	spade	trench	spade	spade	spade	spade	pit
Material							
spade	X	X	X	X	X	X	X
plastic basin					X		
hard square board	X				X		
plastic bag or sheet				X	X	X	
knife	X			X	X	X	X
auger							X
water bottle					X		
tape measure or ruler			X	X	X	X	X
Time needed (min)	25-90	60-180	?	5-15	25	5-15	10-40
General observations							
soil layers, A-horizon			X				X
surface crusting or cover			X		X		
surface ponding					X		X
slope							X
soil erosion					X		

Table 2 continued.

Country	**Australia**	**France**	**Australia**	**UK**	**New Zealand**	**Brazil/UK**	**Germany**
Reference	**McKenzie (2001)**	**Roger-Estrade et al. (2004)**	**McGarry (2006)**	**Ball et al. (2007)**	**Shepherd et al. (2008)**	**Guimaraes et al. (2011)**	**Mueller et al. (2014)**
Soil physical properties							
soil texture			X		X		X
soil structure	X	X	X	X	X	X	X
soil consistence	X		X				
aggregate size distrib.			X	X	X	X	X
aggregate shape	X						
slaking/dispersion			X				
soil porosity	X			X	X	X	
soil colour	X		X		X		
soil mottles (no., colour)					X		
available water							X
water infiltration			X				
Soil chemical properties							
soil pH			X				
labile organic C			X				
Soil biological properties							
earthworms (no., size)			X		X		
potential rooting depth					X		X
root development	X		X	X		X	

[1] visual evaluation of soil structure

[2] Muencheberg Soil Quality Rating

4. Soil quality indicators: requirements, selection, frequency, interpretation

Requirements for soil quality indicators

Various conceptual, practical and output-related criteria for soil quality indicators have been listed in some (but by far not all) soil quality concepts (Table 3). All concepts which list such criteria mention at least one conceptual condition such as that a chosen indicator must be related to a given soil function, or that an ideal indicator would integrate soil physical, chemical and biological properties. Of the practical issues, ease of sampling and measurement is a prerequisite for a soil quality indicator in almost all concepts, and reliability and cost are also considered important aspects. Sensitivity to changes in management or land use is usually desired, and availability of similar data for comparison is another important consideration. Finally, the importance of interpretation has been recognized more frequently since about 2000.

The importance of selecting indicators which could be used to estimate other soil properties which are more difficult to measure directly, i.e. the use of pedotransfer functions, was already stressed in early soil quality concepts (Doran & Parkin, 1996; Doran & Safley, 1997; Larson & Pierce, 1994). The use of such estimates, also with the use of computer programs, has again been advocated more recently (Bone et al., 2010).

A proposition how to evaluate the sensitivity of a given indicator was made by Bolinder et al. (1999) who suggested to calculate the ratio of a given indicator in two contrasting management systems. In the soil quality concept from New Zealand, the suitable level of precision was at first considered to be able to detect a 10% change from the mean at the 90% confidence level (Schipper & Sparling, 2000). However, in many cases too many replicates were required to achieve this. Therefore, the desired sensitivity was later defined as that detecting a 25% change from the median (Sparling et al., 2004).

Comparison to data from other sampling campaigns would often be useful. In this respect, Morvan et al. (2008) observed that organic C (or soil organic matter) and pH are often measured, whereas bulk density or earthworm diversity are rarely assessed, making organic C and pH more suitable. However, if availability of comparative data is considered a very important prerequisite for soil quality indicators, novel indicators will hardly stand a chance to be included in soil quality evaluation programs.

Table 3: Considerations and criteria for soil quality indicators mentioned in various publications.

Criteria and considerations		Larson and Pierce (1994)	Doran and Parkin (1996)	Burger & Kelting, (1999)[1]	Southorn and Cattle (2000)	Nortcliff (2002)	Merrington (2006)	Idowu et al. (2008)	Ritz et al. (2009)	West et al. (2010)	Oberholzer et al. (2012)	Bone et al. (2014)
Conceptual	Related to soil function and/or ecosystem processes;		x	x		x	x	x	x	x	x	
	Relevance, representation of key variables controlling soil quality, correlated to long-term response, allow evaluation of assessment criteria	x		x			x				x	x
	Significance at the appropriate scale				x							
	Integrate soil physical, chemical, biological properties		x									
	Allow estimation of soil properties or functions which are more difficult to measure directly		x									x
Practical	Ease of sampling and measurement (simplicity, practicality, single or repeated sampling and measurement, provide information in short timeframe)	x	x	x	x	x	x	x	x	x		x
	High throughput of analysis, wide applicability								x			x
	Amount of soil needed								x			
	Sample storage before analysis								x			
	Reliability and reproducibility of measurement	x			x	x		x	x		x	x
	Existence of a standard method of estimation (standard operating procedure)				x				x			
	Availability of reference material for quality control								x			
	Cost (sampling, hardware, analysis, labour)	x		x	x		x	x	x	x		x
Sensitiv	Spatial variation					x						
	Temporal variation (not influenced by short-term weather patterns)		x		x	x				x		
	Sensitivity to changes in management, or land use, response to perturbation as well as corrective measures	x	x	x	x	x	x	x		x	x	
Interpretation	Comparability with routing sampling and monitoring programs (context data available); part of standard tests; baseline available		x	x	x	x	x	x	x			
	Ease of interpretation, interpretation criteria available				x	x	x				x	x
	Archivability, capable of continuous assessment			x					x			
	Mappable trend indicators				x							
	Generic or diagnostic value				x							

[1] as cited in Bone et al. (2010)

Arguably, the most important step in the selection of indicators is the identification of management goals or soil functions which should be represented (Andrews & Carroll, 2001). In the SMAF, for example, the selection of a minimum dataset for a given site starts with defining the main management goal which is related to a set of soil functions. In the version presented by Andrews et al. (2004), three management goals (productivity, waste recycling and environmental protection) are defined, but more could be added. A set of indicators to assess the soil functions of interest is then proposed, which is selected out of 81 potential indicators using selection rules. The user can however disregard or alter the proposed minimum dataset as desired. This kind of flexibility is quite unique among existing soil quality concepts.

Methods for selecting a minimum dataset

Due to financial constraints, the number of soil quality indicators that is actually analyzed on a given set of samples often needs to be reduced to a minimum dataset. This selection can be done based on expert opinion, as in early proposed minimum dataset (e.g. Doran & Parkin, 1994), or using statistical data reduction, or by a combination of both. For example, Schipper and Sparling (2000) tested a set of 16 soil quality indicators on a set of samples from 29 sites in New Zealand and used principal component analysis (PCA) to identify the indicators with the greatest influence on the separation of samples from different land-uses (arable, grassland, native forest and plantation). A subset of six of these indicators that covered soil physical, chemical and biological properties gave a similar separation of the samples as the complete set of soil quality indicators. While the authors warn against using only a very limited set of indicators, they suggest identifying strong correlations among indicators in order to avoid unnecessary measurements, and to assess the variability of indicators measured on separate samples per site in order to identify highly variable and thus insensitive indicators. In a subsequent study on 222 soils from New Zealand, PCA identified four principal components representing physical properties, organic matter related indicators, soil water characteristics and chemical properties (Sparling & Schipper, 2002). Expert opinion was used to choose between highly correlated properties such as pH and base saturation based on the consideration that pH is more easily measured.

A clear procedure on how to choose the most representative indicators from a larger dataset was presented by Andrews and Carroll (2001) in a case study on options for poultry litter management on two soil types. Using multivariate statistics, the minimum set of indicators that accounted for 85% of the variation was selected, including only those indicators which showed significant differences between the treatments. Subsequently, those principal components explaining at least 5% of the variation were examined more closely, selecting the single factors within them with the highest weight. The set of indicators was then reduced further by considering well-correlated variables redundant. Importantly, the selected minimum dataset was validated by testing its relation to predefined and independently measured management goals such as litter disposal, productivity and P losses.

Shukla et al. (2006) used factor analysis to identify the most important indicators discriminating soil quality in combined tillage, fertilization and crop rotation treatments. Interestingly, the main factors were named according to the soil attributes with the highest eigenvalues for a given principal component, e.g. water transmission where infiltration measurements contributed most to the variation. Another option to reduce the number of indicators was presented by Kosmas et al. (2014) in a study on desertification risk in Mediterranean regions around the world. Here, stepwise multiple regression was used to identify the most important indicators, and the dataset was further reduced by discarding one of two highly correlated indicators.

A more participatory approach of selecting soil biological indicators from a long list of potential indicators created based on the literature was presented by Ritz et al. (2009). Scoring of potential indicators by experts and end-users was used in a “logical sieve” approach, which allowed several iterations in order to ensure that the outcome matched the expectations of the stakeholders. Importantly, the different requirements for an indicator were weighted, i.e. reproducibility was considered absolutely essential, whereas the existence of a standard protocol had the lowest weight. Similarly, the selection procedure for a minimum dataset described by West et al. (2010) was based on a participatory approach, in which experts were asked to rank soil properties according to their importance as well as to how they met the requirements for indicators as listed in Table 3, with sensitivity to management being considered essential.

Practical considerations such as the disadvantage of indicators requiring undisturbed samples (e.g. bulk density) naturally also play an important role in discarding otherwise suitable soil quality indicators (Idowu et al., 2008). Sensitivity to management is often considered most important, but there may be tradeoffs with robustness to seasonal variation. Indications on how soil quality indicators actually fulfill the requirements as listed in Table 3 are often not given. In comparative studies, the approach of Bolinder et al. (1999) would allow assessing the sensitivity of a given indicator to management.

Frequently proposed soil quality indicators

To identify the most frequently proposed (combinations of) soil quality indicators (Figure 5), we summarized 45 conceptual publications (Table 4). Some of these publications also included the evaluation of the proposed indicators in case studies. Concepts dealing exclusively with forest soils (e.g. Schoenholtz et al., 2000; Zhang, 1992) or focusing on biological indicators only, without also looking at chemical and/or physical indicators (Filip, 2002; Parisi et al., 2005; Ritz et al., 2009), were not included in this compilation. If the same authors proposed the same set of indicators twice, then only the first publication was considered. If authors in one publication proposed two different sets of indicator, then they were both included, thus increasing the number of proposed indicator sets to 49.

