

1 **Identification of sensitive indicators to assess the**  
2 **interrelationship between soil quality, management**  
3 **practices and human health.**

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5 R. Zornoza<sup>1</sup>, J.A. Acosta<sup>1</sup>, F. Bastida<sup>2</sup>, S. G. Domínguez<sup>1</sup>, D.M. Toledo<sup>3</sup>, A. Faz<sup>1</sup>

6 [1] Sustainable Use, Management and Reclamation of Soil and Water Research Group.  
7 Department of Agrarian Science and Technology. Universidad Politécnica de Cartagena.  
8 Paseo Alfonso XIII, 48. 30203 Cartagena. Spain

9 [2] Department of Soil and Water Conservation, CEBAS-CSIC, Campus Universitario de  
10 Espinardo, 30100 Murcia. Spain

11 [3] Cátedra de Edafología. Departamento de Suelo y Agua. Facultad de Ciencias Agrarias.  
12 Universidad Nacional del Nordeste. Sargent Cabral 2131, 3400 Corrientes. Argentina.

13 Correspondence to: R. Zornoza (raul.zornoza@upct.es)

14 **Abstract**

15 Soil quality (SQ) assessment has been a challenging issue since soils present high variability  
16 in properties and functions. This paper aims to increase the understanding of SQ through the  
17 review of SQ assessments in different scenarios providing evidence about the  
18 interrelationship between SQ, land use and human health. There is a general consensus that  
19 there is a need to develop methods to assess and monitor SQ for assuring sustainable land use  
20 with no prejudicial effects on human health. This review points out the importance of  
21 adopting indicators of different nature (physical, chemical and biological) to achieve a  
22 holistic image of SQ. Most authors use single indicators to assess SQ and its relationship with  
23 land uses, soil organic carbon and pH being the most used indicators. The use of nitrogen and  
24 nutrients content has resulted sensitive for agricultural and forest systems, together with  
25 physical properties such as texture, bulk density, available water and aggregate stability.  
26 These physical indicators have also been widely used to assess SQ after land use changes.  
27 The use of biological indicators is less generalized, microbial biomass and enzyme activities  
28 being the most selected indicators. Although most authors assess SQ using independent  
29 indicators, it is preferable to combine some of them into models to create a soil quality index  
30 (SQI), since it provides integrated information about soil processes and functioning. The  
31 majority of revised articles used the same methodology to establish a SQI, based on scoring  
32 and weighting of different soil indicators, selected by multivariate analyses. The use of  
33 multiple linear regressions has been successfully used for forest land use. Urban soil quality  
34 has been poorly assessed, with lack of adoption of SQIs. In addition, SQ assessments where  
35 human health indicators or exposure pathways are incorporated are practically nonexistent.  
36 Thus, further efforts should be carried out to establish new methodologies not only to assess  
37 soil quality in terms of sustainability, productivity and ecosystem quality, but also human  
38 health. Additionally, new challenges arise with the use and integration of stable isotopic,  
39 genomic, proteomic and spectroscopic data into SQIs.

40 **1. Introduction**

41 **1.1. Concept of soil quality**

42 Soil is a complex environmental medium with high heterogeneity where solid, liquid and  
43 gaseous components interact within multitude physical, chemical and biological interrelated  
44 processes. Soil provides ecosystem services (benefits people obtain from the soil) such as as  
45 food, water, timber, and fiber; regulating services that affect climate, floods, disease, wastes,  
46 and water quality; cultural services that provide recreational, aesthetic, and spiritual benefits;  
47 and supporting services such as nutrient cycling. (Millennium Ecosystem Assessment, 2005).  
48 Nonetheless, owing to unsustainable land uses, soil is degrading by loss of organic matter,  
49 salinization/alkalinization, compactness, structural destruction, sealing, contamination,  
50 acidification, etc., compromising the maintenance of further productivity. Thus, there is a  
51 tendency towards preservation of soils to promote its sustainable use (Blum, 2003). Because  
52 of the intrinsic association between soil and economy, several economic activities depend on  
53 soil quality, which include agriculture, forestry, industry and tourism, which could benefit  
54 from establishment of methods for soil quality assessments (Bone et al., 2010).

55 The definition of soil quality (SQ) has been a challenging issue since soils present high  
56 variability in properties, characteristics and functions. Up to our knowledge, the first user of  
57 the concept was Alexander (1971) who recommended the establishment of SQ criteria (Bone  
58 et al., 2010). After that, there have been several definitions (e.g. Larson and Pierce, 1991;  
59 Parr et al., 1992; Doran and Parkin, 1994; Harris et al., 1996). The most integrative  
60 definitions are those established by Doran and Parkin (1994) and Harris et al. (1996) who  
61 defined SQ as the capacity of a soil to function within the limits of use, landscape and climate  
62 (ecosystem) to protect air and water quality, and to sustain productivity and plants, animals  
63 and human health. Nonetheless, despite the different definitions for SQ, there is no general  
64 consensus yet, likely due to the innate difficulty of definition of soil (Carter, 2002).

65 This paper aimed to provide new insights through review of soil quality assessments in  
66 different scenarios linked to forest management, agricultural management, urban systems  
67 and land use changes. The selection of indicators or indices to assess soil quality in an  
68 effective and sensitive way in terms of the ecological ambient and the purpose of the  
69 assessment is synthesized. Major concerns about the effect of land use or management is  
70 incorporated to select suitable indicators, providing evidence about the interrelationship  
71 between soil quality, environmental quality and human health.

72

73 **1.2. Interrelationship between soil quality, land management and human**  
74 **health**

75 Management practices in agriculture, forestry or urban environments can have negative or  
76 positive impacts on SQ, favoring the exhaustion of nutrients, loss of SOM, pollution,  
77 biodiversity reduction, etc, or favoring trends in the opposite direction. Suitable management  
78 practices for each land use within each geographical area are essential to preserve soil  
79 functions and thus promote SQ. Additionally, there is always a feedback interaction between  
80 SQ and the management practice selected, since modifications in SQ could also warn the land  
81 manager to change that practice, which is no longer suitable or needed.

82 Less attention has been given to soil degradation and its direct or indirect effects on human  
83 health, despite SQ deterioration may possibly lead to a variety of human diseases (Deng,  
84 2011). [Bone et al. \(2010\)](#) suggested that this is because the links to human health are not  
85 evident for soil to the same extent as water and air. To assess the effects of SQ to organisms,  
86 soil quality standards (SQS) are normally developed, which represent the concentration of a  
87 chemical or group of chemicals or pathogen in soil that should not be exceeded in order to  
88 prevent harmful effects ([Rodríguez and Lafarga, 2011](#)).

89 Thus, SQ has interconnections with management practices, productivity and other ecosystem  
90 aspects, showing an interdependence controlled by feedback mechanisms. SQ is also  
91 connected to human health since soil can play as source and/or pathway of disease vectors.  
92 Management practices can directly affect productivity, ecosystem functioning and human  
93 health, but also indirectly by shifts in SQ (Fig. 1). Doran (2002) postulated that soil  
94 management practices are primary determinants of SQ, and SQ indicators must not only  
95 identify the condition of the soil resource but also define the economic and environmental  
96 sustainability of land management practices. One of the greatest challenges for researchers is  
97 “translating science into practice” through identifying soil indicators capable of showing  
98 rapid changes in the ecosystems performance, needed by land managers and decision makers  
99 to assess the economic, environmental, social and health impacts of management practices.

100

101 **1.3. Approaches to assess soil quality and the selection of suitable**  
102 **indicators.**

103 There is an increasing acknowledge and international interest in developing methodologies  
104 to characterize and define management practices which control degradation and enhance SQ.

105 It is necessary a methodology to select indicators to assess SQ with the aim of identifying  
106 problems in productivity, monitor changes in ecosystems sustainability, track ecological  
107 effects after land use changes or reducing risks for human health. Although many studies  
108 have been conducted on SQ assessment, there is not a general methodology to characterize  
109 SQ and define a set of indicators. SQ indicators are measurable properties or characteristics  
110 which provide information about the ability of the soil to provide essential environmental  
111 services. Those attributes most sensitive to management practices or land use changes are the  
112 most adequate as indicators (Arshad and Martin, 2002). A wide range of physical, chemical  
113 and biological properties are available to be measured on routine basis, but due to the  
114 impossibility of considering them all, it is necessary to make a selection. Larson and Pierce  
115 (1991) (cited in Larson and Pierce, 1994) suggested a minimum data set (MDS) for SQ  
116 assessment, with the objective of standardizing methodologies and procedures at  
117 international level. This list was later extended, including biological properties by Doran and  
118 Parkin (1994). These proposals have been further adapted, modified or extended in posterior  
119 studies. Physical properties reflect limitation for the development of roots, seedlings  
120 emergency, infiltration, water retention of movement of fauna (Burger and Kelting, 1998).  
121 The chemical condition affects the soil-plant relations, water quality, buffering capacity,  
122 availability of nutrients and contaminants (Muckel and Mausbach, 1996). Biological  
123 indicators are more sensitive and rapidly respond to perturbations and changes in land use;  
124 soil organisms, besides, play a direct role in the ecosystems processes, mainly in the nutrient  
125 recycling and soil aggregation (Doran and Zeiss, 2000; Rillig, 2004). The selection of  
126 indicators of different nature (physical, chemical and biological) is essential to achieve a  
127 holistic image of SQ (Nannipieri et al., 1990).

128 Even though most authors assess SQ using different independent indicators, others prefer  
129 their combination into models or expressions in which various properties are involved (Fig.  
130 2). These expressions are called soil quality indices (SQI) that can help determine SQ trends  
131 and thereby indicate whether one or more changes in practice are necessary (Karlen et al.,  
132 2001). Despite computer modelling can simplify this process, novel approaches that  
133 recognize relationships among highly disparate types of data associated with SQ are needed  
134 to assess the value of different indicators for guiding land management decisions. In the last  
135 years a new approach has emerged for integrating great amounts of data, the artificial neural  
136 networks, which extract and recognize patterns in relationships among descriptive variables  
137 and used to predict specific outputs variables (Mele and Crowley, 2008).

