

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

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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 inexistent.
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).

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 NO_3^- , 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 β -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 qCO_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, $\text{SOC} < 1\%$ was assigned an index value of 0, while $\text{SOC} > 5\%$ 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_2 . 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 ($E_{Fi} = [Ci\text{-sample}/C_{ref\text{-sample}}]/[Bi\text{-background}/B_{ref\text{-background}}]$), where n is the number of measured elements, C_i (sample) is the metal
337 concentration (i), B_i (background) is the baseline concentration, C_{ref} (sample) is the content
338 of the reference element in the sample and B_{ref} is the content of the reference element in the
339 reference soil. However, metals can be present in soils with different speciation, and so with
340 different bioavailability and solubility. Hence, to assess urban SQ, the soluble or bioavailable
341 fractions of the metals should be taken into account besides total concentrations (Rodrigues et
342 al., 2013). There are several methods based on single or sequential schemes of chemical
343 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.,](#)
380 [2011](#)). 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 inexistent. 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, 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., Grosso, 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 Vliegheer, 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 Xinping, 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 mangement. p. 37

-51, in : Dora

- 632 environment. SSSA
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. Ecosist. 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 Römken, 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. *Environ. 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

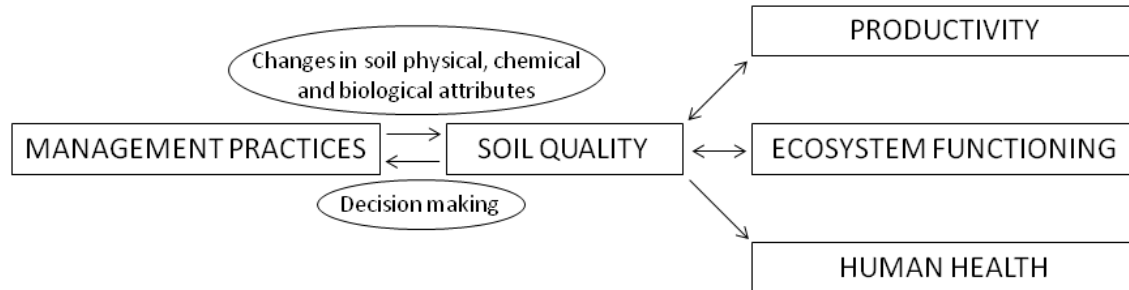
831 abandonment of agricultural terraces in mountainous areas of Eastern Spain, Appl.
832 Soil Ecol., 42, 315-323, 2009.

833 **Figure Captions**

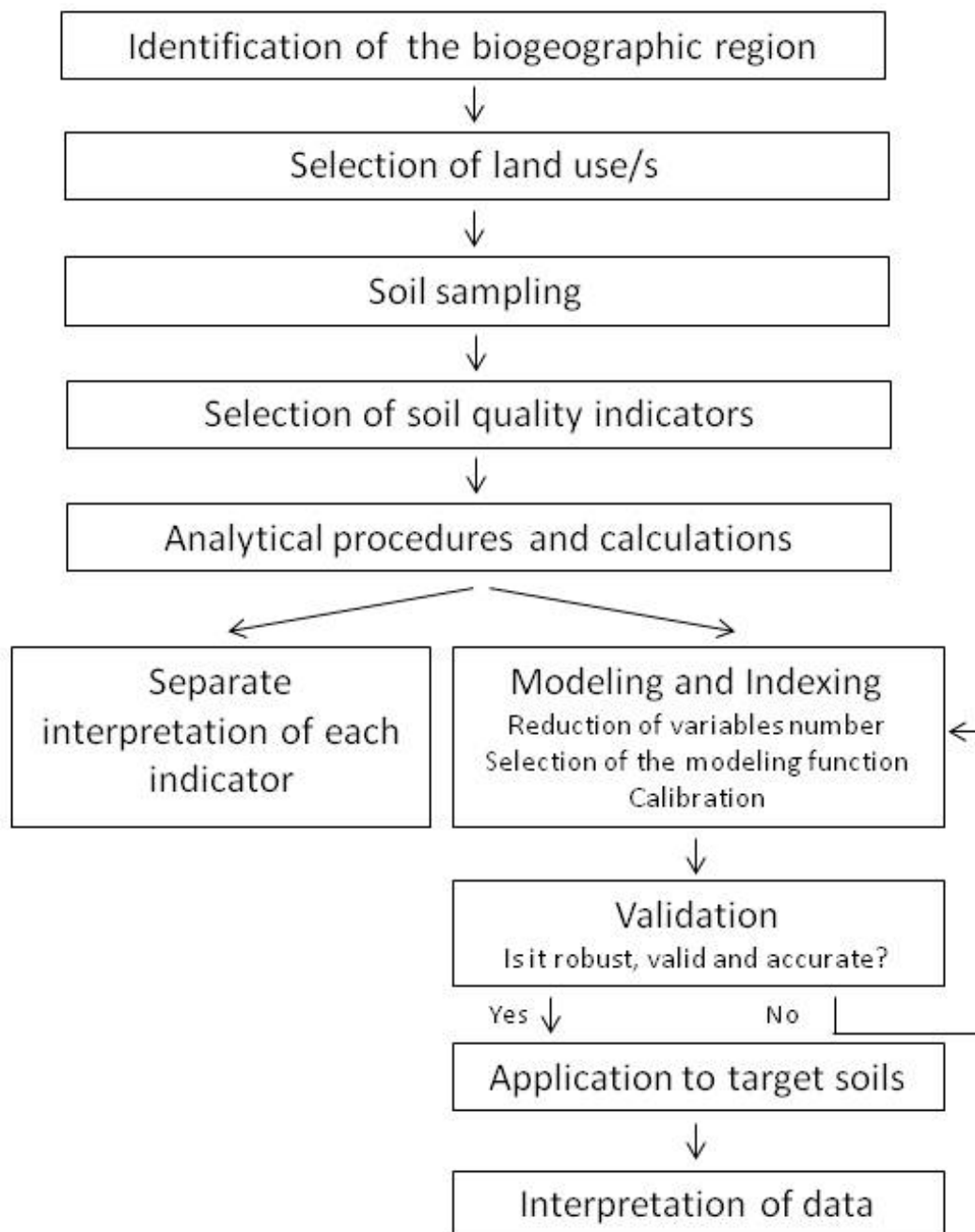
834 Figure 1. Interconnection between management practices, soil quality, productivity,
835 environmental functions and soil health. Only indirect effects of management practices to
836 other components through soil quality are taken into consideration.

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

838 Figure 1



839



842 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); Pelfrène et al. (2013); Qin et al. (2013); Rafiq et al. (2014)
Organic pollutants					Wenrui et al. (2009); Cachada et al. (2012);
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)	Murray et al. (2011); Landa-Cansigno 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)	

843 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 Porosity	Armenise et al. (2013);	Burger and Kelting (1999); Pang et al. (2006); Amacher et al. (2007); Zornoza et al. (2007) Burger and Kelting (1999)	Marzaioli et al. (2010); Veum et al. (2014)	Santorufu et al. (2012a,b)	
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); Santorufu 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)