

# Soil Quality Assessment under Emerging Regulatory Requirements

James Bone<sup>1</sup>, Martin Head<sup>1</sup>, Declan Barraclough<sup>2</sup>, Michael Archer<sup>2,3</sup>, Catherine Scheib<sup>4</sup>, Dee Flight<sup>4</sup>, Nikolaos Voulvoulis<sup>1\*</sup>

<sup>1</sup> Centre for Environmental Policy, Imperial College London, London, SW7 2AZ, UK

<sup>2</sup> Environment Agency, Science Department, Evenlode House, Wallingford, OX10 8BD, UK

<sup>3</sup> ERM, St Nicholas House, 31-34 High Street, Bristol, BS1 2AW, UK

<sup>4</sup> British Geological Survey, Kingsley Dunham Centre, Keyworth, Nottingham NG12 5GG, UK

## Abstract

New and emerging policies that aim to set standards for protection and sustainable use of soil are likely to require identification of geographical risk/ priority areas. Soil degradation can be seen as the change or disturbance in soil quality and it is therefore crucial that soil and soil quality are well understood to protect soils and to meet legislative requirements. To increase this understanding a review of the soil quality definition evaluated its development, with a formal scientific approach to assessment beginning in the 1970's, followed by a period of discussion and refinement. A number of reservations about soil quality assessment expressed in the literature are summarised. Taking concerns into account, a definition of soil quality incorporating soil's ability to meet multifunctional requirements, to provide ecosystem services, and the potential for soils to affect other environmental media is described. Assessment using this definition requires a large number of soil function dependent indicators that can be expensive, laborious, prone to error, and problematic in comparison. Findings demonstrate the need for a method that is not function dependent, but uses a number of cross functional indicators instead. This method to systematically prioritise areas where detailed investigation is required, using a ranking based against a desired level of action, could be relatively quick, easy and cost effective. As such this has potential to fill in gaps and compliment existing monitoring programs and assist in development and implementation of current and future soil protection legislation.

Keywords: Soil; Soil Degradation; Soil Quality; Soil Function; Environmental Monitoring; Indicators; EU Environmental Policies for Soil Protection;

## 29 **Introduction**

30 Soil is relatively complex compared to other environmental media. The complexity is  
31 confounded by its spatial heterogeneity both over the Earth's land surface but also with depth.  
32 Soil is a continuum covering the earth's surface, not a discrete set of entities, and most soil is  
33 below ground and not readily visible (Buol et al. 2003). The complexity of the natural systems is  
34 manifested in the subject of soil science, which involves the study of complicated interrelated  
35 and interdependent processes (Shainberg 2000). Soil science is interdisciplinary and includes  
36 soil physics, soil chemistry, soil pedology, and soil biology.

37 Soil degradation is the long term decline in soil's current or future productivity and its  
38 environment moderating capacity (Lal 1994; Lal 1997; Lal 2001; Oldeman 1988). The main soil  
39 degradation processes include soil erosion by water and wind, development of extreme soil  
40 reaction (acidification, salinisation/alkalization), physical degradation (structural destruction,  
41 compaction, extreme moisture regime), biological degradation, unfavourable changes in the  
42 nutrient regime, decrease of buffering capacity, and contamination from natural or  
43 anthropogenic sources (Blum 1997; Várallya 1989). Major threats for soil in Europe, highlighted  
44 in the EU soil thematic strategy, are erosion, decline in organic matter, local and diffuse  
45 contamination, sealing, compaction, decline in biodiversity, salinisation, floods and landslides  
46 (European Commission (EC) 2006b). Soil degradation normally signifies a change or  
47 disturbance of soil quality, implying decline in quality and capacity of soil through natural or  
48 anthropogenic perturbations (Johnson et al. 1997; Lal 2009).

49 There is a move toward protection of soils to the same extent as water and air and to promote  
50 sustainable use of soil (Blum 2003; Quevauviller and Olazabal 2003). This increased  
51 importance of soil in environmental disciplines has occurred for a number of reasons. The  
52 drivers for this rise has been a proliferation of contaminated land legislation, soil geography and  
53 soil-geographical zoning, agricultural soil management zone identification, and environmental  
54 impact assessments and strategic environmental assessment taking into account soil quality,  
55 their characterisation and management (Fleming et al. 2000; Glasson et al. 2005; Nathanail and

56 Bardos 2004; Urusevskaya 2007; Wood 2003). Soil is the basis of economic and cultural  
57 activities; however the economic value of soil has not adequately been recognised (Görlach et  
58 al. 2004). Due to the fundamental link between soil and the economy there are many economic  
59 activities that depend both directly and indirectly on soil quality including agriculture, industry  
60 and tourism. These economic activities could benefit from development of soil quality  
61 assessment methods, action prioritisation systems, and more generally from sustainable soil  
62 use and conservation.