138

139 **2. Agricultural practices and soil quality indicators**

140 SQ has been assessed in agricultural systems in different agroclimatic regions and soil types  
141 under different crops and management practices. Even though crops productivity is the main  
142 concern in agriculture due to economic issues, there is a need to maintain SQ to preserve  
143 global sustainability. Assessment of SQ is needed to identify problems in production areas  
144 and to assist in formulation and evaluation of realistic agricultural and land-use policies  
145 (Doran, 2002).

146 Soil organic carbon (SOC) has been suggested as the most important single indicator of SQ  
147 and agricultural sustainability since it affects most soil properties (Reeves, 1997; Arias et al.,  
148 2005). In the literature reviewed, SOC is the most used indicator for SQ assessments,  
149 followed by pH, electrical conductivity (EC) and nutrients (indicators of soil fertility) (Table  
150 1). Physical indicators have been applied in about 70% of the reviewed literature, being  
151 particle size, aggregates stability and bulk density the most common used. About 50% of  
152 authors incorporated biological properties, mainly microbial biomass carbon (MBC) or  
153 nitrogen (MBN) and enzymatic activities, probably owing to its high sensitivity and ease to  
154 measure. Fewer studies (around 40% of the consulted literature) included organisms like  
155 earthworms and arthropods as indicators, even though they respond sensitively to land  
156 management practices (Doran and Zeiss, 2000), likely because they are useful only at local  
157 scale (Rousseau et al., 2013).

158 Despite most authors assess SQ by analysis and description of single indicators, others  
159 consider the importance of a SQI to relate SQ with crop production and management  
160 practices. The majority of revised articles used the same methodology to establish a SQI,  
161 based on scoring and weighing different soil indicators (Hussain et al., 1999; Andrews and  
162 Carroll, 2001). A MDS was used to create the index, being selected in most cases by  
163 multivariate analyses (such as principal components analysis (PCA)). The most common  
164 parameters used were pH, EC, SOC, total nitrogen (Nt) and available P. Other indicators such  
165 as  $\text{NO}_3^-$ ,  $\text{NH}_4^+$ , Na, K, Ca, Mg, bulk density, sand, silt, clay and available water content have  
166 been also used by various authors. After indicators have been transformed using a linear or  
167 nonlinear scoring curve into unitless values and weighted, SQIs have been normally  
168 calculated using the Integrated Quality Index equation (IQI) (Doran and Parkin, 1994) or the  
169 Nemoro Quality Index equation (NQI) (Qin and Zhao, 2000) by summation of the weighted  
170 scored indicators. Qi et al. (2009) measured 14 chemical indicators (SOC, Nt, pH, cation

171 exchange capacity (CEC) and several nutrients) and compared the IQI and NQI in  
172 combination with three methods for indicators selection: Total Data Set (TDS), MDS, and  
173 Delphi Data Set (indicators selected by the opinion of experts). They concluded that results  
174 were similar regardless of the method or model applied. [Rahmanipour et al. \(2014\)](#) compared  
175 two sets of indicators, TDS (composed of 10 physical and chemical properties, mainly the  
176 erodibility factor, pH, EC, SOC, CEC and heavy metals) and MDS (indicators reduced by  
177 PCA), and two different indices, IQI and NQI. These authors concluded that IQI/MDS  
178 approach was the most suitable tool to evaluate the effects of land management practices on  
179 SQ.

180 [D'Hose et al. \(2014\)](#) assessed the relationship between SQ and crop production under  
181 different management practices by the adoption of the IQI, using five soil indicators selected  
182 by PCA (SOC, Nt, earthworms, nematodes and MBC). These authors concluded that SQ was  
183 higher when farm compost was applied and SOC was pointed out as the most important  
184 indicator influencing crop production. [Liu et al. \(2014a\)](#) calculated a SQI in acid sulfate  
185 paddy soils with different productivity. They scored five soil chemical and biochemical  
186 indicators after their selection by PCA (pH, Nt, MBC, Si and Zn), which were integrated into  
187 an index, showing lower SQ in systems with low productivity. [Liu et al. \(2014b\)](#) validated  
188 their SQI ([Liu et al., 2014a](#)) in low productive albic soils from Eastern China, and observed  
189 significant correlations between the SQI and crop yield.

190 Merrill et al. (2013) assessed SQ in two different soil types sampled at different depths. For  
191 these purposes, authors made use of the Soil Management Assessment Framework (SMAF), a  
192 pre-established SQI ([Andrews et al., 2004](#)), which evaluates SQ in the basis of critical soil  
193 functions. Authors highlighted that soil surface and subsurface properties should be  
194 integrated for SQ assessments. [Li et al. \(2014\)](#) also used the SMAF to assess SQ in  
195 agrosystems where mulch was added, concluding that MBC and  $\beta$ -glucosidase activity were  
196 the most responsive indicators to mulching and production systems.

197 There have been fewer attempts to calibrate SQIs based on other methodologies. For  
198 instance, [García-Ruiz et al. \(2008\)](#) established a SQI by the calculation of the geometric mean  
199 of several enzyme activities (GMea). Soil enzymes and the GMea were suitable to  
200 discriminate between a set of organic and comparable conventional olive oil orchard crops.

201

### 202 **3. Forest management and soil quality indicators.**

203 About 31 % of the world's land surface is covered by forests (FAO, 2012) which provide  
204 different goods and services, such as water reservoirs, biodiversity, carbon sequestration,  
205 timber, gum, recreation, etc. Previous research mainly focused on the assessment of SQ to  
206 promote highest forest productivity. Nonetheless, in the last years, international  
207 environmental concern about forest management made a shift in research focus towards the  
208 sustainability of the forest ecosystem functions.

209 In order to assess forest SQ, the most used indicators are SOC, followed by pH, nutrient  
210 levels, MBC and mineralizable N (Table 1). Miralles et al. (2009) observed that most soil  
211 properties measured in forest soils from Southeast Spain were highly correlated with SOC.  
212 They established SQ indicators consisting of ratios to SOC, which inform about the specific  
213 activity (per C unit) or performance of the organic matter, independently of its total content.  
214 These authors concluded that these ratios are more effective to assess SQ since they provide  
215 information about soil resilience. Physical attributes have been used in about 23% of the  
216 reviewed literature, being water availability or water holding capacity (WHC), soil porosity  
217 and aggregate stability the most common indicators. In the recent years, there has been a  
218 general concern about the importance of soil biological indicators and their ecological  
219 relevance to assess SQ, and some authors have included in their studies microbial indicators  
220 such as microbial community composition (Zornoza et al., 2009; Banning et al., 2011;  
221 Blecker et al., 2012). The adoption of SQIs under forest use has been less developed than for  
222 agro-ecosystems. Most authors have applied simple ratios, such as C/N, the metabolic  
223 quotient or  $q\text{CO}_2$  (soil respiration to MBC), enzyme activities-to-microbial biomass, SOC  
224 and N stratification ratios, MBC-to-SOC, MBN-to-Nt, ATP-to-MBC, ergosterol-to-MBC, or  
225 fungal-to-bacteria biomass (Trasar-Cepeda et al. 1998; Franzluebbers, 2002; Dinesh et al.,  
226 2003; Mataix-Solera et al., 2009; Toledo et al., 2012; Zhao et al., 2014). However, using only  
227 two soil indicators to create a SQI does not provide enough information about soil processes  
228 and functioning. Despite this fact, the development of algorithms in which different  
229 indicators are combined, has not been generalized, likely because they are limited to the area  
230 and situation in which they have been described (Gil-Sotres et al., 2005).

231 Burger and Kelting (1999) provided an index to assess the net effect of forest management  
232 using different soil physical, chemical and biological indicators such as porosity, available  
233 water capacity, pH, SOC or respiration. They applied the principles proposed by Gale et al.  
234 (1991), and the SQI was calculated as the summation of five weighted indicators (sufficiency  
235 for root growth, water supply, nutrient supply, sufficiency for gas exchange and biological

236 activity). Trasar-Cepeda et al. (1998) obtained a biochemical SQI using natural soils under  
237 climax vegetation where Nt can be estimated by multiple linear regression using MBC,  
238 mineralizable N and enzyme activities as independent variables. This index was validated by  
239 Leirós et al. (1999) in disturbed soils by contamination and tillage, concluding that it can be  
240 used for the rapid evaluation of soil degradation, since it distinguished among high quality  
241 soils, soils in a transient status, and degraded soils. This methodology, based on the  
242 calculation of a soil property by multiple regressions, which suggests a balance among soil  
243 properties, was also used by other authors. Under semiarid Mediterranean conditions,  
244 Zornoza et al. (2007) obtained two SQIs to assess soil degradation by estimation of SOC  
245 through linear combination of physical, chemical and biological indicators (pH, CEC,  
246 aggregate stability, WHC, EC and enzyme activities). These indices were further validated by  
247 Zornoza et al. (2008a) in eleven undisturbed forest soils confirming their viability and  
248 accuracy. Chaer et al. (2009) calibrated a SQI using multiple linear regressions with SOC as  
249 combination of MBC and phosphatase activity, confirming previous evidence of a balance in  
250 soil properties in undisturbed soils, being this balance disrupted after perturbations.

251 Pang et al. (2006) established in forest soils from China an Integrated Fertility Index (IFI)  
252 with the objective of detecting changes in soil fertility in relation to vegetation, climate and  
253 disturbance practices. They applied PCA to 14 physical and chemical indicators, and  
254 calculated a value for each identified PC as the summation of each indicator value multiplied  
255 by its loading. The IFI was calculated as the summation of each weighted PC. Authors found  
256 that IFI was highly correlated to trees growth.

257 Amacher et al. (2007) developed a SQI that integrated 19 physical and chemical properties  
258 (bulk density, water content, pH, SOC, inorganic C, Nt and nutrients) with the aim of creating  
259 a tool for establishing baselines and detecting forest health trends in USA. These authors  
260 ranged each soil indicator into different categories selecting threshold levels according to its  
261 functional significance in soil, and assigned an individual index value for each category. For  
262 instance,  $SOC < 1\%$  was assigned an index value of 0, while  $SOC > 5\%$  was assigned an  
263 index value of 2. The SQI is then calculated as the summation of all individual soil property  
264 index values. Contrarily to the common procedure, these authors did not reduce the quantity  
265 of indicators before calculating the SQI, which greatly contributes to reduce time and  
266 resources. Authors strongly recommend the measurement of the 19 selected soil properties,  
267 since using less quantity could provide a distorted assessment of soil quality.