Table 4: Soil quality concepts evaluated for frequency of suggested indicators (Figure 5) by geographical origin

Region	**References**
USA and Canada	Larson and Pierce (1991), Arshad and Coen (1992), Doran and Parkin (1994), Acton and Gregorich (1995), Doran and Parkin (1996), Harris et al. (1996), Carter et al. (1997), Wang et al. (1997), Doran and Safley (1997), Karlen et al. (1998), Seybold et al. (1999), Andrews and Carroll (2001), Karlen et al. (2001), Wienhold et al. (2004), Shukla et al. (2006), Idowu et al. (2008), Wienhold et al. (2009), Moebius-Clune et al. (2016)
New Zealand and Australia	Schipper and Sparling (2000), Southorn and Cattle (2000), Sparling and Schipper (2002), Cotching and Kidd (2010)
Europe	Torstensson et al. (1998), Stenberg et al. (1998), (Martin et al., 1998), Kirchmann and Andersson (2001), Huber et al. (2001), Candinas et al. (2002), Loveland and Thompson (2002), Merrington (2006), Rutgers et al. (2008), Bone et al. (2010), Wattel-Koekkoek et al. (2012), Oberholzer et al. (2012), Armenise et al. (2013)
Asia	Wan and Zhang (1991), Chen (1996), Chen (1999), Wang et al. (2001), Hu et al. (2001), Lou (2002), Xu et al. (2008), Chauhan and Mittu (2015)
South America	Lima et al. (2013), Velasquez et al. (2007)

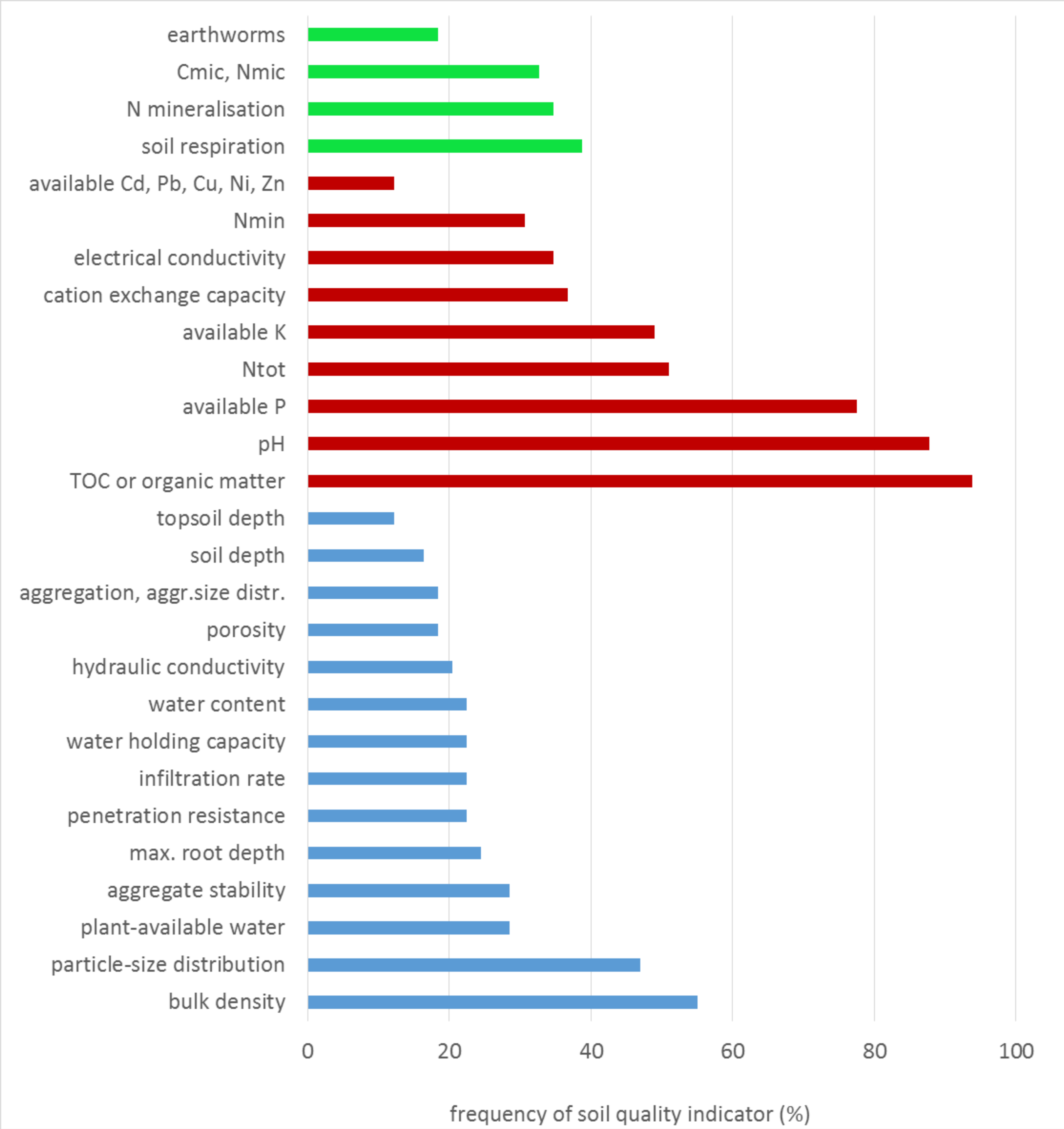


Figure 5: Frequency of different indicators (min. 10%) in all reviewed soil quality concepts (n=49). Soil biological, chemical and physical indicators shown in green, red and blue, respectively.

In Figure 5, it can be seen that total organic carbon and pH are the most frequently proposed soil quality indicators, followed by phosphorus availability, bulk density, total N and particle-size distribution (texture). These top indicators are quite similar to the ones selected by a panel of experts based on rankings of how indicators match the requirements shown in Table 3, which were organic C, pH, electrical conductivity, bulk density soil structure, wet aggregate stability, total N, and soil stability (West et al., 2010).

In most concepts, at least one indicator of each category (physical (Table 5), chemical (Table 6) and biological (Table 7)) is included. These categories are typically represented automatically when all soil functions or soil-based ecosystem services are addressed. For example, (Velasquez et al., 2007) proposed indicators to reflect 1) soil hydraulic properties, 2) chemical soil fertility, 3) aggregation and soil morphology, 4) quality and stocks of organic matter, and 5) biodiversity. Thus, indicators from each of the three categories were included.

The explicit mentioning of non-soil-indicators (Table 8) such as climate, management or site data is surprisingly rare. In particular, yield and other measurements of ecosystem services are very often not included. This means that soil quality assessment is typically not explicitly linked to ecosystem services or soil threats. In addition, few concepts propose true minimum datasets of only six or seven indicators (Table 8), and the average number of proposed indicators is 13, which is probably much more than is feasible from a practical as well as an economic viewpoint under most circumstances.

Soil physical indicators were more frequently proposed in the early concepts and have become more diverse over time (Table 5). Among the soil chemical indicators, soil organic carbon, pH, available P and K, total N, cation exchange capacity, electrical conductivity, and mineral N are more often proposed than all other indicators (Table 6). Likewise, N mineralization, soil respiration, microbial biomass and earthworms are more frequent among the biological indicators than the other 21 indicators that have been proposed in at least one of the 50 reviewed concepts (Table 7). Possibly, some indicators such as nematodes have not been suggested very often yet because they are still relatively novel, or because they require specific knowledge and skills.

The objectives and target groups are often not clearly stated. Recent concepts advocate indicators that are applicable to several soil functions (Bone et al., 2010). In the concept of Lima et al. (2013), for example, earthworms serve as indicators for both water cycling and nutrient cycling. However, many of the other concepts lack a clear conceptual relation between indicators and soil functions.

Table 5: Soil physical indicators proposed in 49 reviewed soil quality concepts

Reference		Larson&Pierce 1991	Wan et al. 1991	Arshad & Coen 1992	Doran & Parkin 1994	Acton & Gregorich 1995	Doran & Parkin 1996	Harris et al. 1996	Chen et al. 1996	Carter et al. 1997	Doran & Safley 1997	Wang et al. 1997	Karlen et al. 1998	Torstensson et al. 1998	Stenberg et al. 1998	Martin et al. 1998	Chen 1999	Seybold et al. 1999	Kirchmann&Andersson 2000	Schipper & Sparling 2000	Southorn & Cattle 2000	Wang et al. 2001	Andrews & Carroll 2001	Andrews & Carroll 2001	Huber et al. 2001	Karlen et al. 2001	Hu et al. 2001	Candinas et al. 2002	Loveland & Thompson 2002	Loveland & Thompson 2003	Lou, 2002	Sparling & Schipper 2002	Wienhold et al. 2004	Wienhold et al. 2004	Merrington 2006	Shukla et al. 2006	Velasquez et al. 2007	Idowu et al. 2008	Rutgers et al. 2008	Xu et al. 2008	Wienhold et al. 2009	Bone et al. 2010	Cotching & Kidd 2010	Wattel-Koekkoek et al. 2012	Oberholzer et al. 2012	Armenise et al. 2013	Armenise et al. 2013	Lima et al. 2013	Chauhan & Mittu 2015	Moebius-Clune et al. 2016	sum
Country		USA	China	Canada	USA	Canada	USA	USA	China	Canada/USA	USA	Canada	USA	Sweden	Sweden	France	Taiwan	USA	Sweden	New Zealand	Australia	China	USA	USA	EU	USA	China	Switzerland	UK	UK	China	New Zealand	USA	USA	UK	USA	Colombia	USA	Netherland	China	USA	UK	Australia	Netherlands	Switzerland	Italy	Italy	Brazil	India	USA	
physical	bulk density	1		1	1	1	1	1		1	1	1	1			1	1			1	1		1		1	1				1		1	1	1	1	1	1			1	1		1					1			27
	particle-size distribution	1			1	1	1	1		1	1	1	1	1	1	1	1			1								1	1				1					1	1			1		1		1	1			1	23
	plant-available water	1	1						1	1							1	1		1			1															1		1	1					1	1	1		1	14
	aggregate stability			1						1			1				1						1	1		1		1		1								1			1		1		1					1	14
	max. root depth	1		1	1		1			1	1		1					1				1						1	1													1			1						12
	penetration resistance	1		1		1				1		1							1		1					1											1	1				1								1	11
	hydraulic conductivity	1		1		1			1			1						1		1	1	1					1				1																				10
	infiltration rate			1	1		1	1			1		1								1					1							1									1							1		11
	water holding capacity			1	1	1	1	1			1									1									1				1			1													1		11
	water content		1		1		1				1	1		1						1	1		1						1								1														11
	porosity																			1	1					1		1			1	1				1	1								1						9
	aggregation, aggr.size distr.				1							1	1					1								1					1					1	1											1			9
	soil depth		1		1		1				1											1			1	1			1																						8
	topsoil depth						1		1		1						1												1				1																		6
	soil temperature				1		1				1		1																1																						5
	water retention				1							1	1																																	1					4
	particle density																			1																	1									1					3
	structure / consistence		1											1				1																																	3
	water filled pore space												1													1																									2
	surface condition																									1				1																					2
	soil colour																																									1							1		2
	water-dispersible clay																													1																					1
	shear strength																																				1														1
	surface residue kg/ha																																																1		1
	stone content																																					1													1
	clay mineralogy											1																																							1
	total surface area											1																																							1
	biopores											1																																							1
	soil odour																																									1									1
	tilth, friability																																																1		1
	previous consolidation																																																1		1