63 Countries including the USA, Japan, Canada, Australia, Brazil and a number of developing  
64 countries have established soil protection policies (European Commission (EC) 2006a).  
65 Legislation aiming to protect soils in Europe includes the soil thematic strategy (European  
66 Commission (EC) 2006b), and the proposed soil framework directive (European Commission,  
67 2006b). In addition in the UK reform to the cross compliance good agricultural and  
68 environmental condition (GAEC) standards is taking place to strengthen soils protection  
69 (Department for Environment Food and Rural Affairs (DEFRA) 2009), and a code of practice for  
70 the sustainable use of soils on construction sites has been developed (Department for  
71 Environment Food and Rural Affairs (DEFRA) 2008).

72 A number of EU member states have legislation that alludes to soil protection; however the  
73 majority of this is focused on soil contamination. A number of states do have policies addressing  
74 broader soil protection issues including Netherlands, Germany and Belgium. These states are  
75 some of the most advanced states for soil protection in EU, and found in a survey in 2003 to be  
76 the only states with a specific legally binding definition of soil (Van-Camp et al. 2003). The  
77 Netherlands have a number of policies to address long term protection, management and  
78 sustainable use of soils including the 1987 soil protection act (amended 2008) (VROM (The  
79 Netherlands Ministry of Housing, Physical Planning and the Environment) 1986), the 2003 Soil  
80 Policy Letter (van Geel 2003) and the 2009 soil remediation circular (VROM (The Netherlands  
81 Ministry of Housing, Physical Planning and the Environment) 2009). German policy for the  
82 protection of soils include the 1998 Federal Soil protection act (Federal Ministry for the  
83 Environment Nature Conservation and Nuclear Safety 1998), and the 1999 Federal Soil

84 Protection and Contaminated Sites Ordinance (Federal Ministry for the Environment Nature  
85 Conservation and Nuclear Safety 1999). There are a number of government agencies that have  
86 been established for soil protection, the Federal Institute for Geosciences and Natural  
87 Resources formally established in 1975 and the Federal Environment Agency Soil Protection  
88 Commission (KBU) in 2004. The Public Waste Agency of Flanders (OVAM) of the Flanders  
89 region of Belgium developed a soil remediation and protection decree in 2007, replacing a  
90 previous version of 1995 (Public Waste Agency of Flanders (OVAM) 2007). The Flemish  
91 government approved the 'Order of the Flemish Government establishing the Flemish regulation  
92 on soil remediation and soil protection' that accompanied the decree in December 2007  
93 (Flemish Government 2007), replacing the previous version of 1995.

94 The soil framework directive proposes integration of soils into all policy making, prevention of  
95 degradation and pollution of soils, implementation of risk/priority areas and action programmes  
96 for erosion, compaction, loss of organic matter, salinisation, acidification and landslides,  
97 limitation and containment of soil sealing, and identification and remediation of contaminated  
98 sites (de Souza 2009). The proposed directive will require identification of risk areas on the  
99 basis of common elements, encouraging use of existing monitoring schemes with a move  
100 toward development of a harmonised monitoring approach (European Commission (EC)  
101 2006c). There is general support for a Framework directive on soil protection, with the majority  
102 of states holding the view that the proposed directive will fill a gap in Union environmental  
103 legislation and provide a more holistic approach to soil protection (Council of the European  
104 Union 2010). Development of the soil framework has, however, been slow for a number of  
105 reasons including problems agreeing on an approach for identifying geographical "risk areas" or  
106 "priority areas" (ENDS Europe 2007). A knowledge based approach to soil monitoring aimed at  
107 delivering soil protection and sustainable use is introduced and required by the soil thematic  
108 strategy (Blum et al. 2004a; Blum et al. 2004b; Quevauviller and Olazabal 2003).