268

269 **4. Land use changes and soil quality**

270 Changes in land use are human derived impacts with high affection in ecosystems  
271 functioning. Land uses have a strong impact in the level of SOC, which has been widely used  
272 as indicator of SQ (Table 1). Overall, soil management that lead an accumulation of SOC are  
273 related to ecosystem benefits. However, land misuse can cause degradation of soil as a  
274 consequence of reducing SOC levels (Lal, 2004). Land conversion from native forest to  
275 cropland is prone to soil C losses (Camara-Ferreira et al., 2014). Conversion of croplands to  
276 grasslands has been elucidated as a successful approach for C sequestration (Chen et al.,  
277 2009). Albaladejo et al. (2013) studied the effect of climate with regards to land use in South-  
278 East Spain. These authors concluded that C sequestration in cropland through appropriate  
279 land management can be suitable when forestland is limited by bedrock surfaces. Gelaw et al.  
280 (2014) revealed that conversion of Ethiopian croplands to grasslands or integration of  
281 appropriate agroforestry trees in cropping fields has a huge potential for C sequestration.  
282 Agroforestry, the practice of growing trees and crops in interacting combinations on the same  
283 unit of land, can be proposed as a promising strategy for C sequestration with special  
284 emphasis in arid and semiarid areas that are usually degraded by SOC losses.

285 Microbial biomass and enzyme activity have been widely used to assess impacts of land-use  
286 changes on SQ. In Brazilian semiarid ecosystems, Nunes et al. (2012) reported that MBC was  
287 highly sensitive to shifts in land use. Mijangos et al. (2014) observed that replacing meadows  
288 by pine plantations under temperate climate influences enzyme activities and nutrient cycling.  
289 Moreover, enzyme activity was sensitive to human-induced alterations in a land-use sequence  
290 from natural forest-pastures and shrublands (Tischer et al., 2014). Zhao et al. (2013b)  
291 evaluated natural forest, parks, agriculture, street garden and roadside trees land-uses using  
292 MBC and microbial functional diversity as indicators. In comparison to forest, MBC was  
293 lower in the rest of land uses, but functional diversity was higher in the roadside-tree soils.

294 The simple index most used in the revised literature is the qCO<sub>2</sub>. This ratio has resulted a  
295 suitable indicator to provide evidences of soil perturbation after deforestation or other land  
296 use changes (Dilly et al., 2003; Bastida et al., 2006a). The establishment of multiparametric  
297 indices have been used as an adequate tool for integrating greater information of soil quality,  
298 and some of them have been recently applied to assess the impact of land use changes on SQ.  
299 Veum et al. (2014) evaluated SQ of perennial vegetation plots in comparison to agricultural  
300 soils under no-tillage or conventionally treated plots, using for these purposes the SMAF with  
301 indicators such as aggregate stability, bulk density, EC, pH, SOC, MBC, mineralizable N and

302 nutrients. SQ was greatest under native, perennial vegetation, and declined with increasing  
303 levels of soil disturbance resulting from cultivation.

304 Singh et al. (2014) selected indicators from a data set of 29 soil properties by PCA and  
305 produced a SQI which indicated that SQ in the natural forest land and grasslands was higher  
306 than in the cultivated sites. Interestingly, these authors highlighted that SOC and  
307 exchangeable Al were the two most powerful indicators of SQ in the eastern Himalayan  
308 region of India. Ruiz et al. (2011) elaborated an index of biological soil quality (IBSQ) based  
309 on macroinvertebrates and concluded that well-managed crops and pastures may have better  
310 SQ than some forests.

311 Marzaioli et al. (2010) established a SQI (without minimum data set selection) using  
312 physical, chemical and biological indicators such as aggregate stability, WHC, bulk density,  
313 particles size, pH, EC, CEC, SOC, Nt, nutrients, MBC, respiration and fungal mycelium.  
314 Authors observed a low SQ in almost all permanent crops; an intermediate quality in  
315 shrublands, grazing lands, coniferous forest and middle-hill olive grove; and a high quality in  
316 mixed forests.

317 Li et al. (2013) measured the impact of human disturbances in SQ, developing a SQI based  
318 on Bastida et al. (2006b). SQI was evaluated in alpine grasslands with different levels of  
319 degradation, based on plant cover, production, proportion of primary plant and height of the  
320 plant. Fifteen indicators (chemical, physical and biological) were used to build up the SQI  
321 after selection of a MDS by PCA. Indicators related to nitrogen cycling (urease, MBN-to-Nt,  
322 proteinase) and SOC were found to be the most sensitive indicators.

323

## 324 **5. Urban management and soil quality indicators**

325 Soil is an essential element in urban ecosystems (Luo et al., 2012). However, urban soil  
326 receives a major proportion of pollutants from industrial, commercial, and domestic activities  
327 (Cheng et al., 2014). Therefore, urban SQ must be included in urban management practices  
328 by selection of appropriate indicators. (Vrscaj et al., 2008). Since pollution is the factor which  
329 drives the most intense degradation in urban environments (Zhang et al., 2003), most research  
330 have dealt with the distribution and dispersion of pollutants (Davidson et al., 2006; Rodrigues  
331 et al., 2006; Wong et al., 2006; Szolnoki et al., 2013). Urban soil pollution is normally  
332 assessed relating pollutant levels with the environmental guidelines, or by establishment of  
333 different simple indices. In this context, several simple indices have been developed and

334 applied in urban soil for heavy metal pollution (Muller, 1969; Sutherland, 2000): geo-  
335 accumulation index ( $I_{geo} = \log_2[Ci/1.5Bi]$ ), pollution index ( $PI = Ci/Bi$ ), integrated pollution  
336 index ( $IPI = \sum PI/n$ ), enrichment factor ( $EFi = [Ci\text{-sample}/Cref\text{-sample}]/[Bi\text{-background}/Bref\text{-}$   
337 background]) $]$ ), where  $n$  is the number of measured elements,  $Ci$  (sample) is the metal  
338 concentration (i),  $Bi$  (background) is the baseline concentration,  $Cref$  (sample) is the content  
339 of the reference element in the sample and  $Bref$  is the content of the reference element in the  
340 reference soil. However, metals can be present in soils with different speciation, and so with  
341 different bioavailability and solubility. Hence, to assess urban SQ, the soluble or bioavailable  
342 fractions of the metals should be taken into account besides total concentrations (Rodrigues et  
343 al., 2013). There are several methods based on single or sequential schemes of chemical  
344 extraction to determine the availability of metals in urban soils (Li et al., 2001).

345 Besides heavy metals, other indicators such as particle size distribution, SOC, pH and CEC  
346 should be included in urban SQ studies to integrate soil functions with pollution effects  
347 (Pouyat et al., 2008). Rodrigues et al. (2009) studied the influence of metals concentration  
348 and soil properties on urban SQ. These authors concluded that the concentration of metals are  
349 not the dominant factor controlling variability in SQ, and soil texture, pH and SOM must be  
350 considered affecting this variability, which has often been ignored in urban systems. Papa et  
351 al. (2010) determined urban SQ evaluating the influence of soil trace metal concentrations in  
352 relation to distance from urban roads on MBC, respiration and eight enzyme activities,  
353 observing a negative relationship between microbial activity and metals concentration.  
354 Santorufo et al. (2012a) assessed urban SQ by integrating chemical and ecotoxicological  
355 approaches. They revealed that the toxicity to invertebrates seemed to be related to heavy  
356 metals, since the largest effects were found in soils with high metal concentrations. However,  
357 SOC and pH played an important role in mitigating the toxicity of metals. Santorufo et al.  
358 (2012b) studied soil invertebrates as bioindicators of urban SQ, being the community more  
359 abundant and diverse in the soils with high SOM and water content and low metal  
360 concentrations. The taxa more resistant to the urban environment included Acarina,  
361 Enchytraeids, Collembola and Nematoda. Gavrilenko et al. (2013) used the soil-ecological  
362 index (SEI), which was created for agricultural soils, to assess SQ in different ecosystems  
363 including urban areas. The SEI is a product of several indices accounting for seven physical  
364 and chemical properties and for the climatic characteristics of the region. They concluded that  
365 this SEI was correlated with MBC, and thus reflects the ecological function of the soil.

366

367 **6. Soil quality indicators directly related to human health**

368 Relating the state of the soil with effects on human wellbeing is a challenging task, difficult  
369 to monitor, quantify and model. [Kentel et al., \(2011\)](#) highlighted the importance of taking  
370 into account the human health perspective on SQ assessment. They postulated that health-  
371 risk-based decision making may help to manage associated costs and to identify priority sites  
372 with regard to health risks. This allows better allocation of available resources and  
373 identification of necessary actions that are protective of human health. Because of these  
374 reasons, traditional SQ assessment should include health-risk-based indicators such as  
375 pollutants or pathogens, taking into account the potential exposure pathways.

376 Since soil pollution is a threat for public health, the study of soil pollutants has been an  
377 important topic in literature. The source-pathway-receptor pollutant linkage has been used  
378 extensively in the risk assessment of polluted soils. Risk assessment aims to characterize the  
379 potential adverse health effects of human exposures to environmental hazards ([Murray et al., 2011](#)).  
380 A potential risk exists if there is a source of pollutants, a receptor sensitive to the  
381 pollutant at the exposure level, and a pathway linking both ([Bone et al., 2010](#)). Soil can be  
382 source of pollutants with human as receptor through pathways such as direct ingestion of soil  
383 particles, the ingestion of plant or animal which bioaccumulated the contaminants, inhalation,  
384 and dermal contact ([Collins et al., 2006](#); [Sjöström et al., 2008](#)). The levels of pollutants that  
385 reach man through the above pathways are normally calculated by the use of different  
386 quotients or equations, which relate the concentration of the pollutant in soil with SQS,  
387 ingestions/inhalation/adhesion rates, body weight, exposure time or exposure frequency  
388 ([Masto et al. 2011](#); [Nadal et al., 2011](#); [Pelfrêne et al., 2013](#)).