Table 6: Soil chemical indicators proposed in 49 reviewed soil quality concepts

Reference		Larson&Pierce 1991	Wan et al. 1991	Arshad & Coen 1992	Doran & Parkin 1994	Acton & Gregorich 1995	Doran & Parkin 1996	Harris et al. 1996	Chen et al. 1996	Carter et al. 1997	Doran & Safley 1997	Wang et al. 1997	Karlen et al. 1998	Torstensson et al. 1998	Stenberg et al. 1998	Martin et al. 1998	Chen 1999	Seybold et al. 1999	Kirchmann&Andersson 2000	Schipper & Sparling 2000	Southorn & Cattle 2000	Wang et al. 2001	Andrews & Carroll 2001	Andrews & Carroll 2001	Huber et al. 2001	Karlen et al. 2001	Hu et al. 2001	Candinas et al. 2002	Loveland & Thompson 2002	Loveland & Thompson 2003	Lou, 2002	Sparling & Schipper 2002	Wienhold et al. 2004	Wienhold et al. 2004	Merrington 2006	Shukla et al. 2006	Velasquez et al. 2007	Idowu et al. 2008	Rutgers et al. 2008	Xu et al. 2008	Wienhold et al. 2009	Bone et al. 2010	Cotching & Kidd 2010	Wattel-Koekkoek et al. 2012	Oberholzer et al. 2012	Armenise et al. 2013	Armenise et al. 2013	Lima et al. 2013	Chauhan & Mittu 2015	Moebius-Clune et al. 2016	sum
Country		USA	China	Canada	USA	Canada	USA	USA	China	Canada/USA	USA	Canada	USA	Sweden	Sweden	France	Taiwan	USA	Sweden	New Zealand	Australia	China	USA	USA	EU	USA	China	Switzerland	UK	UK	China	New Zealand	USA	USA	UK	USA	Colombia	USA	Netherland	China	USA	UK	Australia	Netherlands	Switzerland	Italy	Italy	Brazil	India	USA	
chemical	TOC or organic matter	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	46
	pH	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1			1	1	43
	P-availability				1	1	1	1	1		1	1	1		1	1	1	1	1	1	1	1	1	1	1	1	1	1	1		1	1	1		1		1	1	1	1	1		1	1		1	1		1	1	38
	Ntot			1	1		1	1	1		1	1	1	1	1	1				1	1	1	1	1	1	1						1	1		1	1	1			1						1					25
	available K				1		1	1			1	1	1		1		1	1	1			1			1	1	1	1	1		1		1					1		1						1	1		1	1	24
	cation exchange capacity			1	1	1			1	1		1				1		1		1	1		1		1	1		1		1	1									1					1							18
	electrical conductivity	1		1	1	1	1	1		1	1	1	1				1				1						1			1			1	1							1					1					17
	Nmin				1		1	1			1		1				1	1				1		1	1			1		1		1				1											1		15
	available Cd, Pb, Cu, Ni, Zn															1	1		1										1							1					1											6
	labile C incl. active C	1																				1															1					1		1				1	5
	Ca, Mg, K (extractable)													1	1											1												1									1					5
	micronutrients availability																							1				1															1										1		1	5
	base saturation															1			1	1						1				1																				5
	organic pollutants (PAK, PCB)																									1		1		1																1	1						5
	selected heavy metals																								1	1				1																1	1						5
	total P							1																1						1						1								1							5
	carbonate content					1						1				1																														1							4
	nutrient availability	1	1			1				1																																														3
	exchangeable Na (ESP)			1																				1														1						1							4
	137Cesium distribution											1	1														1																										3
	total Al, Ca, Co, Cr, Cu, Fe, K, Li, Mg, Na, Ni, Pb, Zn					1						1																												1												3
	extractable Fe, Al					1						1												1																												3
	sodicity (Na adsorption ratio)									1																															1										2
	total K								1																1																											2
	available S																											1																										1
	Mg																													1																								1
	C/N														1																																					1
	particulate OM																											1																										1
	water-extractable organic N																																															1					1
	light fraction C and N																																						1													1
	Al, Fe, Mn																																													1							1
	total Cu, Ni, Zn																																				1															1
	Ca 2+																									1																												1
	clay mineralogy					1																																														1

Table 7: Soil biological indicators proposed in 49 reviewed soil quality concepts

Reference		Larson&Pierce 1991	Wan et al. 1991	Arshad & Coen 1992	Doran & Parkin 1994	Acton & Gregorich 1995	Doran & Parkin 1996	Harris et al. 1996	Chen et al. 1996	Carter et al. 1997	Doran & Safley 1997	Wang et al. 1997	Karlen et al. 1998	Torstensson et al. 1998	Stenberg et al. 1998	Martin et al. 1998	Chen 1999	Seybold et al. 1999	Kirchmann&Andersson 2000	Schipper & Sparling 2000	Southorn & Cattle 2000	Wang et al. 2001	Andrews & Carroll 2001	Andrews & Carroll 2001	Huber et al. 2001	Karlen et al. 2001	Hu et al. 2001	Candinas et al. 2002	Loveland & Thompson 2002	Loveland & Thompson 2003	Lou, 2002	Sparling & Schipper 2002	Wienhold et al. 2004	Wienhold et al. 2004	Merrington 2006	Shukla et al. 2006	Velasquez et al. 2007	Idowu et al. 2008	Rutgers et al. 2008	Xu et al. 2008	Wienhold et al. 2009	Bone et al. 2010	Cotching & Kidd 2010	Wattel-Koekkoek et al. 2012	Oberholzer et al. 2012	Armenise et al. 2013	Armenise et al. 2013	Lima et al. 2013	Chauhan & Mittu 2015	Moebius-Clune et al. 2016	sum
Country		USA	China	Canada	USA	Canada	USA	USA	China	Canada/USA	USA	Canada	USA	Sweden	Sweden	France	Taiwan	USA	Sweden	New Zealand	Australia	China	USA	USA	EU	USA	China	Switzerland	UK	UK	China	New Zealand	USA	USA	UK	USA	Colombia	USA	Netherland	China	USA	UK	Australia	Netherlands	Switzerland	Italy	Italy	Brazil	India	USA	
biological	soil respiration				1		1	1			1		1	1	1		1			1	1		1			1		1	1				1				1		1						1					1	19
	N.mineralisation				1		1	1			1		1	1	1		1			1						1			1			1	1	1				1	1		1										17
	Cmic, Nmic				1		1	1			1		1	1			1			1	1		1			1		1	1				1								1				1						16
	earthworms					1						1					1								1	1													1						1			1	1		9
	microbial diversity / comunity		1															1								1													1												4
	phosphatase activity													1	1								1																												3
	soil fauna diversity																	1																			1		1												3
	respiration/Cmic				1										1																										1										3
	nematodes																						1																1												2
	microbial/bacterial activity																	1																					1												2
	SIR														1																																				1
	Pmic																1																																		1
	nitrification/denitrification													1																																					1
	N fixation/fixing bacteria													1																																					1
	enzyme activities																									1																									1
	urease activity																						1																												1
	root health (soil-borne pests)																																					1													1
	mycorrhiza populations																									1																									1
	potential ammonium oxidation														1																																				1
	potential denitrification activity														1																																				1
	bacterial biomass																																						1												1
	functional diversity (Biolog)																																						1												1
	fungal biomass																																						1												1
	total species number																																						1												1
	Cmic/TOC				1																																														1

Table 8: Non-soil indicators and total number of indicators proposed in 49 reviewed soil quality concepts

Reference		Larson&Pierce 1991	Wan et al. 1991	Arshad & Coen 1992	Doran & Parkin 1994	Acton & Gregorich 1995	Doran & Parkin 1996	Harris et al. 1996	Chen et al. 1996	Carter et al. 1997	Doran & Safley 1997	Wang et al. 1997	Karlen et al. 1998	Torstensson et al. 1998
Country		USA	China	Canada	USA	Canada	USA	USA	China	Canada/USA	USA	Canada	USA	Sweden
climate	temperature			1										1
	precipitation			1										1
	evaporation			1										1
mgnt.	crop rotation			1										1
	tillage			1										1
	livestock density													
	type of manure			1										1
plant data	yield					1						1		
	Cd concentration in crops													
	plant cover													
	root counts, conditions of roots											1		
site data	elevation			1										
	slope			1										
	soil type													
	hydrology			1										
	signs of erosion													
	evidence of anthropogenic disruption													
	sum physical indicators	6	4	7	10	5	9	4	3	6	9	10	9	3
	sum chemical indicators	5	2	6	8	10	7	7	6	6	7	11	8	4
	sum biological indicators	0	1	0	5	1	3	3	0	0	3	1	3	6
	sum	11	7	22	23	17	19	14	9	12	19	24	20	19