109 Despite the relatively recent introduction of policies for its protection, soil is an environmental  
110 medium that is often neglected, because there is not widespread understanding of the  
111 importance it has for ecosystems and the economy (Dimas and Gnacadja 2008). Despite the

112 increase in environmental awareness, the same cannot be shown of the general society's  
113 attitude toward soil {160 Ferreira, M. da G. de V. X. 2006}}. The public's knowledge of, and  
114 interest in other environmental media such as air and water are higher than of soils. For the  
115 case of air, the level of knowledge is mainly because of the impact on public perception of the  
116 history of air pollution and dramatic local events (Brimblecombe 2001). Similarly, water is  
117 perceived as very important and has played its part in both historical and current conflicts  
118 (Gleick 2008). The link between human health and both air and water quality has been a driver  
119 for developing public perception and the need for environmental regulations.

120 Even when conflicts have been associated with the availability of arable land and farm  
121 production, soil has never properly understood or perceived as important. On the contrary, soil  
122 has often been pushed to the background in public commitment to environmental conservation.  
123 This is in part due to the unaddressed problem of clearly defining soil, and the more  
124 complicated issue of defining or assessing its quality. The links to the environment and human  
125 health are not evident for soil to the same extent as water and air. Soil is often taken for granted  
126 and often mistakenly confused with dirt. There is a need for defining and communicating a  
127 richer, more broadly nuanced, and positive societal value of soil and its quality.

128 In an effort to protect soils through encouraging development of soil protection policy and  
129 legislation there is a need to clearly define soil and in order to assess the state of degradation to  
130 understand the term soil quality. This paper aimed to increase understanding of soil and soil  
131 quality through review of the definition of soil and developments in the definition of soil quality  
132 and its assessment. The paper summarises concerns that have emerged following a phase of  
133 development since the initial definition of soil quality in the 1970's. The historical review was  
134 undertaken to understand the difficulties in defining soil quality as well as problems and  
135 concerns with assessment of soil quality. The review incorporates major concerns and unease  
136 in the field of soil quality and developments in the field of environmental protection to refine the  
137 definition of soil quality. This work has suggested development of a complimentary method to  
138 inform and prioritise further detailed assessment of soil's quality.

139 This review is particularly relevant due to the simultaneous development of a number of country  
140 specific legislative instruments for soil protection and particularly with the emergence of  
141 European legislative drivers. The work has relevance to the situation surrounding the proposed  
142 framework directive on soil protection. As such the concepts presented in this work have  
143 potential EU- wide application, with relevance at member state level but more importantly for  
144 harmonisation across states.

#### 145 **Soil and Soil Quality**

146 There is some variability in the definition of soil; a selection of definitions is presented in Table  
147 1. An early legislative definition by the Netherlands Ministry of Housing, Physical Planning and  
148 the Environment (VROM) is a simple statement about the physical nature of the soil; a definition  
149 very similar to that of the Public Waste Agency of Flanders. The German Federal Ministry for  
150 the Environment, Nature Conservation and Nuclear Safety definition is more detailed than that  
151 of the Netherlands and Flanders, and includes not only the physical components of soil but  
152 reference to soil's function. The Soil Science Society of America provides the definition that is  
153 accepted by the US Department of Agriculture and this definition of soil demonstrates the  
154 complex and multifaceted nature of soils (Soil Science Glossary Terms Committee 2008) The  
155 definition as used by the Environment Agency of England and Wales (EA) introduces the idea  
156 that soil is often seen as a resource, and therefore can be exploited (Environment Agency  
157 2004). The definition in the proposed soil framework directive (in the proposal of the Czech  
158 presidency) text is restricted to the chemical, physical and biological aspects of the soil, not  
159 mentioning function or economic production.

#### 160 **Table 1 Definitions of soil in legislation and literature.**

161 A lot of research has been undertaken to understand soil and describe its characteristics in  
162 more general terms. For example, the chemical function of soil has been assessed on national,  
163 regional and local levels by use of geochemical mapping (Barraclough 2007; Johnson et al.  
164 2005). The technique was developed in the 1950's to give information on the spatial distribution  
165 of chemical elements and compounds at the earth's surface (Johnson and Ander 2008). In

166 general, there has been a great deal of work to investigate simplified functions and processes of  
167 soil science; these however are regularly limited to the specific sub discipline such as soil  
168 physics, soil biology or soil chemistry. There is a need to review the advances and development  
169 in the term soil quality, to define how the term relates to the uses of land and to anthropogenic  
170 activities.

171 The potential effects upon other media from the soil system have the ability to influence  
172 compliance with regulatory standards such as the European Union Water Framework Directive  
173 which sets controls on the diffuse pollution from soil (European Commission (EC) 2006b). A  
174 method for prioritisation of impacts to groundwater from soils on a city wide scale is being  
175 developed by the British Geological Survey that takes into account factors including soil  
176 properties and soil metal concentration from urban soil survey data (Ó'Dochartaigh et al. 2009).