389 Most studies about soil pollution deal with the presence of heavy metals. In the attempt to  
390 assess the mobility of trace elements and thus to quantify their transmission from soil to other  
391 organisms, the use of bioaccumulation or bioconcentration factors are gaining acceptance,  
392 which describe the concentration of an element in a biological tissue relative to the  
393 concentration in the soil ([Murray et al., 2011](#); [Zhao et al., 2012](#)). Even though it is not  
394 recognized as a SQI, it could be stated that soils with low bioconcentration factors are less  
395 hazardous for population. It has been assessed that there are physicochemical soil  
396 characteristics controlling metals availability such as pH, SOM or clay contents. [Fordyce et  
397 al. \(2000\)](#) identified that Se bioavailability in villages from China with high Se toxicity was  
398 controlled by pH. [Zhao et al. \(2012\)](#) reported that the spatial patterns of the heavy metal  
399 concentrations and soil pH indicated that the areas with the highest human health risk did not

400 directly coincide with the areas of highest heavy metal concentrations, but with the areas of  
401 lower soil pH. [Qin et al. \(2013\)](#) observed that the concentration of Se in rice plants was  
402 associated with the soil fraction bound to SOM, suggesting that SOM controls Se uptake by  
403 rice and thus increases hazards to human health. [Pelfrêne et al. \(2011\)](#) concluded that the  
404 inclusion of bioavailability analyses during health risk assessment (fraction of pollutant that  
405 is soluble in the gastrointestinal environment and potentially available for absorption) would  
406 provide a more realistic assessment of heavy metals exposure than traditional measurements.

407 Many fewer studies treat the problem of soil organic pollution and human health, maybe due  
408 to the higher difficulty in analysis and identification, and temporal decay through  
409 physicochemical and biological processes. [Wenrui et al. \(2009\)](#) established the levels of  
410 different pollutants in soil and assessed the affection to population by bioaccessibility  
411 evaluations (e.g. *in vitro* simulators of human digestion) or development of exposure  
412 scenarios and health hazard equations. In general, no other soil properties are measured  
413 together with the target contaminant to relate its dynamics and fate. However, [Cachada et al.](#)  
414 ([2012](#)) found that SOC was an important factor for polycyclic aromatic hydrocarbons and  
415 organochlorides retention in soils.

416 Despite there is a broad concern about soil pollution and human health, very few studies  
417 directly and explicitly relate the pollution with SQ, and how deterioration of SQ can affect  
418 human wellbeing ([Poggio et al., 2008; Masto et al., 2011; Pelfrêne et al., 2013](#)). [Abrahams](#)  
419 ([2002](#)), even not explicitly, related SQ and human health at stating the deleterious impacts  
420 that soil properties pose to human societies. [Murray et al. \(2011\)](#) reported the need to include  
421 soil characteristics, specifically SOM quantity and quality, pH or clay content, when setting  
422 threshold criteria for metal content under human risk evaluations. [Rafiq et al. \(2014\)](#) was the  
423 only consulted study dealing with health risk assessment who established SQ standards for  
424 potential dietary toxicity to humans. They observed that soil pH, CEC and SOM were the  
425 main factors which influenced the Cd bioavailability in different soil types.

426 The sanitary status of the soil is evaluated on the basis of indicator bacteria, usually  
427 *Escherichia coli*, faecal streptococci, *Salmonella* sp, *Shigella* sp and the persistent sporulated  
428 *Clostridium* (e.g. [Liang et al., 2011; Benami et al., 2013; Ceuppens et al., 2014](#)). Some of  
429 them also use protozoa or helminths (e.g. [Landa-Cansigno et al., 2013](#)). All revised articles  
430 identify different taxonomic groups in soil and monitor their survival, persistence and  
431 movement with time in terms of different soil characteristics and management practices  
432 ([Benami et al., 2013; Sepehrnia et al., 2014](#)). [Voidarou et al. \(2011\)](#) actually related the

433 presence of pathogens/parasites with SQ, indicating that a systematic monitoring of the soil  
434 ecosystems must include bacteriological parameters to obtain information adequate for  
435 assessing their overall quality. It has been reported that SOM, pH, EC and clay contents are  
436 determinant on the adsorption capacity of pathogen bacteria, protozoa or nematodes (Landa-  
437 Cansigno et al. 2013), and thus they should be considered when assessing the persistence of  
438 pathogens in soil. The complexity of the soil microbial community can also affect the  
439 survival of pathogens. Liang et al. (2011) observed that the die-off rate of *E. coli*  
440 progressively declined with the reduction of microbial community diversity.

441

## 442 **7. Conclusions and researchable challenges**

443 There is a need to develop methods to assess and monitor soil quality for assuring sustainable  
444 land use with no prejudicial effects on human health. A review of different soil quality  
445 assessment studies indicated that there is an increased concern of using indicators of different  
446 nature to assess soil quality. The most used indicators are soil organic carbon and pH, since  
447 different management practices strongly affect their value. Total nitrogen and the content of  
448 nutrients are often used in agricultural and forest systems, since they provide information  
449 about the fertility of a soil, essential to support adequate production. At physical features,  
450 particle size distribution, bulk density, available water and aggregate stability are the most  
451 widely used parameters, mainly to assess the impact of agricultural management and changes  
452 in land use on soil quality. Biological indicators are less generalized in literature, being  
453 enzyme activities and microbial biomass the most common indicators used as a routine basis  
454 in agricultural and forest systems. Despite the attempts to calibrate soil quality indices, the  
455 establishment of a global index for general use seems to be difficult nowadays due to the  
456 wide range of soils, conditions and management practices. The transformation (by linear or  
457 nonlinear scoring functions) and weighting of indicators and their summation into an index is  
458 the tool most widely used and validated in literature for most land uses. Nonetheless, the use  
459 of multiple linear regressions has been successfully used under forest land use.

460 Although urban soil quality has been linked with wellbeing life for city residents, it has been  
461 less studied than other soil uses, with lack of adoption of soil quality indices. In consequence  
462 there is an urgent need to establish a framework that can be adjusted based on different  
463 management goals for urban soil quality evaluation. There is also a lack of concern about the  
464 influence of soil on human health, so that soil quality assessments where human health  
465 indicators or exposure pathways are incorporated are practically nonexistent. Further efforts

466 should be carried out to establish new methodologies not only to assess soil quality in terms  
467 of sustainability, productivity and ecosystems quality, but also human health. This gap is  
468 mainly due to the extreme difficulty of relating a *per se* complicate concept as soil quality to  
469 soil-born diseases, owing to the vast existent pathways of exposure.

470 The application and development of new methodologies such as stable isotopes, genomic and  
471 proteomic tools addressing the structure of microbial communities, as well as the  
472 functionality of microbial populations in soil might be potentially used as indicators of soil  
473 quality (Bastida et al., 2014). Spectroscopy is becoming a powerful tool in the assessment of  
474 soil quality as well, for it is accurate, inexpensive and rapid, essential attributes for the  
475 adoption of these techniques in soil quality establishment (Zornoza et al., 2008b).  
476 Nevertheless, the integration of these new parameters into soil quality index is still a  
477 challenge.

478

## 479 **References**

480 Abrahams, P.W.: Soils: their implications to human health, *Sci. Total Environ.*, 291, 1-32,  
481 2002

482 Albaladejo, J., Ortiz, R., García-Franco, N., Ruíz-Navarro, A., Almagro, M., García-Pintado,  
483 J. and Martínez-Mena, M.: Land-use and climate change impacts on soil organic  
484 carbon stocks in semi-arid Spain, *J. Soils Sediments*, 13, 265-277, 2013.

485 Alexander, M.: Agriculture's responsibility in establishing soil quality criteria,  
486 Environmental improvement – agriculture's challenge in the seventies, National  
487 Academy of Sciences, Washington, USA, 1971.

488 Amacher, M.C., O'Neil, K.P. and Perry, C.H.: Soil vital signs: A new Soil Quality Index  
489 (SQI) for assessing forest soil health, *Res. Pap.*, RMRS-RP-65WWW, Fort Collins,  
490 CO: USDA, Forest Service, Rocky Mountain Research Station, 12 p,  
491 [http://www.fs.fed.us/rm/pubs/rmrs\\_rp065.pdf](http://www.fs.fed.us/rm/pubs/rmrs_rp065.pdf), 2007.

492 Andrews, S.S. and Carroll, C.R.: Designing a soil quality assessment tool for sustainable  
493 agroecosystem management. *Ecol. Appl.*, 11, 1573-1585, 2001.

494 Andrews, S. S., Karlen, D. L. and Cambardella, C. A.: The soil management assessment  
495 framework: a quantitative soil quality evaluation method. *Soil Sci. Soc. Am. J.*, 68,  
496 1945-1962, 2004.

497 Arias, M.E., González-Pérez, J.A., González-Vila, F.J., Ball, A.S.: Soil health – a new  
498 challenge for microbiologists and chemists. *Int. Microbiol.*, 8, 13-21, 2005.

499 Armenise, E., Redmile-Gordon, M.A., Stellacci, A.M., Ciccarese, A. and Rubino, P.:  
500 Developing a soil quality index to compare soil fitness for agricultural use under  
501 different managements in the Mediterranean environment, *Soil Till. Res.*, 130, 91–98,  
502 2013.

503 Arshad, M. A., Martin, S.: Identifying critical limits for soil quality indicators in agro-  
504 ecosystems, *Agr. Ecosyst. Environ.*, 88, 153-160, 2002.

505 Banning, N. C., Gleeson, D. B., Grigg, A.H., Grant, C. D., Andersen, G. L., Brodie, E. L.  
506 and Murphy, D. V.: Soil Microbial Community Successional Patterns during Forest  
507 Ecosystem Restoration, *Appl. Environ. Microbiol.*, 77 (17), 6158-6164, 2011.

508 Bastida, F., Moreno, J.L., Hernández, T., García, C.: Microbiological activity in a soil 15  
509 years alter its devegetation, *Soil Biol. Biochem.*, 38, 2503-2507, 2006a.

510 Bastida, F., Moreno, J.L., Hernández, T., García, C.: Microbiological degradation index of  
511 soils in a semiarid climate, *Soil Biol. Biochem.*, 38, 3463-3473, 2006b.

512 Bastida, F., Hernández, T., García, C.: Metaproteomics of soils from semiarid environment:  
513 functional and phylogenetic information obtained with different protein extraction  
514 methods, *J. Proteomics.*, 101, 31-42, 2014.