Reference		Stenberg et al. 1998	Martin et al. 1998	Chen 1999	Seybold et al. 1999	Kirchmann&Andersson 2000	Schipper & Sparling 2000	Southorn & Cattle 2000	Wang et al. 2001	Andrews & Carroll 2001	Andrews & Carroll 2001	Huber et al. 2001	Karlen et al. 2001	Hu et al. 2001	Candinas et al. 2002	Loveland & Thompson 2002	Loveland & Thompson 2003	Lou, 2002	Sparling & Schipper 2002
Country		Sweden	France	Taiwan	USA	Sweden	New Zealand	Australia	China	USA	USA	EU	USA	China	Switzerland	UK	UK	China	New Zealand
climate	temperature											1							
	precipitation											1							
	evaporation											1							
mgnt.	crop rotation																		
	tillage																		
	livestock density																		
	type of manure																		
plant data	yield			1				1									1		
	Cd concentration in crops					1													
	plant cover																		
	root counts, conditions of roots																		
site data	elevation	1										1							
	slope								1			1		1					
	soil type											1		1					
	hydrology								1								1		
	signs of erosion																		
	evidence of anthropogenic disruption																		
	sum physical indicators	1	2	5	5	1	8	6	3	4	1	2	9	1	4	7	4	3	2
	sum chemical indicators	7	8	7	6	6	6	6	4	8	7	10	16	4	8	6	6	7	4
	sum biological indicators	7	0	5	3	0	3	2	0	5	0	1	7	0	2	3	0	0	1
	sum	16	10	18	14	8	17	15	9	17	8	19	32	7	14	16	12	10	7

Reference		Wienhold et al. 2004	Wienhold et al. 2004	Merrington 2006	Shukla et al. 2006	Velasquez et al. 2007	Idowu et al. 2008	Rutgers et al. 2008	Xu et al. 2008	Wienhold et al. 2009	Bone et al. 2010	Cotching & Kidd 2010	Wattel-Koekkoek et al. 2012	Oberholzer et al. 2012	Armenise et al. 2013	Armenise et al. 2013	Lima et al. 2013	Chauhan & Mittu 2015	Moebius-Clune et al. 2016	sum
Country		USA	USA	UK	USA	Colombia	USA	Netherland	China	USA	UK	Australia	Netherlands	Switzerland	Italy	Italy	Brazil	India	USA	
climate	temperature																			3
	precipitation																			3
	evaporation																			3
mgnt.	crop rotation							1												3
	tillage																			2
	livestock density							1												1
	type of manure																			2
plant data	yield																			5
	Cd concentration in crops																			1
	plant cover										1									1
	root counts, conditions of roots																	1		2
site data	elevation																			3
	slope																			4
	soil type																			2
	hydrology																			3
	signs of erosion																	1		1
	evidence of anthropogenic disruption										1									1
	sum physical indicators	5	1	1	4	7	5	1	2	3	6	2	1	3	4	2	3	6	4	
	sum chemical indicators	7	3	6	3	9	6	3	8	5	2	4	10	3	9	3	2	4	6	
	sum biological indicators	3	1	0	0	2	2	11	0	3	0	0	0	3	0	0	1	1	1	mean
	sum	15	5	7	7	18	13	17	10	11	9	6	11	9	13	5	6	12	11	13

Example: establishing indicators linked to soil functions by expert opinion

During the iSQAPER WP2/3 workshop in October 2015 in Frick, a World Café session was organized in which participants were asked to discuss about soil properties that could indicate a given ecosystem service. The basis for this group work was the proposed relationship between soil functions and ecosystem services (Figure 2). Table 9 shows the outcome of the group work, with the most frequently named indicators being total organic C, texture and soil depth, each of which were thought to be indicative of four or even five ecosystem services. With such a scheme, it would also be possible to choose indicators depending on the targeted functions and services, and thus it would be possible to compose modular extensions to a soil quality indicator system.

Table 9: Indicators selected by group work during the iSQAPER WP2/3 workshop in Frick, October 12-14, 2015, to reflect a given soil-based ecosystem service. For example, pH was considered to reflect 3 out of 6 ecosystem services.

	SOM (TOC)	texture / particle size distribution	soil depth / topsoil depth	pH	max. root depth / root distribution	DOC	water holding capacity	bulk density	mineral N / mineralisable N	biocontrol potential / natural enemies	nematode community	CEC	aggregate stability	DNA tools / molecular diversity	organic pollutants
1. production of food, feed, fibre	1	1	1	1	1	1	1	1	1			1			
2. water quality & supply	1	1	1	1	1		1					1			1
3. Erosion control	1	1	1		1								1		
4. Climate regulation	1	1					1		1				1		
5. Pest & disease control	1					1				1	1			1	
6. Biodiversity control			1	1		1		1		1	1			1	1
sum	**5**	**4**	**4**	**3**	**3**	**3**	**3**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**

Interpretation of indicator values

An indicator is only valuable if its values can be interpreted. For example, Schipper and Sparling (2000) rejected soil respiration as a suitable indicator due to the absence of a clear interpretation. In a simplistic approach, reference values for a given indicator could be either the conditions of a native soil, or of a soil with maximum production and/or environmental performance (Doran & Parkin, 1994). In the Netherlands (Rutgers et al., 2009), reference soil profiles were identified using expert opinion and proved generally useful as reference sites which could be examined again later, and to provide reference values (Figure 6). Acceptable values for an indicator can also be defined as those at which there is no loss or significant impairment of function (Loveland & Thompson, 2002). In the context of pollution, thresholds of contamination are often used (Chen, 1999).

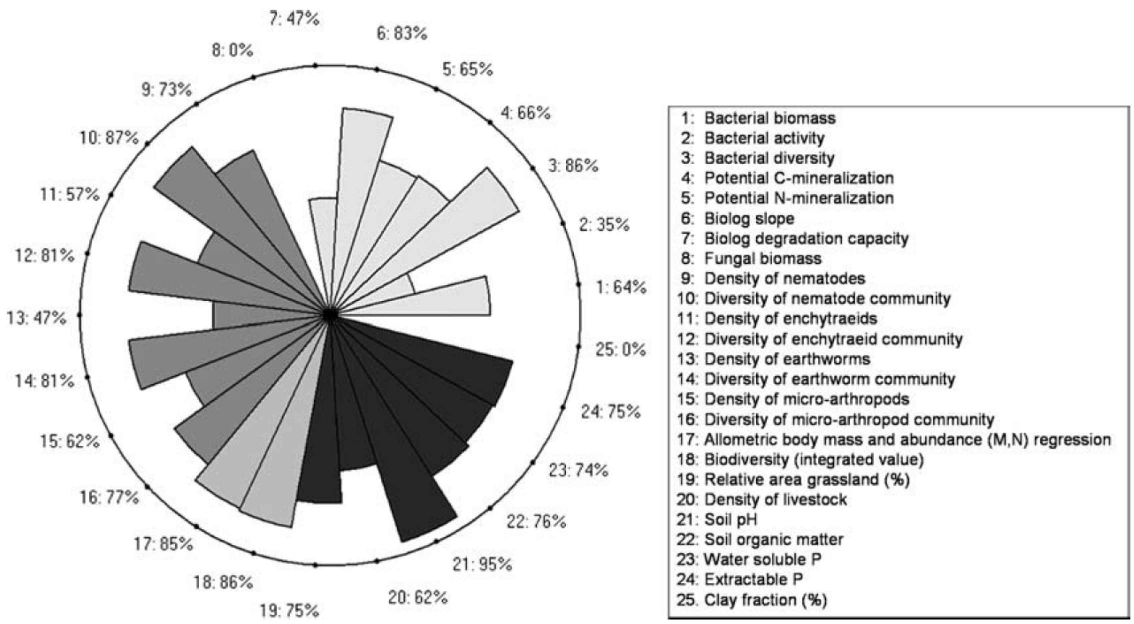


Figure 6: Amoeba diagram to illustrate values of 25 soil parameters relative to six benchmark sites considered to have healthy soils (Rutgers et al., 2009). The circle (100%) represents the average of the six benchmark sites. The segments represent the average deviation from the benchmark for 25 parameters in 81 locations.

A more advanced way to evaluate soil quality indicators is the establishment of standard non-linear scoring functions, which typically have the shapes i) more is better, ii) optimum range, iii) less is better, and iv) undesirable range, with i-iii being most common in soil science. The shape of such curves is established based on a combination of literature values and expert opinion (Andrews et al., 2004). Each indicator measurement is thus transformed to a value between 0 and 1 (or 0 and 100) using the scoring algorithm (Karlen & Stott, 1994), with a score of 0 being the poorest (lower threshold) and a score of 1 (or 100) the best (upper threshold). The baseline value equals the midpoint between threshold values. Validation of scoring curves is possible if datasets with measurements of the given soil quality indicator and a related soil function are available.

Acceptable target ranges of soil quality indicators need to be soil- and land-use-specific, and they need to balance agricultural production and environmental impacts (Lilburne et al., 2002). Target ranges can be established by a variety of approaches: i) based on experimental results such as agronomic response trials, ii) statistically, e.g. defining the lower quartile of a distribution of data as unacceptable values, iii) using simulation modeling and iv) based on expert knowledge (Lilburne et al., 2004). Importantly, acceptable ranges depend on both spatial and temporal scale of soil quality assessments, with regional target ranges typically being more narrow than national ones (Lilburne et al., 2004; Wienhold et al., 2009).

In the Netherlands, a participatory approach with experts was used to select ten reference soils for good soil biological quality (Figure 6) out of 285 sites that had been monitored for over ten years (Rutgers et al., 2008). In this approach, the reference soils, which represent specific combinations of land-use and soil type (e.g. arable land on clay soil), are existing locations and reflect real conditions, with the disadvantage that the sites may not be at an optimum in all parameters. Soil quality indicators at a given site can thus be compared to those at the reference site as well as to the average, 5% and 95% percentiles of all sites under a given land-use, with the percentiles given as a means to express the frequency distribution. The reference values were subsequently termed maximum ecological potential, but their limitations were clearly pointed out (Rutgers et al., 2012). Nevertheless, it would be more precise to refer to these reference values as obtained by the best currently practiced management in a given region.