177 Despite the great deal of research into specific aspects of soil's quality, most of this work  
178 defines and assesses soil quality based on different simplified functions and processes of soil  
179 itself. An example of this is the agricultural land classification developed implemented in the UK  
180 to assess quality of agricultural land taking into account climate, site and soil characteristics and  
181 the interactions between them (Ministry of Agriculture, Fisheries and Food 1988). Another  
182 example is the great increase in research into, and investigation of, contaminated land since the  
183 1970's. This was mainly a reaction to a number of high profile contamination incidents that  
184 attracted media attention, such as Love Canal and Times Beach in the USA, Lekkerkerk in the  
185 Netherlands, Minimata in Japan, and incidents in the UK such as the landfill gas explosion at  
186 Loscoe, redevelopment of a munitions factory in Enfield, the detection of hexachlorobutadiene  
187 in houses in Cheshire, and The Corby Litigation Group v Corby District Council case concerning  
188 reclamation of a former steel works in Corby (Nathanail and Bardos 2004; Williams and  
189 Aitkenhead 1991). The increase in contaminated land research is also due to an increase in  
190 development of Brownfield sites, inclusion of contaminated land as a consideration in the  
191 planning process, and a willingness of companies to identify environmental liabilities (Alker et al.  
192 2000; Department for Environment Food and Rural Affairs (DEFRA) 2002; Harrison and Hester  
193 2001).

194 Contaminated land has the potential to pose serious environmental risks, including surface and  
195 groundwater contamination, and risks to human health and safety (Balasubramaniam et al.  
196 2007). Although likely to be covered in future holistic soil protection regimes contaminated land  
197 is just one aspect of soil quality. It has traditionally had a separate legislative area with its own  
198 related legislation and policy, independent from that of soil science and soil quality.  
199 Environmental standards used to assess contaminated land should not be confused with  
200 assessment of soil quality. The contaminated land legislative area includes not only legislation  
201 specific to contaminated land but also general environmental, waste and resources, health  
202 protection, and planning and building control. Exhaustive lists of contaminated land legislation  
203 are available from state governments; however examples of the main acts relating to  
204 contaminated land in a number of European states are detailed in Table 2.

#### 205 **Table 2 Examples of main contaminated land legislation in EU member states**

206 There are some states with legislation specific to contaminated soil, and a number of states that  
207 have overarching soil protection legislation; however these still focus to a large extent on soil  
208 contamination. The legislative framework in EU member states has similarities in investigation  
209 of presumed contamination; mostly following a similar stepwise approach with preliminary  
210 investigation followed by detailed investigation and remediation (Provoost et al. 2006). Soil  
211 cleanup standards are seen as a trigger for detailed investigation and remediation, however  
212 these values vary in derivation and application across member states. For the case of soil  
213 quality indicators, apart from contaminant concentration, trigger values for action have mostly  
214 not been adequately researched and there is a lack of implementation so far within member  
215 states (UK Soil Indicators Consortium 2006).

216 To support development of national contaminated land management programmes, a likely  
217 requirement of the EU SFD (European Commission (EC) 2006c) a driver-pressure-state-impact-  
218 response (D-P-S-I-R) framework has been suggested to provide an information framework to  
219 support interventions on contaminated land management at a national level and the source-  
220 pathway- receptor model to provide guidance at a site level (Rodrigues et al. 2009). This



221 method would meet the requirement in the proposed SFD of identification of contaminated sites  
222 but would not go so far as to meet the requirement to identify geographical risk or priority areas.  
223 However, this identification will not be carried out by environmental policy itself and is likely to  
224 require the development and use of additional tools.

225 Presence of contaminants from diffuse sources potentially present below traditional risk  
226 screening levels should not be overlooked. Although through risk assessment the presence of  
227 these contaminants is not necessarily considered a threat to human health, their presence can  
228 impact upon other aspects of soil quality such as soil biodiversity (van Straalen and van Gestel  
229 2008). Diffuse pollution of soils also has the potential to exacerbate the impact of other soil  
230 quality aspects such as erosion, leaching and run off and ultimately upon a number of soil  
231 functions (Quevauviller 2007).