515 Benami, M., Gross, A., Herberg, M., Orlofsky, E., Vonshak, A., Gillor, O.: Assessment of  
516 pathogenic bacteria in treated graywater and irrigated soils, *Sci. Total Environ.*, 458-  
517 560, 298-302, 2013.

518 Biau, A., Santiveri, F., Mijangos, I. and Lloveras, J.: The impact of organic and mineral  
519 fertilizers on soil quality parameters and the productivity of irrigated maize crops in  
520 semiarid regions, *Europ. J. Soil Biol.* 53, 56-61, 2012.

521 Blecker, S. W., Stillings, L. L., Amacher, M. C., Ippolito, J. A. and DeCrappeo, N. M.:  
522 Development of vegetation based soil quality indices for mineralized terrane in arid  
523 and semi-arid regions, *Ecol. Indic.*, 20, 65-74, 2012.

524 Blum, W.: European soil protection strategy, *J Soils Sediments*, 3, 242, 2003.

525 Bone, J., Head, M., Barraclough, D., Archer, M., Scheib, C., Flight, D. and Voulvoulis, N.:  
526 Soil quality assessment under emerging regulatory requirements, *Environ. Int.*, 36,  
527 609-622, 2010.

528 Burger, J.A. and Kelting, D.L.: Using soil quality indicators to assess forest stand  
529 management, *Forest Ecol. Manag.*, 122, 155-166, 1999.

530 Cachada, A., Pato, P., Rocha-Santos, T., Ferreira da Silva, E. and Duarte, A.C.: Levels,  
531 sources and potential human health risks of organic pollutants in urban soils, *Sci.  
532 Total Environ.*, 430, 184-192, 2012.

533 Camara-Ferreira, A.C., Carvalho-Leite, L.F., Ferreira de Araujo, A. and Eisenhauer, N.:  
534 Land-use type effects on soil organic carbon and microbial properties in a semi-arid  
535 region of Northeast Brazil, *Land Degrad. Dev.*, DOI: 10.1002/ldr.2282, 2014.

536 Carter, M.R.: Soil quality for sustainable land management: organic matter and aggregation  
537 interactions that maintain soil functions. *Agron. J.*, 94, 38-47, 2002.

538 Ceuppens, S., Hessel, C.T., de Quadros Rodrigues, R., Bartz, S., Tondo, E.C. and  
539 Uyttendaele, M.: Microbiological quality and safety assessment of lettuce production  
540 in Brazil, *Int. J. Food Microbiol.*, 181, 67-76, 2014.

541 Chaer, G.M., Myrold, D. and Bottomley, P.J.: A soil quality index based on the equilibrium  
542 between soil organic matter and biochemical properties of undisturbed coniferous  
543 forest soils of the Pacific Northwest, *Soil Biol. Biochem.*, 41, 822-830, 2009.

544 Chen, H., Marhan, S., Billen, N. and Stahr, K.: Soil organic-carbon and total nitrogen stocks  
545 as affected by different land uses in Baden-Württemberg (southwest Germany), *J.*  
546 *Plant Nutr. Soil Sc.*, 172, 32-42, 2009.

547 Cheng, H.X., Li, M., Zhao, C.D., Li, K., Peng, M., Qin, A.H.: Overview of trace metals in the  
548 urban soil of 31 metropolises in China, *J. Geochem. Explor.*, 139, 31-52, 2014.

549 Collins, C., Fryer, M., Gross, A.: Plant uptake on non-ioninc organic chemicals, *Environ.*  
550 *Sci. Technol.*, 40, 45-52, 2006.

551 Davidson, C.M., Urquhart, G.J., Ajmone-Marsan, F., Biasioli, M., da Costa Duarte, A., Diaz-  
552 Barrientos, E.: Fractionation of potentially toxic elements in urban soils from five  
553 European cities by means of a harmonised sequential extraction procedure, *Anal.*  
554 *Chim. Acta*, 565, 63-72, 2006.

555 Deng, X.: Land Quality: Environmental and Human Health Effects, in: Elias, S.A. (ed).  
556 Reference Module in Earth Systems and Environmental Sciences, Elsevier,  
557 Amsterdam, 362-365, 2011.

558 D'Hose, T., Cougnon, M., De Vliegher, A., Vandecasteele, B., Viaene, N., Cornelis, W., Van  
559 Bockstaele, E. and Reheul, D.: The positive relationship between soil quality and crop  
560 production: A case study on the effect of farm compost application, *Appl. Soil Ecol.*  
561 75, 189– 198, 2014.

562 Dilly, O., Blume, H. P., Sehy, U., Jiménez, M. and Munch, J. C.: Variation of stabilised,  
563 microbial and biologically active carbon and nitrogen soil under contrasting land use  
564 and agricultural management practices, *Chemosphere*, 52, 557-569, 2003.

565 Dinesh, R , Ghoshal Chaudhuri, S., Ganeshamurthy, A. N. and Chanchal, D.: Changes in soil  
566 microbial indices and their relationships following deforestation and cultivation in  
567 wet tropical forests, *Appl. Soil Ecol.*, 24, 17-26, 2003.

568 Doran, J.W.: Soil health and global sustainability: translating science into practice, *Agr.*  
569 *Ecosyst. Environ.*, 88, 119–127, 2002.

570 Doran, J.W. and Parkin, T.B.: Defining and Assessing Soil Quality, in: Doran, J.W.,  
571 Coleman, D.F., Bezdicek, D.F., Stewart, B.A. (Eds.), *Defining soil quality for a*  
572 *sustainable environment*, *Soil Sci. Soc. Am.*, Special Publication 35, Madison, WI, 3-  
573 21, 1994.

574 Doran, J. W. and Zeiss, M.R.: Soil health and sustainability: managing the biotic component  
575 of soil quality, *Appl. Soil Ecol.*, 15, 3-11, 2000.

576 FAO: *El estado de los bosques del mundo*. Organización de las Naciones Unidas para la  
577 Alimentación y la Agricultura. <http://www.fao.org/docrep/016/i3010s/i3010s.pdf>.  
578 Rome, 2012.

579 Fordyce, F.M., Guangdi, Z., Green, K. and Xinpings, L.: Soil, grain and water chemistry in  
580 relation to human selenium-responsive diseases, in: Enshi District, China, *Appl.*  
581 *Geochem.*, 15, 117-132, 2000.

582 Franzluebbers, A.J.: Soil organic matter stratification ratio as an indicator of soil quality, *Soil*  
583 *Till. Res.*, 66, 95-106, 2002.

584 Gale, M.R., Grigal, D.F. and Harding, R.B.: Soil productivity index: predictions of site  
585 quality for white spruce plantations, *Soil Sci. Soc. Am. J.*, 55, 1701-1708, 1991.

586 García-Ruiz, R., Ochoa, V., Hinojosa, M. B. and Carreira, J. A.: Suitability of enzyme  
587 activities for the monitoring of soil quality improvement in organic agricultural  
588 systems, *Soil Biol. Biochem.*, 40, 2137–2145, 2008.

589 Gavrilenko, E.G., Ananyeva, N. D., Makarov, O.A.: Assessment of Soil Quality in Different  
590 Ecosystems (with Soils of Podolsk and Serpukhov Districts of Moscow Oblast as  
591 Examples), *Eurasian Soil Sci.*, 46, 1241-1252, 2013.

592 Gelaw, A.M., Singh, B.R. and Lal, R.: Soil organic carbon and total nitrogen stocks under  
593 different land uses in a semi-arid watershed in Tigray, Northern Ethiopia, *Agr.*  
594 *Ecosyst. Environ.*, 188, 256-263, 2014.

595 Giacometti,C., Demyan, M.S., Cavani, L., Marzadori, C., Ciavatta, C. and Kandeler, E.:  
596 Chemical and microbiological soil quality indicators and their potential to  
597 differentiate fertilization regimes in temperate agroecosystems, *Appl. Soil Ecol.* 64,  
598 32–48, 2013.

599 Gil-Sotres, F., Trasar-Cepeda, C., Leirós, M.C. and Seoane, S.: Different approaches to  
600 evaluating soil quality using biochemical properties, *Soil Biol. Biochem.*, 37, 877-  
601 887, 2005.

602 Hankard, P.K., Bundy, J.G., Spurgeon, D.J., Weeks, J.M., Wright, J., Weinberg, C.:  
603 Establishing principal soil quality parameters influencing earthworms in urban soils  
604 using bioassays, *Environ. Pollut.*, 133, 199-211, 2005.

605 Harris, R. F., Karlen, D.L. and Mulla, D.J.: A conceptual framework for assessment and  
606 management of soil quality and health, in: Doran, J.W., Jones, A.J. (Eds.), *Methods*  
607 for assessing soil quality, *Soil Sci. Soc. Am. J.*, Madison, Wisconsin, USA, 61-82,  
608 1996.

609 Hussain, I., Olson, K.R., Wander, M.M. and Karlen, D.L.: Adaptation of soil quality indices  
610 and application to three tillage systems in southern Illinois, *Soil Till. Res.*, 50, 237-  
611 249, 1999.

612 Jiménez Esquilín, A.E., Stromberger, M.E. and Shepperd, W.D.: Soil Scarification and  
613 Wildfire Interactions and Effects on Microbial Communities and Carbon. *Soil Sci.*  
614 *Soc. Am. J.*, 72, 111-118, 2008.

615 Karlen, D.L., Andrews, D.D. and Doran, J.W.: Soil quality: Current concepts and  
616 applications, *Adv. Agron.*, 74, 1-40, 2001.

617 Kentel, E., Aksoy, A., Büyüker, B., Dilek, F., Girgin, Ipek, M.H., Polat, Ş., Yetiş, Ü. and  
618 Ünlü, K.: Challenges in Development and Implementation of Health-Risk-Based Soil  
619 Quality Guidelines: Turkey's Experience, *Risk Anal.*, 31, 657-667, 2011.

620 Laird, D. A. and Chang, C.W.: Long-term impacts of residue harvesting on soil quality, *Soil*  
621 *Till. Res.*, 134, 33-40, 2013.

622 Lal, R.: Soil carbon sequestration to mitigate global change, *Geoderma*, 123, 1-22, 2004.

623 Landa-Cansigno, O., Durán-Álvarez, J. C. and Jiménez-Cisneros, B.: Retention of  
624 *Escherichia coli*, *Giardia lamblia* cysts and *Ascaris lumbricoides* eggs in agricultural  
625 soils irrigated by untreated wastewater, *J. Environ. Manag.*, 128, 22-29, 2013.