Acceptable ranges of soil quality indicators are often highly dependent on the value of another soil property. For example, the report of Merrington (2006) gives different “trigger” or threshold values of bulk density, depending on the organic matter content of the soil (Table 10). Similarly, in the Swiss system reference values for microbial biomass are calculated based on soil texture (Candinas et al., 2002). Also the scoring curves for soil quality indicators in the Cornell Soil

Health Test differentiate between the three main textural classes sand, silt and clay (Idowu et al., 2008), or coarse, medium and fine (Moebius-Clune et al., 2016).

Despite considerable effort, several authors claim that the interpretation of soil quality indicators, i.e. the establishment of target or workable ranges, will always remain contentious, which is partly due to a lack of data and partly due to the curvilinear pattern which many indicators follow (Merrington, 2006). Comparative approaches in which indicator values or scores of a given sampling point are put in relation to other sampling points may be the most intuitive and flexible way for interpretation, since it gives a relative assessment (e.g. top 25%) and allows continuing evolvement of the system.

Table 10: Example of how to link the interpretation of one soil quality indicator to another (Merrington, 2006). Bulk density (Mg/m^3) trigger values for top soils with different organic matter content in the UK.

Organic matter content (%)*		
	Tilled land	*Untilled land*
Mineral soils		
<2	>1.60	>1.50
2-3	>1.50	>1.40
3-4	>1.40	>1.35
4-5	>1.30	>1.25
5-6	>1.25	>1.20
6-8	>1.20	>1.15
Organic mineral soils	>1.00	

* if measured as organic carbon, multiply by 1.72 to obtain organic matter content

Deriving a soil quality index and alternatives

Many studies on soil quality have searched for a way to aggregate the information obtained for each soil quality indicator into a single soil quality index, which was deemed impossible by Sojka and Upchurch (1999). Nevertheless, we will below give a few examples of propositions how to derive such an index or final judgement.

In the Canadian soil quality monitoring (Acton & Gregorich, 1995), soils were ranked according to the following four elements that determine productivity:

1. Soil porosity (providing air and water for biological processes)

2. Nutrient retention (retaining plant nutrients)
3. Physical rooting conditions (promoting root growth as a result of certain physical characteristics)
4. Chemical rooting conditions (promoting root growth as a result of chemical characteristics).

Similarly, Hussain et al. (1999) suggested to calculate a soil quality index as a function of water, nutrient and rooting relations, and Velasquez et al. (2007) summed the contribution of each of the five subindicators (hydraulic properties, chemical fertility, aggregation, organic matter and biodiversity) to derive the general indicator of soil quality (GISQ).

In the SMAF, an additive index is used which sums the scores (between 0 and 1) for each indicator, divides them by the number of indicators, and multiplies the resulting number by 10 to yield a number between 1 and 10, because this seems more suitable for communication purposes than a number between 0 and 1 (Andrews et al., 2004). Such an additive soil quality index revealed a similar ranking of poultry litter management options on two soil types, even though the underlying selected soil quality indicators differed slightly between the two sites (Andrews & Carroll, 2001). An example of an additive index is shown in Figure 7.

A multi-objective approach based on principles of systems engineering was proposed by Karlen and Stott (1994). The main soil functions are weighted according to their importance for the overall goal in soil quality management at a given site. Different levels of indicators for a given function are proposed, with the first level being the most direct measure(s) that can be replaced by second or third level indicators if first level indicators cannot be obtained. Indicators at a given level can also be weighted, and they are transformed or standardized to a value between 0 and 1 using scoring functions. Finally, an overall rating of soil quality with respect to the predefined goal is obtained by summing the weighted soil functions. This approach is designed to be flexible with respect to local conditions and management goals (Karlen et al., 2001). An exemplary application of this approach can be found in Lima et al. (2013), who used SIMOQS (Sistema de Monitoramento da Qualidade do Solo) software developed in Brazil to calculate a soil quality index (Table 11).

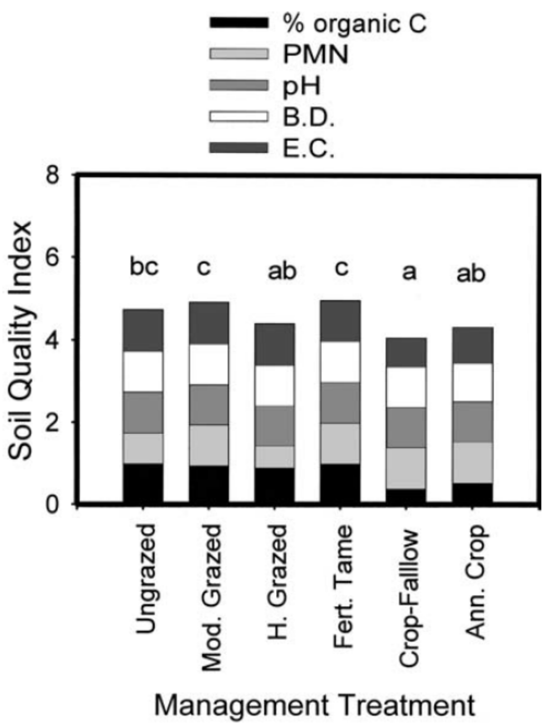


Figure 7: Example of an additive soil quality index. Soil quality indices are shown for a range of management practices in the Northern Great Plains, USA (Wienhold et al., 2004). PMN: potentially mineralizable nitrogen; B.D.: bulk density; E.C. = electrical conductivity.

Larson and Pierce (1994) suggested that it should be possible to calculate the effect of a change in soil quality indicators on productivity. However, soil quality is not necessarily positively related to yield (Figure 8). Likewise, when the soil quality index based on the three functions water cycling, nutrient cycling and biological activity was evaluated for different rice management systems in Brazil, soil quality was negatively related to yield (Lima et al., 2013). Such findings reflect the potential trade-off between different objectives or ecosystem functions and services in soil management.

Also visual soil assessment is often summarized in an overall soil quality rating (McGarry, 2006; Mueller et al., 2014; Shepherd et al., 2008). Typically, the scores for the different indicators are summed up, with some weighting applied. In the Muencheberg Soil Quality Rating, the weighted sum of the basic indicators is multiplied with values for hazard indicators such as contamination, acidification and flooding (Mueller et al., 2014).

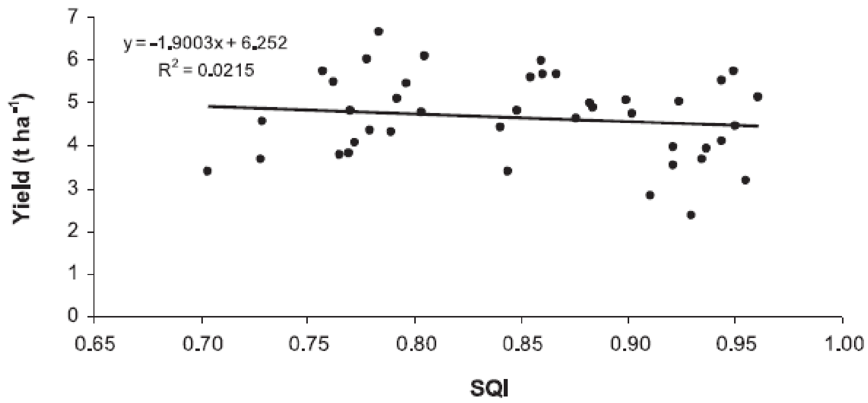


Figure 8: Lack of correlation of grain yield with a weighted additive soil quality index (SQI) based on five physical and chemical soil properties (Armenise et al., 2013)

Table 11: Example of weighting of soil functions and associated indicators (Lima et al., 2013)

Soil function	Weight	Indicator level 1	Weight	Indicator level 2	Weight
Water infiltration, storage and supply	0.33	Available water	0.25		
		Mean weight diameter	0.25		
		Earthworms	0.25		
		Correlated indicators	0.25	Soil organic matter	0.50
				Bulk density	0.50
Nutrient storage, supply and cycling	0.33	Available water	0.25		
		Earthworms	0.25		
		Soil organic matter	0.25		
		Micronutrients	0.25	Manganese	0.33
				Copper	0.33
				Zn	0.33
Sustain biological activity	0.33	Soil organic matter	0.50		
		Earthworms	0.50		

As an alternative to deriving a soil quality index, Fox et al. (2014) proposed to add five levels of lowercase A horizon designators to describe soil processes, soil structure and bulk density, organic carbon, pH and electric conductivity, and landscape context in order to monitor changes in dynamic soil properties due to management and disturbances. They developed an electronic form that allows choosing between the different classes of each level and demonstrated that the system is able to differentiate between different fertilization, tillage and crop rotation treatments in long-term field experiments. For example, the A horizon under ploughing in a silty loam in German would be described as “Ap[cd1-sbk1-gr1](lw;0.85)(n)”. While such a code is certainly useful for pedologists, it is probably not suited for communicating with farmers or the general public. Colour coding may be more intuitive for this kind of communication. For example, in the outputs of both the Cornell soil health test and Sindi, a traffic light system of 3-5 colours indicates low, adequate or even excessive values for a given indicator. Other graphical presentations such as the amoeba diagrams (Figure 6) can likewise convey more information than a single number or index.

5. Potential novel biological soil quality indicators

Background on biological soil quality indicators

In the last decades, the number of studies on soil biological processes and diversity has increased, revealing the important contribution of soil organisms to soil functions (Table 12). In particular, the role of soil organisms in decomposition, nutrient cycling and soil structure is well recognized. Soil biota are considered the most sensitive indicators of soil quality due to their fast responsiveness to changes in environmental conditions (Bastida et al., 2008; Bone et al., 2010; Kibblewhite et al., 2008b; Nielsen & Winding, 2002). At the same time, soil microbial communities have the capacity to mitigate the effects of disturbances on soil ecosystem services, due to their resistance, resilience and/or functional redundancy (Allison & Martiny, 2008). Soil scientists and soil managers are therefore increasingly interested in measuring biological next to chemical and physical properties, and in making use of soil biological functions (Barrios, 2007).