232 Soil quality needs to include such contamination aspects, within a holistic assessment approach  
233 that includes other aspects of soil quality. As previously stated, soil degradation can be defined  
234 as a decline in soil quality, and major soil degradation processes are erosion, decline in organic  
235 matter, local and diffuse contamination, sealing, compaction, decline in biodiversity, salinisation,  
236 floods and landslides. Ultimately extreme degradation leads to desertification, an advanced  
237 stage of land degradation where the soil has lost part of its capability to support human  
238 communities and ecosystems (European Environment Agency (EEA) 1999). These soil  
239 degradation processes can, therefore, be seen as key threats to decline in soil quality and seen  
240 as a key focus of the definition, identification and assessment of soil quality.

#### 241 **Historical Review of Assessment of Soil Quality**

242 Proposals to assess soil quality emerged initially in the USA. An early proponent of the concept  
243 was Alexander (Alexander 1971) who first suggested developing soil quality criteria. The  
244 development of the definition of soil quality over time is detailed in Table 3.

#### 245 **Table 3 Development of the definition of soil quality**

246 The report “*A framework for land evaluation*” by the Food and Agriculture Organization (FAO) of  
247 the United Nations defined land quality as “*a complex attribute of land which acts in a distinct*  
248 *manner in its influence on the suitability of land for a specific kind of use*” (Food and Agriculture  
249 Organisation (FAO) 1976). The FAO report introduced the idea that land quality is complex and  
250 should be assessed in relation to the specific function that the land serves Carter *et al.* (Carter  
251 *et al.* 1997) outlined the differences between land and soil quality whereby soil quality is more  
252 restrictive than land quality but frequently incorporates the same emphasis on use.

253 Warkentin and Fletcher (Warkentin and Fletcher 1977) developed soil quality as initially  
254 suggested by Alexander (Alexander 1971) by integrating the relationship of soil quality with the  
255 land function. The authors stated that assessment of soil quality was needed to facilitate better  
256 land use planning because of the increasing number of functions that soil resources must either  
257 provide or accommodate. Warkentin and Fletcher (Warkentin and Fletcher 1977) recognised  
258 the value of soils in the biosphere and stated that soils have not only current use value but also  
259 should have an intrinsic value. The relationship between soil quality and environmental quality is  
260 evident in the Anderson and Gregorich (Anderson and Gregorich 1984) definition.

261 Larson and Pierce (Larson and Pierce 1991) along with their definition of soil quality suggest a  
262 minimum data set of soil parameters which could be used to express the 'health' of a soil. The  
263 Larson and Pierce (Larson and Pierce 1991) definition introduces soil health, a term that can be  
264 used interchangeably with the term soil quality. The term soil quality, however, is one used  
265 more regularly by soil scientists and soil health used by other parties. The phrases, although  
266 used interchangeably, do however have different emphasis. Karlen *et al.* (Karlen *et al.* 1997b)  
267 state that soil quality can be viewed as an inherent characteristic of the soil, or as the condition  
268 or “health” of the soil. However, the difference in emphasis between soil health and soil  
269 condition was highlighted in Mausbach and Tugel (Mausbach and Tugel 1995) with soil health  
270 differing from soil condition whereby soil health “*is the ability of the soil to perform according to*  
271 *its potential. Soil condition changes over time due to human use and management or to unusual*  
272 *natural events*”.

273 Seybold et al. (Seybold et al. 1998) suggested that soil quality evokes various responses  
274 depending on scientific and social background. To the land manager and farmer, soil quality is  
275 often viewed as that of soil health (Romig 1995). Soil health is a term preferred by some as it  
276 portrays soil as a living, dynamic system whose function is mediated by a diversity of living  
277 organisms that require management and conservation (Doran and Zeiss 2000). Doran and  
278 Zeiss (Doran and Zeiss 2000) state that the term soil quality is associated with a soil's fitness for  
279 use and the term soil health is associated with the capacity of a soil to function as a vital living  
280 system, to sustain biological productivity, promote environmental quality and maintain plant and  
281 animal health.

282 Pierce and Lal (Pierce and Lal 1992) differentiated between the intrinsic properties of a soil as  
283 determined by the soils development and degradation processes, and the soils productivity  
284 describing the efficiency in use and management of resource inputs.

285 The classification of soil quality as "fitness for use" aligns soil quality assessment with soil  
286 function (Pierce and Larson 1993). Assessment of soil quality requires the intended soil use to  
287 be determined in order to establish the soils capacity to function (Schoenholtz et al. 2000).  
288 Recent and proposed soil protection policy requires action on threats to soil with regard to the  
289 soil function (Blum et al. 2004a; de Souza 2009). Carter *et al.* (Carter et al. 1997) suggested a  
290 framework for evaluating soil quality that includes describing each soil function on which quality  
291 is to be used, selecting soil characteristics of properties that influence the capacity of the soil to  
292 provide each function, choosing indicators of characteristics that can be measured, and using  
293 methods that provide accurate measurement of those indicators.