626 Larson, W.E. and Pierce, F.J.: Conservation and enhancement of soil quality. p. 175-203, in:  
627 Dumanski et al. (Eds.), *Evaluation for sustainable land management in the developing*  
628 *world. Vol. 2: Technical papers. Proc. Int. Worksh.*, Chiang Rai, Thailand. 15-21  
629 Sept. 1991. *Int. Board. For. Soil Res. Manage.*, Bangkok, Thailand, 1991.

630 Larson, W. E. and Pierce, F. J.: The dynamics of soil quality as a measure of sustainable  
631 management. p. 37

632 environment. SSSA - Special Publ  
633 Madison , WI, 1994.

634 Leirós, M. C., Trasar-Cepeda, C., García-Fernández, F. and Gil-Sotres, F. : Defining the  
635 validity of a biochemical index of soil quality, *Biol. Fert. Soils*, 30,140-146, 1999.

636 Liang, Z., He, Z., Powell, C. A. and Stoffella, P.: Survival of *Escherichia coli* in soil with  
637 modified microbial community composition, *Soil Biol. Biochem.*, 43, 1591-1599,  
638 2011.

639 Li, Y., Dong, S., Wen, L., Wang, X., W, Y.: Assessing the soil quality of alpine grasslands in  
640 the Qinghai-Tibetan Plateau using a modified soil quality index, *Environ. Monit.  
641 Assess.*, 185, 8011-8022, 2013.

642 Li, C., Moore-Kuceraa, J., Leeb, J., Corbin, A., Brodhagen, M., Miles, C. and Inglise, D.:  
643 Effects of biodegradable mulch on soil quality, *Appl. Soil Ecol.* 79, 59–69, 2014.

644 Li, X. D., Poon, C. S. and Liu, P. S.: Heavy metal contamination of urban soils and street  
645 dusts in Hong Kong, *Appl. Geochem.*, 16, 1361-1368, 2001.

646 Liu, Z., Zhou, W., Shen, J., Li, S., Liang, G., Wang, X., Sun, J. and Al, C.: Soil Quality  
647 Assessment of Acid Sulfate Paddy Soils with Different Productivities in Guangdong  
648 Province, China, *Jour. Integ. Agric.*, 13(1), 177-186, 2014a.

649 Liu, Z., Zhou, W., Shen, J., Li, S., He, P. and Liang, G.: Soil quality assessment of Albic  
650 soils with different productivities for eastern China, *Soil Till. Res.* 140, 74–81, 2014b.

651 Luo, X. S., Yu, S., Zhu, Y. G. and Li, X. D.: Trace metal contamination in urban soils of  
652 China, *Sci. Total Environ.*, 421, 17-30, 2012.

653 Marzaioli, R., D'Ascoli, R., De Pascale, R.A. and Rutigliano, F.A.: Soil quality in a  
654 Mediterranean area of Southern Italy as related to different land use types, *Appl. Soil  
655 Ecol.*, 44, 205-212, 2010.

656 Masto, R. E., Ram, L. C., George, J., Selvi, V. A., Sinha, A. K., Verma, S. K., Rout, T. K.,  
657 Priyadarshini, Prabal, P. Status of some soil trace elements and their potential human  
658 health risks around a coal beneficiation plant, *Int. J. Coal Prep. Util.*, 31, 61–77, 2011.

659 Mataix-Solera, J., Guerrero, C., García-Orenes, F., Bárcenas, G. M. and Torres M. P.: Forest  
660 Fire Effects on Soil Microbiology, in: *Fire Effects on Soils and Restoration  
661 Strategies*, Science Publishers, Inc., 133-175, 2009.

662 Mele, P. M. and Crowley, D. E.: Application of self-organizing maps for assessing soil  
663 biological quality, *Agr. Ecosyst. Environ.*, 126, 139-152, 2008.

664 Merrill S. D., Liebig, M. A., Tanaka, D. L., Krupinsky, J. M. and Hanson, J. D.: Comparison  
665 of soil quality and productivity at two sites differing in profile structure and topsoil  
666 properties, *Agr. Ecosyst. Environ.*, 179, 53-61, 2013.

667 Mijangos, I., Epelde, L., Garbisu, C. and González-Oreja, J. A.: Modification of soil enzyme  
668 activities as a consequence of replacing meadows by pine plantations under temperate  
669 climate, *Pedobiologia*, in press, 2014.

670 Millennium Ecosystem Assessment: *Ecosystems and Human Well-being: Synthesis*, Island  
671 Press, Washington, DC, 2005.

672 Miralles, I., Ortega, R., Almendros, G., Sánchez-Marañón, M., Soriano, M.: Soil quality and  
673 organic carbon ratios in mountain agroecosystems of South-east Spain, *Geoderma*,  
674 150, 120-128, 2009.

675 Muckel, G. B. and Mausbach, M. J.: Soil quality information sheets, in: Doran, J.W., Jones,  
676 A.J. (Eds.), *Methods for Assessing Soil Quality*, Soil Sci. Soc. Am., Special  
677 Publication 49, Madison, WI, 393-400, 1996.

678 Muller, G.: Index of geoaccumulation in sediments of the Rhine River. *Geojournal*, 2, 108-  
679 118, 1969.

680 Murray, H., Pinchin, T. A. and Macfie, S. M.: Compost application affects metal uptake in  
681 plants grown in urban garden soils and potential human health risk, *J. Soils*  
682 *Sediments*, 11, 815-829, 2011.

683 Nadal, M., Schuhmacher, M. and Domingo, J. L.: Long-term environmental monitoring of  
684 persistent organic pollutants and metals in a chemical/petrochemical area: Human  
685 health risks, *Environ. Pollut.*, 159, 1769-1777, 2001.

686 Nannipieri, P., Grego, S. and Ceccanti, B.: Ecological significance of the biological activity  
687 in soils, in: Bollag, J. M., Stotzky, G. (Eds.), *Soil biochem.*, Marcel Dekker, New  
688 York, 293-355, 1990.

689 Nunes, J. S., Araújo, A. S. F., Nunes, L. A. P. L., Lima, L. M., Carneiro, R. F. V., Tsai, S.  
690 M., Salviano, A. A. C.: Land degradation on soil microbial biomass and activity in  
691 Northeast Brazil, *Pedosphere*, 22, 88-95, 2012.

692 Pang, X.Y., Bao, W.K. and Zhang, Y.M.: Evaluation of Soil Fertility under different  
693 *Cupressus chengiana* forests using multivariate approach, *Pedosphere*, 16, 602-615,  
694 2006.

695 Papa, S., Bartoli, G., Pellegrino, A. and Fioretto, A.: Microbial activities and trace element  
696 contents in an urban soil, *Environ. Monit. Assess.*, 165, 193-203, 2010.

697 Parr, J. F., Papendick, R. I., Hornick, S. and Meyer, R. E.: Soil quality: Attributes and  
698 relationship to alternative and sustainable agriculture, Am. J. Alternative Agr., 7, 5-  
699 11, 1992.

700 Pelfrêne, A., Waterlot, C. and Douay, F.: In vitro digestion and DGT techniques for  
701 estimating cadmium and lead bioavailability in contaminated soils: Influence of  
702 gastric juice pH. Sci. Total Environ., 409, 5076-5085, 2011.

703 Pelfrêne, A., Douay, F., Richard, A., Roussel, H. And Girondelot, B.: Assessment of potential  
704 health risk for inhabitants living near a former lead smelter. Part 2: site-specific  
705 human health risk assessment of Cd and Pb contamination in kitchen gardens.  
706 Environ. Monit. Assess., 185, 2999–3012, 2013.

707 Poggio, L., Vrščaj, B., Hepperle, E., Schulin, R. and Marsan, F. A.: Introducing a method of  
708 human health risk evaluation for planning and soil quality management of heavy  
709 metal-polluted soils—An example from Grugliasco (Italy), Landscape Urban Plan., 88,  
710 64-72, 2008.

711 Pouyat, R. V., Yesilonis, I. D., Szlavecz, K., Csuzdi, C., Hornung, E. and Korsos, Z.:  
712 Response of forest soil properties to urbanization gradients in three metropolitan  
713 areas, Landscape Ecol., 23, 1187-1203, 2008.

714 Qi, Y., Darilek, J. L., Huang, B., Zhao, Y., Sun, W. and Gu, Z.: Evaluating soil quality  
715 indices in an agricultural region of Jiangsu Province, China, Geoderma, 149, 325–  
716 334, 2009.

717 Qin, M. Z., and Zhao, J.: Strategies for sustainable use and characteristics of soil quality  
718 changes in urban-rural marginal area: a case study of Kaifeng, Acta Geogr. Sin., 55,  
719 545–554 (in Chinese with English abstract), 2000.

720 Qin, H., Zhu, J., Liang, L., Wang, M. and Su, H.: The bioavailability of selenium and risk  
721 assessment for human selenium poisoning in high-Se areas, China, Environ. Int., 52,  
722 66-74, 2013.

723 Rafiq, M. T., Aziz, R., Yang, X., Xiao, W., Rafiq, M. K., Ali, B. and Li, T.: Cadmium  
724 phytoavailability to rice (*Oryza sativa* L.) grown in representative Chinese soils. A  
725 model to improve soil environmental quality guidelines for food safety. Ecotox.  
726 Environ. Safe., 103, 101-107, 2014.

727 Rahmanipour, F., Marzaiolib, F., Bahramia, H. A., Fereidounia, Z. and Bandarabadi, S. R.:  
728 Assessment of soil quality indices in agricultural lands of Qazvin Province, Iran,  
729 Ecol. Ind., 40, 19–26, 2014.

730 Reeves, D.W.: The role of organic matter in maintaining soil quality in continuous cropping  
731 systems, *Soil Till. Res.*, 43, 131–167, 1997.

732 Rillig, M. C.: Arbuscular mycorrhizae, glomalin, and soil aggregation, *Can. J. Soil Sci.*, 84,  
733 355-363, 2004.

734 Rodrigues, S. M., Cruz, N., Coelho, C., Henriques, B., Carvalho, L., Duarte, A. C., Pereira,  
735 E. and Römkens, A. M.: Risk assessment for Cd, Cu, Pb and Zn in urban soils:  
736 Chemical availability as the central concept, *Environ. Pollut.*, 183, 234-243, 2013.