Table 12. Groups of soil organisms as indicators: relation to soil functions and ecosystem services, processes involved, and ease of application

Soil organism	Soil functions	Processes involved	Ecosystem services	Ease of application	Reference
Macroorganisms (fauna)					
Earthworms (macrofauna)	Soil structure formation, Water, pollutant and nutrient cycling	Soil aggregation, porosity, decomposition, humification, organic matter distribution	Food, feed, fibre and biofuel production, erosion control, water purification, climate mitigation	Easy to sample but not ubiquitous	(Blouin et al., 2013; Lavelle et al., 2006)
Nematodes (microfauna)	Nutrient cycling, decomposition, population regulation, biodiversity and habitat	Grazing on microorganisms, control of pests and diseases	Food, feed, fibre and biofuel production, pest and pathogen control	Identification via morphology currently only by specialists, but will be facilitated by molecular tools in the future. Ubiquitous, easy to sample, abundant, sensitive. Key role in soil food web. Known information about feeding preferences and life strategy.	(Mulder et al., 2005; Neher, 2001; Schloter et al., 2003)
Protists (micro-/mesofauna)	Nutrient cycling, population regulation	Grazing on microorganisms	Food, feed, fibre and biofuel production	Rapid growth, highly sensitive, poorly defined taxonomically, difficult isolation and identification	(Foissner, 1999; Riches et al., 2013)
Collembola (mesofauna)	Decomposition, water and nutrient cycling, degradation of pollutants	Fragmentation of residues, biopores	Food, feed, fibre and biofuel production	Difficult to sample and isolate, responsive to seasonality and climatic variation.	(Brussaard et al., 2004; Cardoso et al., 2013; Pulleman et al., 2012; Ruf et al., 2003)
Enchytraeids (mesofauna)	Decomposition, soil structure formation	Soil aggregation, porosity, decomposition, humification, organic matter distribution	Food, feed, fibre and biofuel production	Easy to sample but difficult to identify.	
Mites (mesofauna)	Population regulation	Fragmentation of residues, biopores	Food, feed, fibre and biofuel production	Difficult to sample and isolate.	
Macroarthropods (macrofauna)	Nutrient cycling, soil structure formation	Stimulation of microbial activity, biopores, plant pests	Food, feed, fibre and biofuel production, pest and pathogen control	Relatively easy to sample.	
Microorganisms (microbes)					
Bacteria	Nutrient cycling, plant health promotion	Symbiotic association, decomposition, mineralization and transformation of organic	Food, feed, fibre and biofuel production, environmental filter, pest and pathogen control	Primary role in soil processes. Spatial and temporal variability.	(Brussaard, 2012; Brussaard et al., 2004; Lehman et al., 2015;

		material.			Pulleman et al., 2012; Schloter et al., 2003)
Fungi	Nutrient cycling, soil structure formation, carbon sequestration, plant health promotion	Symbiotic association, decomposition and transformation of recalcitrant material.	Food, feed, fibre and biofuel production, environmental filter, water purification, erosion control, pest and pathogen control		

Table 13. Soil biological indicators, methodology, related soil functions, and advantages/disadvantages at different scales.

INDICATORS	METHODOLOGY	FUNCTION	PROS	CONS	REFERENCE
Individual, population and community level					
Presence, richness, abundance of individual soil organisms	Traditional microscopic methods; advancement in molecular quantitation (qPCR). Key organisms (Mycorrhizae, denitrifiers, rhizobia); functional groups.	Nutrient cycling, soil organisms diversity	Taxonomic and functional level.	Not always linked directly with functions. Difficult to apply to fauna, e.g. protozoa, mites and collembola.	(Brussaard et al., 2004; Cardoso et al., 2013; Nielsen & Winding, 2002; Visser & Parkinson, 1992)
Microbial biomass and fungal biomass, fungal:bacteria ratio	Direct counting, chloroform fumigation extraction, SIR, PLFA, molecular quantitation.	Nutrient cycling and retention, aggregate stability, cycling of xenobiotics.	Sensitive and well related with other soil quality indicators.	Spatially variable, difficult interpretation, contradictory results. Unclear link to functionality	(Bloem et al., 2009; Brussaard et al., 2004; Cardoso et al., 2013; Nielsen & Winding, 2002)
Indices based on faunal communities	Counting and identification of specific groups of organisms (e.g. Maturity Index, Enrichment Index, Channel Index, Structural Index for nematodes)	Nutrient cycling, population regulation, decomposition, level of disturbance.	Sensitive. Taxonomic and functional level.	Time and cost consuming. Specialist required for morphological identification.	(Ferris et al., 2012; Neher, 2001; Parisi et al., 2005)
Community composition	Manual counting and identification	Soil organisms diversity	Division in functional groups can give an indication of functions.	Time-consuming, expertise required. Not indicative of active biota.	(Bloem et al., 2009; Brussaard et al., 2004; Lehman et al., 2015)
	PLFA	Microbial diversity and abundance	Correlated with other measurements. Good indicator of active microbial biomass. Integrated information on the microbial community.	Time-consuming. No direct link with functions. Coarse resolution	(Cardoso et al., 2013; Nielsen & Winding, 2002; Riches et al., 2013; Stenberg, 1999)
	Fingerprinting methods (e.g. DGEE, T-RFLP, A-RISA, ARDRA, TGGE), microarrays	Soil organisms diversity	Greater phylogenetic resolution.	No direct link with function. Difficult comparison between studies due to great variety in methods. Difficulties to extract and amplify DNA.	(Cardoso et al., 2013; Nielsen & Winding, 2002; Stenberg, 1999; Torsvik & Ovreas, 2002)
	Sequencing (metabarcoding)	Soil organisms diversity	Detailed view of diversity and easier comparison. Enormous amounts of data low-cost. Detect less-abundant organisms. Permits discovery of new diversity.	Taxonomic genes no direct link with functions. Difficulties to extract and amplify DNA.	(de Groot et al., 2014; Orgiazzi et al., 2015; Riches et al., 2013; Stenberg, 1999)
	Community Level Physiological Profiling (Biolog™, MicroResp)	Microbial metabolic and functional diversity	Insight into functionality of the community. MicroResp closer to *in situ* conditions, shorter time	Affected by growth associated bias (Biolog™). Selection of fast growing bacteria. Variable	(Campbell et al., 2003; Creamer et al., 2016; Nielsen & Winding, 2002;

			of measurements.	results, no standardize methodology. No relationship with soil functions.	Rutgers et al., 2016; Stenberg, 1999; Torsvik & Ovreas, 2002)
Ecosystem studies					
Soil respiration, nitrogen mineralization, denitrification, nitrification	CO_2 evolution, N_2O emission, NO_3 produced.	Mineralization, microbial activity	Sensitive and ecologically relevant.	Highly variable and fluctuating.	(Anderson & Domsch, 1990; Cardoso et al., 2013; Gil-Sotres et al., 2005; Nielsen & Winding, 2002; Stenberg, 1999; Visser & Parkinson, 1992)
Potentially mineralizable nitrogen	Anaerobic incubation.	Microbial activity	Good correlation with MB and total soil N.		
Metabolic quotient (qCO_2), microbial quotient ($Micr_c/Soil_c$)		Metabolic condition of the microbial community	Sensitive, simple and inexpensive.	Difficult interpretation: confound disturbance with stress.	
DNA and protein synthesis.	Thymidine and leucine DNA incorporation.	Microbial activity	Reflection of active microbial biomass.		(Blagodatskaya & Kuzyakov, 2013; Bloem et al., 2009)
Enzymatic activities	Extraction of enzymes in the soil and incubation with various substrates.	Nutrient cycling, decomposition, soil carbon storage, detoxification, disease suppression	Closely related to important soil quality parameters. Very sensitive. Simple and inexpensive methods.	Standard procedure not available. Contradictory results, complex behaviour and variable for each enzymes. Potential activity.	(Cardoso et al., 2013; Gil-Sotres et al., 2005; Nielsen & Winding, 2002; Stenberg, 1999; Trasar-Cepeda et al., 2008; Visser & Parkinson, 1992)
Functional genes and transcripts	FISH, Microarrays, meta-transcriptomic, qPCR, metagenome analysis.	Nutrient cycling.	Closer link to functionality. FISH and microarrays can give an idea of active microorganisms. High sensitivity and throughput.	Restricted to known gene sequences. Genes and transcripts might not be expressed. Difficulties linked with RNA extraction.	(Blagodatskaya & Kuzyakov, 2013; Rocca et al., 2015; Saleh-Lakha et al., 2005)
Metabolomics and metaproteomics	Assessment and quantitation of metabolites and proteins in the soil.	Nutrient cycling, microbial activity, disease suppression, soil structure formation.	Close link to functionality.	Field in development.	(Bastida et al., 2008; Simon & Daniel, 2011)
Stable isotope probing	Incorporation of ^{13}C- or ^{15}N-labelled substrates into DNA, RNA, PLFA, proteins	Microbial activity, nutrient cycling.	Permit to establish link between biodiversity and functions. Allow in situ analysis of active microbial population.	Field in development. Time involved in the assimilation of the substrates.	(Bastida et al., 2008; Saleh-Lakha et al., 2005; Watzinger, 2015)

In early studies, the seasonal fluctuation of soil biological indicators in the field was often seen as an obstacle. More recently, it has been stated that this problem can be overcome by standardizing sampling time, methodology and pre-treatment, or by presenting the data relative to another soil property such as soil organic carbon (Philippot et al., 2012; Stenberg, 1999; Stenberg et al., 1998). Alternatively, the high sensitivity can be viewed as an advantage, which allows soil biological indicators to be used to evaluate short-term changes (De La Rosa, 2005).

Microbial communities have received much more attention in soil quality assessment than other components of soil biota because of their important contribution to energy and nutrients flows in ecosystems and their fast responsiveness to changes in the soil environment (Cardoso et al., 2013; Stenberg, 1999). Microbial community composition and activity remain, however, strongly dependent on the activity of soil fauna at higher trophic levels (Nielsen et al., 2011; Torstensson et al., 1998).

Microbial parameters such as microbial biomass, potentially mineralizable N (by anaerobic incubation), and soil respiration were included in early minimum datasets to assess soil quality (Doran & Parkin, 1996; Larson & Pierce, 1991). Subsequently, other biological and biochemical parameters such as potential ammonium oxidation, potential denitrification activity, N_2-fixing bacteria, enzymatic activity (e.g. dehydrogenase) and humification activity were suggested to be included in minimum datasets and soil quality indices (Filip, 2002; Gil-Sotres et al., 2005; Jordan et al., 1995; Stenberg, 1999). More recently, biological indicators based on genotypic and phenotypic community diversity as well as functional traits are being implemented in soil quality assessments (Nielsen & Winding, 2002; Ritz et al., 2009). Table 13 provides an overview of soil biological indicators, which will be discussed in the following section.