294 The Doran and Parkin (Doran and Parkin 1994) definition includes not only soils ability to  
295 function, but includes key soil functions in the definition. A widely used definition of soil quality is  
296 that of Karlen et al. (Karlen et al. 2001), the product of a Soil Science Society of America  
297 (SSSA) Ad Hoc Committee on Soil Quality (S-581). The result of the committee on soil quality is  
298 clearly based upon the Doran and Parkin (Doran and Parkin 1994) definition. The Karlen *et al.*  
299 (Karlen et al. 1997a) definition is used widely by the United States Department of Agriculture

300 including in their recent technical note (USDA- NRCS 2008). The definitions from both Doran  
301 and Parkin (Doran and Parkin 1994) and Karlen *et al.* (Karlen et al. 1997b) include dynamic soil  
302 quality, a term that refers to the condition of soil that is changeable in a short period of time by  
303 human impact including agricultural management practices (Idowu et al. 2008; Seybold et al.  
304 1998).

305 Patzel *et al.* (Patzel et al. 2000) attempted to make a distinction between soil fertility and soil  
306 quality for the German language literature. The distinction of soil quality from soil fertility was  
307 recommended to prevent ideal attributes in soils being included in the definition of soil fertility  
308 and to reduce confusion associated with the two terms as has been seen in the USA.

309 In the USA the establishment, in 1993, of a Soil Quality Institute (SQI) provided the United  
310 States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) with  
311 an emphasis on soil quality. The SQI has a mission to develop and disseminate tools for soil  
312 quality assessment (Ditzler and Tugel 2002).

313 In summary soil quality has developed from the suggestion by Alexander (Alexander 1971) that  
314 soil quality criteria should be developed, later in the 1970's it was suggested that soil quality  
315 should be evaluated in relation to land function (Warkentin and Fletcher 1977). The interaction  
316 with holistic environmental quality, water and air quality was discussed in the mid 1980's  
317 (Anderson and Gregorich 1984). There was much discussion of the subject in the 1990's  
318 including suggestion of minimum data sets for assessment, discussion about the differences  
319 between soil health and soil quality, and a differentiation between the intrinsic properties of a  
320 soil and soils productivity as a result of management practices (Doran and Zeiss 2000; Karlen et  
321 al. 1997b; Larson and Pierce 1991; Mausbach and Tugel 1995; Pierce and Lal 1992; Romig  
322 1995; Seybold et al. 1998). Doran and Parkin (Doran and Parkin 1994) and Pierce and Larson  
323 (Pierce and Larson 1993) developed the definition further by including key soil functions, the  
324 fitness for use and the dynamic state of soils in the definition of soil quality, which clearly  
325 inspired later definitions (Karlen et al. 1997b; USDA- NRCS 2008), and soil protection policy  
326 (Blum et al. 2004a; de Souza 2009).

327 **Concern over the definition of soil quality**

328 Despite formation of a soil quality institute in the USA and a large amount of discussion  
329 predominantly attempting to define soil quality, consensus amongst the scientific community on  
330 a precise definition of soil quality has not been reached (Ditzler and Tugel 2002). This is likely to  
331 be due to the innate difficulty in the definition of soil and the complex nature (i.e., scientific,  
332 personal, and social) of environmental concerns (Carter 2002).

333 Following the large amount of work to define soil quality, there has more recently been some  
334 dispute about the relevance and impact of soil quality. MacEwan and Carter (MacEwan and  
335 Carter 1996) and Carter (Carter 2002) stated that although soil quality describes an objective  
336 state or condition of the soil, it also is subjective, evaluated partly on the basis of personal and  
337 social determinations. Doran and Parkin (Doran and Parkin 1996) described that in the 5 years  
338 preceding the publication there had been concern about deficiencies in the basic understanding  
339 of soil quality and a lack of a mechanistically based soil quality methodology, particularly of the  
340 soil biota.

341 Sojka and Upchurch (Sojka and Upchurch 1999) expressed concern over the move in soil  
342 science from value neutral tradition of edaphology, and specific problem solving to paradigm  
343 based on variable and often subjective societal perceptions of environmental holism. Sojka and  
344 Upchurch (Sojka and Upchurch 1999) suggested that although soil quality does acknowledge  
345 the variable soil functions it fails to integrate simultaneous, diverse and often conflicting soil  
346 functions and emphasises the importance of understanding rather than rating of the soil  
347 resource. Conflicts occurring for example between agricultural production or use as a platform  
348 for construction and functioning as an environmental buffer and store of water.