737 Rodrigues, S., Pereira, M.E., Duarte, A.C ., Ajmone-Marsan, F., Davidson, C.M., Grčman,  
738 H., Hossack, I., Hursthouse, A.S., Ljung, K., Martini, C., Otabbong, E., Reinoso, R.,  
739 Ruiz-Cortés, E., Urquhart, G.J., Vrščaj., B.:Mercury in urban soils: a comparison of  
740 local spatial variability in six European cities, *Sci. Total Environ.*, 368, 926-936,  
741 2006.

742 Rodrigues, S., Urquhart, G., Hossack, I.: Pereira, M. E., Duarte, A. C. and Davidson, C.: The  
743 influence of anthropogenic and natural geochemical factors on urban soil quality  
744 variability: a comparison between Glasgow, UK and Aveiro, Portugal, *Environ.*  
745 *Chem. Lett.*, 27, 141-148, 2009.

746 Rodríguez, M. D. F. and Lafarga, J. C. T.: Soil quality criteria for environmental pollutants,  
747 in: Nriagu J.O. (ed), *Encyclopedia of Environmental Health*, Elsevier, 124-142, 2011.

748 Rousseau, L., Fonte, S. J., Téllez, O., Van der Hoek, R. and Lavelle, P.: Soil macrofauna as  
749 indicators of soil quality and land use impacts in smallholder agroecosystems of  
750 western Nicaragua, *Ecol. Indic.*, 27, 71–82, 2013.

751 Ruiz, N., Jerome, M., Leonide, C., Christine, R., Gerard, H., Etienne, I. and Lavelle, P.:  
752 IBQS: A synthetic index of soil quality based on soil macro-invertebrate  
753 communities, *Soil Biol. Biochem.*, 43, 2032-2045, 2011.

754 Sahrawat, K. L., Wani, S. P., Pathak, P. and Rego, T. J.: Managing natural resources of  
755 watersheds in the semi-arid tropics for improved soil and water quality: a review,  
756 *Agr. Water Manage.*, 97, 375-381, 2010.

757 Sanchez, F. G., Carter, E. A. and Leggett, Z. H.: Loblolly pine growth and soil nutrient stocks  
758 eight years after forest slash Incorporation, *Forest Ecology and Management*, 257,  
759 1413-1419, 2009.

760 Santorufo, L., Van Gestel, C. A. M. and Maisto, G.: Ecotoxicological assessment of metal-  
761 polluted urban soils using bioassays with three soil invertebrates, *Chemosphere*, 88,  
762 418-425, 2012a.

763 Santorufo, L., Van Gestel, C. A. M., Rocco, A. and Maisto, G.: Soil invertebrates as  
764 bioindicators of urban soil quality, *Environ. Pollut.*, 161, 57-63, 2012b.

765 Sepehrnia, N., Mahboubi, A. A., Mosaddeghi, M. R., Safari Sinejani, A. A. And  
766 Khodakaramian, G.: Escherichia coli transport through intact gypsiferous and  
767 calcareous soils during saturated and unsaturated flows, *Geoderma*, 217-218, 83-89.  
768 2014.

769 Singh, A.K., Bordoloi, L.J., Kumar, M., Hazarika, S., Parmar, B.: Land use impact on soil  
770 quality in eastern Himalayan region of India, *Environ. Monit. Assess.*, 186, 2013-  
771 2024, 2014.

772 Sjöström, A. E., Collins, C. D., Smith, S. R. and Shaw, G.: Degradation and plant uptake of  
773 nonylphenol (NP) and nonylphenol-12-ethoxylate (NP12EO) in four contrasting  
774 agricultural soils. *Envion. Pollut.*, 156, 1284-1289, 2008.

775 Sutherland, R. A.: Bed sediment-associated trace metals in an urban stream, Oahu, Hawaii,  
776 *Environ. Geol.*, 39, 611-27, 2000.

777 Szolnoki, Z., Farsang, A. and Puskás, I.: Cumulative impacts of human activities on urban  
778 garden soils: Origin and accumulation of metals, *Environ. Pollut.*, 177, 106-115,  
779 2013.

780 Tischer, A., Blagodatskaya, E. and Hamer, U.: Extracellular enzyme activities in a tropical  
781 mountain rainforest region of southern Ecuador affected by low soil P status and land-  
782 use change, *Appl. Soil Ecol.*, 74, 1-11, 2014.

783 Toledo, D. M., Galantini, J. A., Vazquez, S., and Arzuaga, S.: Soil organic carbon stock and  
784 stratification ratio as indicators of soil quality, 19th ISTRO International Soil Tillage  
785 Research Organization Conference and IV SUCS Meeting Striving for sustainable  
786 high productivity, 24-28 September 2012, Montevideo, Uruguay, Published on DVD,  
787 2012.

788 Trasar-Cepeda, C., Leirós, C., Gil-Sotres, F. and Seoane, S.: Towards a biochemical quality  
789 index for soils: an expression relating several biological and biochemical properties,  
790 *Biol. Fert. Soils*, 26, 100-106, 1998.

791 Veum, K. S., Goyne, K. W., Kremer, R. ., Miles, R. J. and Sudduth, K. A.: Biological  
792 indicators of soil quality and soil organic matter characteristics in an agricultural  
793 management continuum, *Biogeochemistry*, 117, 81-99, 2014.

794 Voidarou, C., Bezirtzoglou, E., Alexopoulos, A., Plessas, S., Stefanis, C., Papadopoulos, I.,  
795 Vavias, S., Stavropoulou, E., Fotoua, K., Tzora, A. and Skoufos, I.: Occurrence of  
796 *Clostridium perfringens* from different cultivated soils, *Anaerobe*, 17, 320-324, 2011.

797 Vrscaj, B., Poggio, L. and Marsan, F. A.: A method for soil environmental quality evaluation  
798 for management and planning in urban areas, *Landscape Urban Plan.*, 88, 81-94, 2008.

799 Wang, Q. and Wang, S.: Response of labile soil organic matter to changes in forest  
800 vegetation in subtropical regions, *Appl. Soil Ecol.*, 47, 210-216, 2011.

801 Wenrui, Y., Rusong, W., Chuanbin, Z. and Feng, C.: Distribution and health risk assessment  
802 of organochlorine pesticides (OCPs) in industrial site soils: A case study of urban  
803 renewal in Beijing, China. *J. Environ. Sci.*, 21, 366-372, 2009.

804 Wong, C. S. C., Li, X. and Thornton, I.: Urban environmental geochemistry of trace metals,  
805 *Environ. Pollut.*, 142, 1-16, 2006.

806 Zhang, G.L., Zhu, Y.G. and Fu, B. J.: Quality changes of soils in urban and suburban areas  
807 and its eco-environmental impacts-a review, *Acta Ecologica Sinica* 23, 539-546,  
808 2003.

809 Zhao, F., Yang, G., Han, X., Feng, Y. and Ren, G.: Stratification of Carbon Fractions and  
810 Carbon Management Index in Deep Soil Affected by the Grain-to- Green Program in  
811 China. *PLOS ONE* 9(6): e99657, 2014.

812 Zhao, H., Xia, B., Fan, C., Zhao, P., Shen, S.: Human health risk from soil heavy metal  
813 contamination under different land uses near Dabaoshan Mine, Southern China. *Sci.  
814 Total Environ.*, 417-418, 45-54, 2012.

815 Zhao, D., Li, F., Yang, Q., Wang, R., Song, Y., Tao, Y.: The influence of different types of  
816 urban land use on soil microbial biomass and functional diversity in Beijing, China,  
817 *Soil Use Manage.*, 29, 230-239, 2013b.

818 Zornoza, R., Mataix-Solera, J., Guerrero, C., Arcenegui, V., Mayoral, A. M., Morales, J.  
819 and Mataix-Beneyto, J.: Soil properties under natural forest in the Alicante Province  
820 of Spain, *Geoderma*, 142, 334-341, 2007.

821 Zornoza, R., Mataix-Solera, J., Guerrero, C., Arcenegui, V., Mataix-Beneyto, J. and Gómez,  
822 I.: Validating the effectiveness and sensitivity of two soil quality indices based on  
823 natural forest soils under Mediterranean conditions, *Soil Biol. Biochem.*, 40, 2079-  
824 2087, 2008a.

825 Zornoza, R., Guerrero, C., Mataix-Solera, J., Scow, K.M., Arcenegui, V., Mataix-Beneyto, J.:  
826 Near infrared spectroscopy for determination of various physical, chemical and  
827 biochemical properties in Mediterranean soils. *Soil Biol. Biochem.*, 40, 1923-1930,  
828 2008b.

829 Zornoza, R., Guerrero, C., Mataix-Solera, J., Scow, K.M., Arcenegui, V. and Mataix-  
830 Beneyto, J.: Changes in soil microbial community structure following the

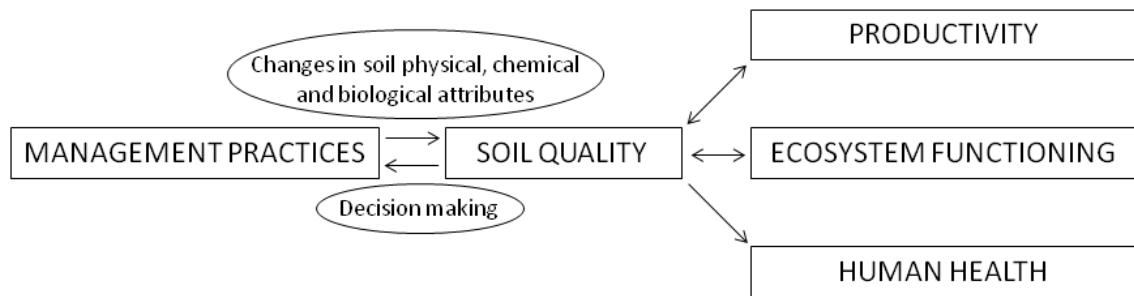
831 abandonment of agricultural terraces in mountainous areas of Eastern Spain, Appl.  
832 Soil Ecol., 42, 315-323, 2009.

833 **Figure Captions**

834 Figure 1. Interconnection between management practices, soil quality, productivity,  
835 environmental functions and soil health. Only indirect effects of management practices to  
836 other components through soil quality are taken into consideration.