Novel potential soil biological indicators

Indicators at the ecosystem level (Table 13) are assumed to provide a better understanding of the link between soil organisms and their contribution to ecosystem services than indicators at the individual or population level (Barrios, 2007; Pulleman et al., 2012; Visser & Parkinson, 1992). The selection of biological indicators and related methodology is however not straightforward, since each indicator has advantages and disadvantages. The most important limitation of many diversity and community composition studies is the lack of an established direct link with soil functions. This is also due to the difficulties in determining the active part of the population of organisms in soil (Blagodatskaya & Kuzyakov, 2013). Recent investigations, however, suggest some direct linkages between biodiversity and function (Allan et al., 2015; Juarez et al., 2013; Tardy et al., 2015; Wagg et al., 2014). For example, microbial richness and diversity have been shown to affect carbon and nitrogen cycling (Philippot et al., 2013; Tardy et al., 2015). In addition, a decreased level of soil biodiversity, namely mycorrhizal and nematode communities, has been found to have negative effects on soil functions such as carbon sequestration and nitrogen turnover (Wagg et al., 2014). Further studies are needed to confirm such relations, and the use of models such as network analysis and structural equation modelling can facilitate the identification of linkages between diversity and functions (Allan et al., 2015; Creamer et al., 2016).

Among the novel molecular methods, high throughput sequencing techniques (including metagenomics and metatranscriptomics) targeting functional and taxonomic genes and transcripts seem to be promising tools in the study of the relationships between taxonomic, structural and functional diversity in soil communities (e.g. Fierer et al., 2012). Other techniques such as DNA or RNA microarrays for functional or phylogenetical genes, quantitative polymerase chain reaction (qPCR) and comparative genome analysis are currently being developed and adopted to link biodiversity, soil functions and ecosystem services (de Bruijn et al., 2015; Xue et al., 2013). These molecular tools could be used to assess biochemical processes, potentially substituting existing biochemical indicators such as enzymatic activities. However, there is an urgent need to examine the relationship between quantification and presence of genes and transcripts and the ability of these metrics to predict process rates (Rocca et al., 2015).

Trait-based approaches may be well-suited for the study of soil functioning (Barrios, 2007; Brussaard, 2012; de Bello et al., 2010; Ferris & Tuomisto, 2015). These approaches consist in the identification and quantification of functional traits (i.e. distinctive characteristics that determine a function). Functional traits are possibly more discriminating than functional groups (e.g. decomposers, denitrifiers, plant pathogens, plant growth promoting bacteria, faunal functional groups) and/or key-stone organisms (e.g. mycorrhizal fungi, diazotrophs, specific earthworm or enchytraeid species) as indicators of ecosystem processes linked to ecosystem services, but quantification across taxonomic groups is still challenging.

In addition, *metabolomics and metaproteomics* appear to be suitable techniques to study soil functions (Simon & Daniel, 2011). These techniques are still in their infancy as soil quality indicators, but they offer the possibility to relate to soil functions, because the detected products are directly responsible for ecosystem functions. *Stable Isotope Probing* (SIP) in conjunction with phospholipid fatty acid (PLFA) analysis or DNA or RNA analysis could also help to link soil biodiversity and functions (Wang et al., 2015; Watzinger, 2015). However, being targeted at biochemical processes, these techniques will not generate novel indicators for soil physical processes and associated ecosystem services.

Thus, as detailed in Table 13, many new methods to assess soil organisms have been developed that could result in soil quality indicators which could become part of regular monitoring programs. In addition, there has been progress recently in using several other soil properties as novel indicators, two of which are briefly discussed below.

Indicators for labile organic carbon

Soil organic matter, which is ubiquitous as a soil quality indicator (Figure 5), is intimately connected with soil organisms, and it is therefore sometimes considered as a biological indicator. Despite its importance for soil quality, changes in total soil organic matter in response to management and land use are difficult to detect since the total pool is large (Haynes, 2005). Components of soil organic matter such as microbial biomass, mineralizable C and N, or labile carbon can typically give a better indication about soil organic matter quality and organisms activity (Gregorich et al., 1994). These labile fractions change more rapidly and to a greater extent than total soil organic matter, and *labile organic carbon* (or active carbon) is the primary source of energy for soil organisms. These characteristics make labile organic carbon an interesting bridge-parameter between chemical and biological soil properties. Increasingly, studies are considering the labile fraction of soil organic matter as a promising parameter to assess management impacts on soil quality (Haynes, 2005; Riches et al., 2013). However, there is no consensus on the best fraction or methodology to determine labile organic carbon. Suggestions to measure this fraction include particulate organic matter (Cambardella & Elliott, 1992), permanganate-oxidizable carbon (Weil et al., 2003), hot water-extractable carbon (Ghani et al., 2003) and dissolved organic carbon (Filep et al., 2015).

Indicators for soil suppressiveness of plant diseases and pathogens

An essential element for a healthy soil is the capacity to control pests and diseases. *Plant disease and pathogen suppressiveness* in soil is defined as the property of a soil to naturally reduce the disease incidence or the development of certain diseases (Hornby, 1983). Disease suppressiveness has been shown to depend on soil biological activity which can be affected by crop management practices (Wu et al., 2015). Several soil abiotic and biotic parameters have been suggested to underlie suppressiveness, such as soil pH, cations, N content, microbial biomass and activity, and diversity and structure of microbial communities (Janvier et al., 2007). However, so far none of the abovementioned indicators have been validated, which is probably due to the incomprehensive understanding of the phenomenon. Since soil suppressiveness bioassays are highly time- and energy-consuming, there is a need to find soil parameters which are strictly connected to the capacity of a soil to resist soil-borne disease. Recently, microbial resilience and resistance to disturbance, and dissolved organic carbon have been suggested as indicators for soil suppressiveness, but further studies need to validate their link with soil suppressiveness (Straathof et al., 2014; Straathof & Comans, 2015; van Bruggen et al., 2015).

6. Conclusions: Strengths and weaknesses of existing concepts and proposition of a novel framework

Our review of existing soil quality concepts has shown that a large number of concepts has been developed during the past three decades, with some having been applied more frequently than others. Based on our review, we have identified some critical points in the development of any soil quality concept (Figure 9).

It has become obvious that the **objective** of a given concept is **often not clearly stated**, i.e. whether the soil quality assessment is meant as a basis for management recommendations, seen as an educational tool, or as part of a monitoring program. Likewise, the **target users** are often not clearly named, with concepts focussing on visual soil evaluation tools being clearly more targeted at farmers than concepts requiring quantitative laboratory measurements, with the exception of a soil-testing service such as the Cornell soil health assessment (Moebius-Clune et al., 2016). Reversely, scientists tend to favour data produced in the laboratory rather than by visual soil evaluation tools. This bias makes it even more important to clearly define target users and involve them in the development of the concept.

Conceptually, **linkages between indicators and soil functions or ecosystem services** have sometimes been proposed but **rarely established firmly**, i.e. with experimental evidence. An asset of a novel soil quality framework would be such a firm linkage, and the possibility to **choose indicators based on the targeted soil function or ecosystem service**. Likewise, the possibility to choose between **substitute indicators** would be beneficial. For example, missing analytical indicators could be substituted by visual assessments in the field. Also, the use of parallel independent lines of evidence in ecological risk assessment (Rutgers & Jensen, 2011) could be a model for soil quality assessment.

A scheme giving these two options of analytical and field assessments was proposed within work package 3 of the iSQAPER project and is shown in Table 14 as well as in Figure 10. Likewise, the relationship of indicators with soil threats has been proposed (Morvan et al., 2008). Conceptually, soil functions, ecosystem services and threats are all linked and concepts focusing on either of these can thus potentially be reconciled.

The **lack of non-soil indicators** in many concepts is rather striking. This concerns on the one hand missing information on climatic and site conditions, and on the other hand the neglected opportunity to use the plant status to reflect soil quality. Classical land evaluation allows inclusion of quantitative and qualitative information (Sonneveld et al., 2010), which is something that should clearly be integrated in future soil quality concepts. Taking non-soil indicators into account fits also with the idea to assess soil quality in connection with soil functions and ecosystem services. A recent study evaluated soil indicators for sustainable development, thus going beyond the concept of soil quality (Jonsson et al., 2016). In this concept, not only physical, chemical and biological soil indicators, but also social indicators such as government policies and economic indicators such as the economic value of ecosystem services were included.

Importantly, the **interpretation** of the values of the proposed soil quality indicators needs to be well-defined. If no system for interpretation is provided, the concepts cannot be used in practice. For many soil properties**, texture-dependent scoring curves** need to be developed, which is possibly one of the greatest challenges of soil quality concepts. In the Cornell soil health assessment, for example, soil data from the Northeast of the USA was used to establish scoring curves that are therefore relative to this regional data. The increased **availability of digital soil maps and soil survey data** such as the LUCAS soil data available from the Joint Research Centre (http://esdac.jrc.ec.europa.eu/content/lucas-2009-topsoil-data) or global soil grids in

250M (https://soilgrids.org/#/?zoom=2&layer=geonode:taxnwrb_250m) provides an opportunity to establish such scoring curves or target values more easily from frequency distributions of a given soil property. However, if soils in a region are badly managed and quite degraded, such a frequency distribution may not include the optimum state. In this case, the principle of **identifying reference sites** with acknowledged good soil quality (Rutgers et al., 2008; Rutgers et al., 2012) would be more suitable.

Other opportunities include **big data approaches** and **mobile data capture** including photographs, which are also used in the proposed LandPKS tool (www.landpotential.org), the SoilInfo App (http://soilinfo.isric.org/) and **high throughput soil analysis approaches**, such as near-infrared spectroscopy (e.g. Cecillon et al., 2009; Kinoshita et al., 2012). In addition, the use of **pedotransfer functions** especially for complex soil properties such as hydrologic characteristics (Saxton & Rawls, 2006; Toth et al., 2015) can be recommended and should be increased.