349 Concerns expressed by Karlen *et al.* (Karlen et al. 2001) emphasise the lack of inclusion of soil  
350 functions and meaningful indicators for those functions. Karlen *et al.* (Karlen et al. 2001)  
351 discussed the difficulty in interpreting indicators for various soil functions that can be used to  
352 track soil quality over time. Letey *et al.* (Letey et al. 2003) expressed that soil quality has a  
353 dysfunctional definition, that there are problems in the approach to quantification of soil quality.

354 Letey *et al.* (Letey et al. 2003) agreed with Sojka and Upchurch (Sojka and Upchurch 1999) who  
355 stated there is a failure of soil quality to integrate simultaneous soil functions which often require  
356 contradictory soil properties and management, for example high levels of mineralisable  
357 nitrogen/ low levels of nitrate nitrogen and levels of available nitrogen to crops (Karlen et al.  
358 1997b).

359 Sojka *et al.* (Sojka et al. 2003) expresses many of the concerns in earlier literature including  
360 those about the elusiveness and value-laden nature of the soil quality definition. The work  
361 reiterates concerns expressed by earlier studies into the often multiple functions of soils that  
362 occur simultaneously and that development of soil quality assessment has diverted research  
363 and management away from developing improved management to solve problems.

364 There have been issues defining the boundaries of assessment when evaluating soil quality.  
365 Rather than focusing on ability to carry out specific functions increasingly issues such as the  
366 environmental cost of agricultural production and the potential for reclamation of degraded soils  
367 is considered when discussing soil quality (Singer and Ewing 2000).

## 368 **Soil Functions**

369 As described by critics of soil quality, soil can have multiple functions. Sojka and Upchurch  
370 (Sojka and Upchurch 1999) describe how soil performs several functions simultaneously not  
371 several functions separately. Letey *et al.* (Letey et al. 2003) described how soil may perform  
372 well for one function and badly for another function that is occurring simultaneously. Letey *et al.*  
373 (Letey et al. 2003) describes how Karlen (Karlen et al. 1997a) acknowledged problems with  
374 assessing soils multiple functions when reviewing Doran and Werner (Doran and Werner 1990)  
375 where the soil management was affecting the rating and performance of two functions.

376 There is considerable overlap in the functions of soil as expressed in the literature, though  
377 expressed in different wording the soil functions expressed by different sources cover the same  
378 areas:

- 379       • Maintains biological activity and productivity (Doran and Parkin 1994; Karlen et al.  
380            2006b; Larson and Pierce 1991; Loveland and Thompson 2002), serves as a medium for plant/food/fibre growth (European Commission (EC)  
381            2006b; Larson and Pierce 1991; Loveland and Thompson 2002), supports plant  
382            productivity/yield (Karlen et al. 1997b), supports human/animal health (Doran and  
383            Parkin 1994; Karlen et al. 1997b);
- 384       • Acts as a biodiversity and gene pool (European Commission (EC) 2006b; Lal 1997; Lal  
385            1998; Montanarella 2008)
- 386       • partitions and regulates water/solute flow through the environment (Karlen et al. 1997a;  
387            Larson and Pierce 1991);
- 388       • serves as an environmental buffer or filter (European Commission (EC) 2006b; Larson  
389            and Pierce 1991; Loveland and Thompson 2002), maintains environmental quality  
390            (Doran and Parkin 1994; Karlen et al. 1997a)(Karlen et al. 1997a){181 Karlen, D.L.  
391            1997})(Karlen et al. 1997a);
- 392       • cycles nutrients, water, energy and other elements through the biosphere (Karlen et al.  
393            1997a);
- 394       • supports socioeconomic structure, cultural and aesthetic values, (Lal 1998) and a  
395            platform for human activities and landscape (European Commission (EC) 2006b;  
396            Sombroek and Sims 1995)(Sombroek and Sims 1995){231 Sombroek, W.G.  
397            1995})(Sombroek and Sims 1995);
- 398       • an archive of heritage (European Commission (EC) 2006b; Lal 1998; Sombroek and  
399            Sims 1995).

400   Lal (Lal 2007) reviewed the scientific literature and classified soil function research into the  
401   themes of food security, bio fuels production, waste disposal, carbon, farming, and water  
402   resources.