837 Figure 2. Flowchart of steps involved in soil quality assessment.

838 Figure 1



839

840 Figure 2

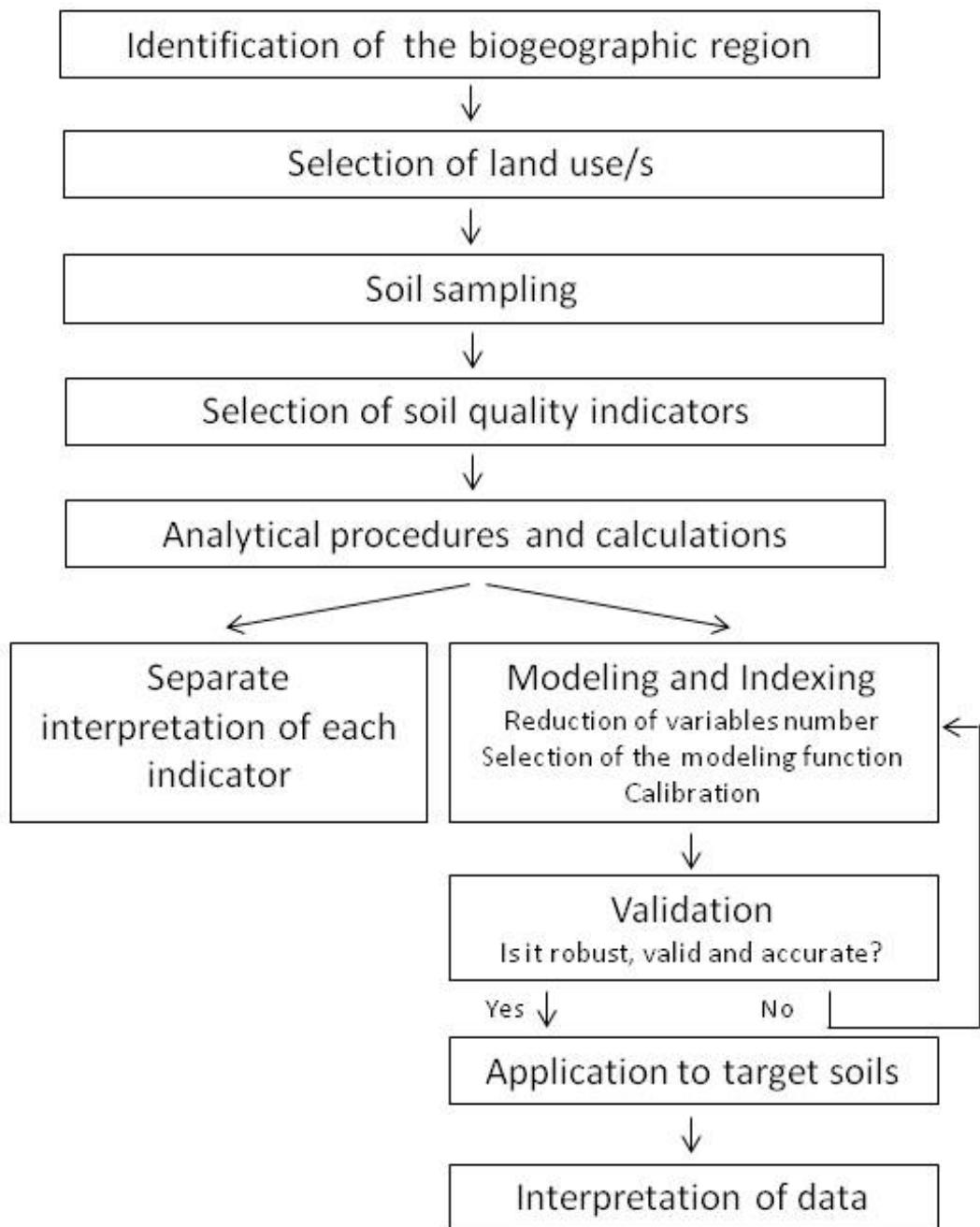


Table 1. Most common indicators used in soil quality assessment under different land uses and approaches

Soil indicator	Agricultural systems	Forest systems	Land use changes	Urban systems	Human health
Soil organic carbon	Qi et al. (2009); Merrill et al. (2013); D'Hose et al. (2014); Li et al. (2014); Liu et al. (2014b); Rahmanipour et al. (2014)	Franzluebbers (2002); Pang et al. (2006); Amacher et al. (2007); Chaer et al. (2009); Zornoza et al. (2007); Toledo et al. (2012)	Marzaioli et al. (2010); Li et al. (2013); Singh et al. (2014); Veum et al. (2014)	Rodrigues et al. (2009); Santorufo et al. (2012a,b); Gavrilenko et al. (2013)	Murray et al. (2011); Cachada et al. (2012); Qin et al. (2013); Rafiq et al. (2014)
Total nitrogen	Qi et al. (2009); Ramos et al. (2010); Laird and Chang (2013); Rousseau et al. (2013); D'Hose et al. (2014); Liu et al. (2014a,b)	Trasar-Cepeda et al. (1998); Leirós et al. (1999); Pang et al. (2006); Amacher et al. (2007)	Marzaioli et al. (2010)		
pH	Qi et al. (2009); Moscatelli et al. (2012); Giacometti et al. (2014); D'Hose et al. (2014); Rahmanipour et al. (2014)	Burger and Kelting (1999); Amacher et al. (2007); Zornoza et al. (2007);	Marzaioli et al. (2010); Veum et al. (2014)	Rodrigues et al. (2009); Santorufo et al. (2012a,b)	Murray et al. (2011); Zhao et al. (2012); Landa-Cansigno et al. (2013); Rafiq et al. (2014)
Electrical conductivity	Merrill et al. (2013); Li et al. (2014); Rahmanipour et al. (2014)	Zornoza et al. (2007, 2008a)	Marzaioli et al. (2010); Veum et al. (2014)		Zhao et al. (2003); Landa-Cansigno et al. (2013)
Available nutrients	Qi et al. (2009); Merrill et al. (2013); Liu et al. (2014a); Rousseau et al. (2013); D'Hose et al. (2014)	Pang et al. (2006); Amacher et al. (2007); Zornoza et al. (2007, 2008a)	Marzaioli et al. (2010); Singh et al. (2014); Veum et al. (2014)		
Cation exchange capacity	García-Ruiz et al. (2008); Qi et al. (2009); Rahmanipour et al. (2014)	Pang et al. (2006); Zornoza et al. (2007);	Marzaioli et al. (2010)	Rodrigues et al. (2009)	Rafiq et al. (2014)
Soluble carbon and/or nitrogen	Merrill et al. (2013)		Wang and Wang (2011);		
Heavy metals	Qi et al. (2009); Rahmanipour et al. (2014)		Singh et al. (2014)	Peijnenburg et al. (2007); Papa et al. (2010); Rodrigues et al. (2013); Santorufo et al. (2012)	Murray et al. (2011); Zhao et al. (2012); Pelfrêne et al. (2013); Qin et al. (2013); Rafiq et al. (2014)
Organic pollutants					Wenrui et al. (2009); Cachada et al. (2012); Murray et al. (2011); Landa-Cansigno et al. (2013)
Particle size	Armenise et al. (2013); Merrill et al. (2013); Rousseau et al. (2013);		Marzaioli et al. (2010); Singh et al. (2014)	Rodrigues et al. (2009); Gavrilenko et al. (2013)	
Bulk density	Merrill et al. (2013); Rousseau et al. (2013);	Sanchez et al. (2008)	Marzaioli et al. (2010); Veum et al. (2014)	Rodrigues et al. (2009); Gavrilenko et al. (2013)	

Table 1. Most common indicators used in soil quality assessment under different land uses and approaches (continuation)

Soil indicator	Agricultural systems	Forest systems	Land use changes	Urban systems	Human health
Soil aggregation	Rousseau et al. (2013); D'Hosea et al. (2014)	Zornoza et al. (2007, 2008a)	Veum et al. (2014)		
Available water content / water holding capacity	Armenise et al. (2013);	Burger and Kelting (1999); Pang et al. (2006); Amacher et al. (2007); Zornoza et al. (2007)	Marzaioli et al. (2010); Veum et al. (2014)	Santorufo et al. (2012a,b)	
Porosity		Burger and Kelting (1999)			
Penetration resistance	Rousseau et al. (2013); D'Hose et al. (2014)	Burger and Kelting (1999)			
Carbon mineralization	Biau et al. (2012); Laird and Chang (2013)	Jiménez-Esquilín et al. (2008); Blecker et al. (2012)	Marzaioli et al. (2010)	Papa et al. (2010); Gavrilenko et al. (2013)	
Nitrogen mineralization	Biau et al. (2012); Laird and Chang (2013); Merrill et al. (2013)	Trasar-Cepeda et al. (1998); Leirós et al. (1999);	Marzaioli et al. (2010); Veum et al. (2014)		
Microbial biomass carbon and/or nitrogen	Bi et al. (2013); D'Hose et al. (2014); Li et al. (2014); Liu et al. (2014a)	Trasar-Cepeda et al. (1998); Chaer et al. (2009); Mataix-Solera et al. (2009); Zhao et al. (2013)	Marzaioli et al. (2010); Li et al. (2013); Veum et al. (2014)	Papa et al. (2010); Gavrilenko et al. (2013)	
Microbial communities	Giacometti et al. (2013)	Zornoza et al. (2009); Banning et al. (2011); Blecker et al. (2012)			Liang et al. (2011)
Enzyme activities	García-Ruiz et al. (2008); Li et al. (2014); Liu et al. (2014b)	Trasar-Cepeda et al. (1998); Leirós et al. (1999); Zornoza et al. (2007); Chaer et al. (2009)	Li et al. (2013)	Papa et al. (2010)	
Ergosterol/fungal mycelium	D'Hose et al. (2014)		Marzaioli et al. (2010)		
Invertebrates	Biau et al. (2012); D'Hose et al. (2014)		Ruiz et al. (2011)	Hankard et al. (2005); Santorufo et al. (2012a,b)	Landa-Cansigno et al. (2013)
Pathogens					Liang et al. (2011); Benami et al. (2013); Ceuppens et al. (2014); Sepehrnia et al. (2014)