Importantly, any soil quality assessment tool should not only give a clear interpretation, but should suggest **improved management options**. An example for this is the output of the Cornell soil health assessment, which gives several pages of management advice in conjunction with the results of the test (Moebius-Clune et al., 2016). The way of doing this varies of course with the targeted soil functions and ecosystem services as well as with the target users.

In conclusion, this review has identified the strengths and weaknesses of existing soil quality concepts and made suggestions towards a novel concept, both in conceptual and practical terms.

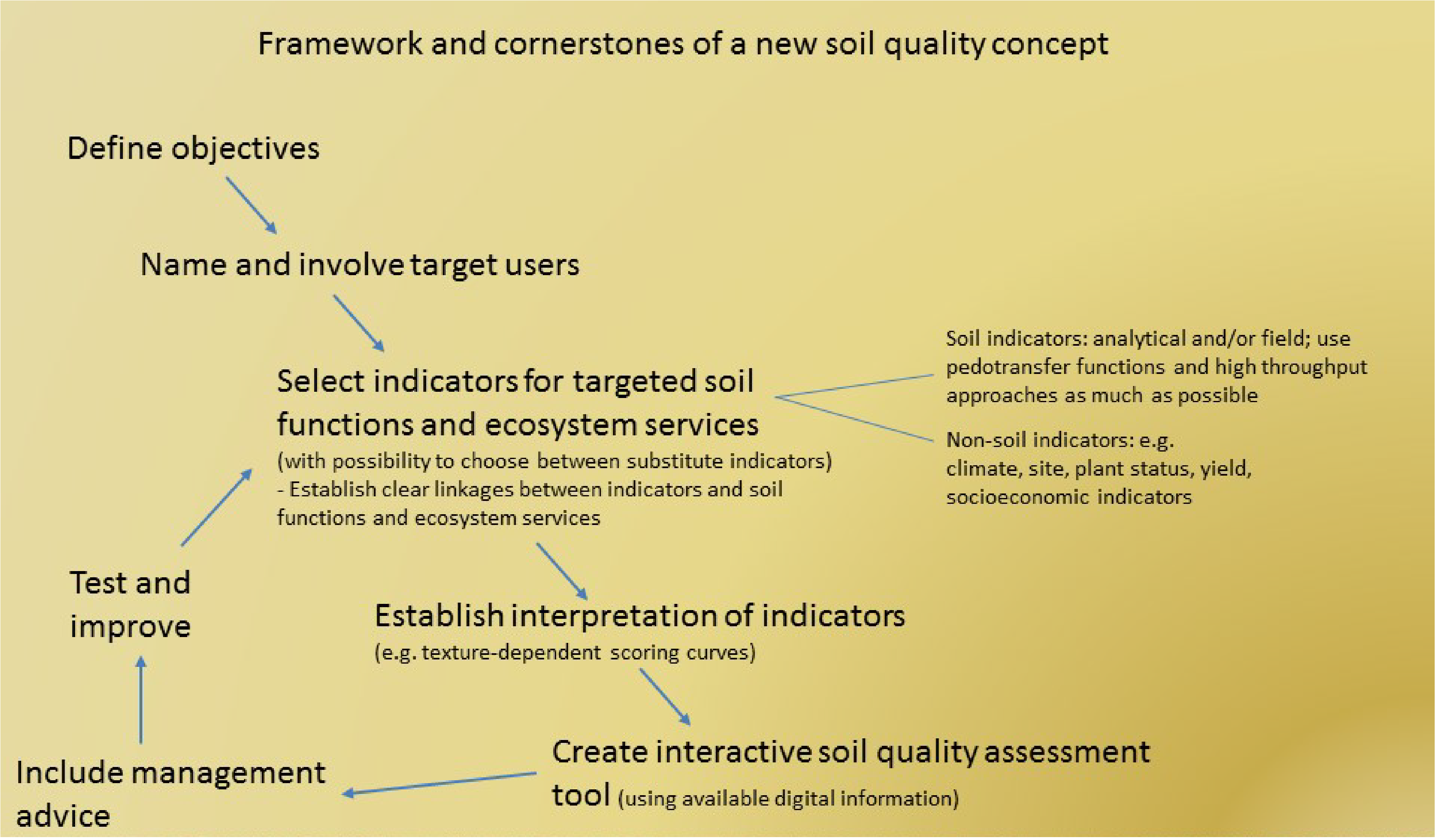


Figure 9: Framework and cornerstones of a new soil quality concept

Table 14: Laboratory analyses and field assessments planned within iSQAPER WP3 as related to soil functions and soil-based ecosystem services.

			Soil functions							Soil based ecosystem services					
	Indicator	**Analytical (A) or field assessment (F)**	**Habitat for roots and soil organisms**	**Nutrient capture and cycling**	**Decomposition (incl. pollutant degradation)**	**Soil structure maintenance**	**Population regulation**	**Water cycling**	**SOM dynamics**	**Food, feed, fiber production**	**Water quality & supply**	**Erosion control**	**Climate regulation**	**Pest and disease control**	**Biodiversity conservation**
Chemical	Total organic C	A		X		X		X	X				**X**		
	Total N	A		X											
	pH	A		X											
	Avail. P	A		X											
	CEC (incl. avail. K)	A		X											
	Labile C[1]	A													
Biological	Microbial Biomass	A	X	X		X			X						
	N mineralization	A		X					X						
	Molecular analyses[3]	A	X				X								**X**
	Earthworms	F	X	X	X	X									**X**
	Disease incidence[4]	F/A					X							**X**	

	Yield	F		X						**X**					
	Tea bag test[5]	F			X				X						
Physical	Bulk density	F				X		X	X				**X**		
	Particle-size distrib.	A				X		X							
	Soil depth	F	X	X				X							
	Aggregate stability	A				X						**X**			
	Water holding cap.	A[2]	X	X				X			**X**				
	Penetration resist.	F	X			X		X							
	Spade diagnosis	F	X		X	X									

[1] included in microbial biomass analysis (K_2SO_4-extractable C)

[2] calculated from particle-size analysis, organic C and bulk density via pedotransfer function

[3] Various molecular analyses (e.g. nematodes, fungi, microbial community etc.)

[4] field assessments, disease suppression assays

[5] (Keuskamp et al., 2013)

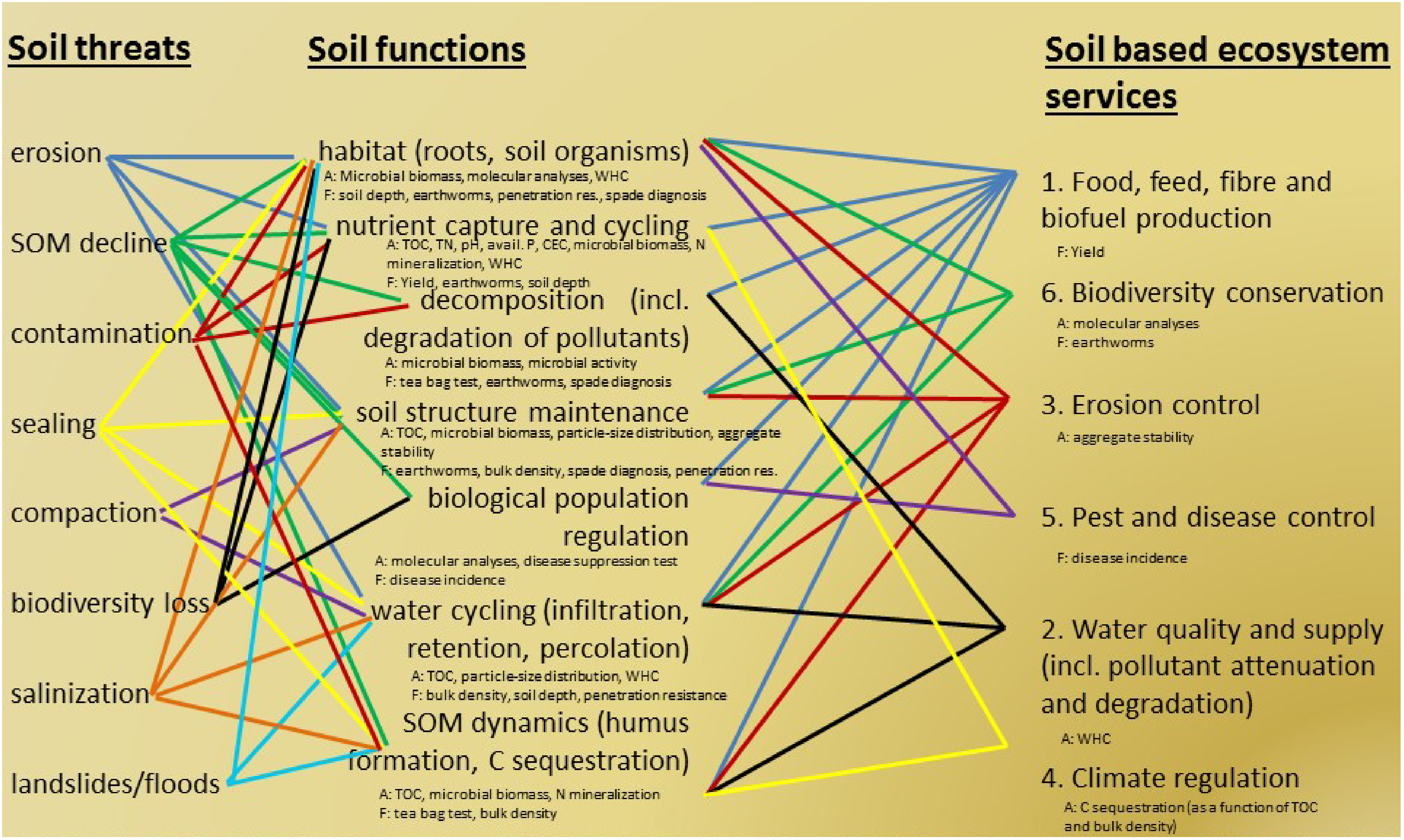


Figure 10: Proposed linkages between soil threats, soil functions and soil based ecosystem services, and suggested indicators to be used within the iSQAPER project. Please note that indicators for soil threats were identified by previous projects (Table 1). A: analytical, F: field indicators. CEC: cation exchange capacity, TOC: total organic carbon, TN: total nitrogen, WHC: water holding capacity.

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