403   The soil functions that have been suggested in the literature generally fit in with the definition of  
404   ecosystem services, the benefits that human beings gain from natural ecosystems as defined  
405   by Daily (Daily 2000). Ecosystem services can be categorised as the production of goods,

406 regeneration processes, stabilizing processes, life fulfilling processes, and preservation of  
407 options (Daily 2000).

408 Soil quality has connections to other environmental mediums, and the biological systems that  
409 are supported by the soil. The interconnections can be described as direct or indirect, as  
410 detailed in Figure 1.

411 **Figure 1 Connections between soil health and the environmental and biological systems supported by soil. Direct**  
412 **(1a-1d) and Indirect (2a-4a) quality and health connections of soil to air, water, plants, animals, and people (after,**  
413 **Harris et al., 1996).**

414 The ecological risk assessment process (also referred to as environmental risk assessment)  
415 evaluates the potential significance of impacts in regard to likely effects upon ecological  
416 receptors as the result of exposure to a stressor (Hope 2006; Suter 2007). Ecological risk  
417 assessment includes evaluation of ecological aspects for each soil use to formulate soil  
418 screening values based upon soil use (European Chemicals Bureau 2002; Quercia et al. 2002).

419 Toxicity of contaminated soils has become a major focus in ecological risk assessment, and can  
420 be used to set generic or site-specific soil quality guidelines and for guiding on-site  
421 contamination mapping and remediation (Burns et al. 1996; Suter 2000). Toxicity data informing  
422 ecological risk assessment can be comprised of single-chemical or single material data;  
423 ambient media toxicity, site-specific insitu or laboratory toxicity tests of contaminated media; or  
424 biological survey, site specific sampling or observations of organisms, populations or  
425 communities in contaminated areas(Suter 2000). Increasingly use of single bioassays have  
426 been found not to provide a full enough picture of the quality of the environment, therefore  
427 battery tests of a number of bioassays of different animal and plant species from different  
428 trophic levels have been used to reduce uncertainty(Bierkens et al. 1998; Juvonen et al. 2000).  
429 Although bioassays have been used extensively in assessing the effects of contaminants in soil,  
430 use in assessment of other aspects of soil quality have been limited (Schloter et al. 2003;  
431 Seybold et al. 1998). It has been suggested that bio assays should not be used as the only  
432 measure of soil quality. The response of a bioassay is a function of many confounding non-soil  
433 factors in addition to soil quality. Soil sustainability and the effects of management should be



434 determined by measuring soil properties and processes directly (Burger 1996; Seybold et al.  
435 1998).

#### 436 **Soil Quality Indicators**

437 Soils have chemical, biological and physical properties that interact in a complex way to give  
438 soil its capacity to function (Seybold et al. 1998). Owing to the wide scope of functions  
439 encompassed in the definition of soil quality, it is not possible to directly assess soil quality  
440 (Burger and Kelting 1999; Ditzler and Tugel 2002; Doran and Parkin 1994). Existing methods  
441 have first identified the functions of interest and selected indicators to observe and measure,  
442 inferring the ability of the soil to perform that function (Ditzler and Tugel 2002). The use of  
443 indicators of soil quality has been discussed widely in the literature and minimum data sets  
444 suggested in a number of studies (Arshad and Cohen 1992; Bouma 1989; Doran and Parkin  
445 1994; Larson and Pierce 1991).

446 Common to the minimum data sets of soil quality indicators suggested in the literature is that  
447 they include a combination of physical, chemical and biological soil properties. This suggests  
448 that for a soil to function effectively all three factors must be addressed, as illustrated in Figure 2  
449 (Ditzler and Tugel 2002; Stenberg 1998). These classes of properties match the physical,  
450 chemical and biological soil degradative processes, mechanisms that set in motion the  
451 degradative trends (Lal 1997). Typically soil assessment has looked at chemical properties,  
452 measured using chemical indicators, or has looked at properties and indicators specific only to  
453 the function of interest. Holistic soil quality attempts to integrate the three types of soil  
454 properties (Karlen et al. 2003). There is rarely an exact match between function and indicator,  
455 with a function often supported by a number of soil properties and a soil property or process  
456 being relevant to several soil attributes or functions simultaneously (Schoenholtz et al. 2000).  
457 Correspondingly categories of soil properties (chemical, biological, physical) do not exactly align  
458 with the soil functions. The complex interactions between soil properties, indicators, and soil  
459 functions require that for assessment of soil quality integration of soil properties into the soil  
460 property categories is necessary.

461 **Figure 2 Relationship between soil quality factors, soil quality and environmental quality (after Andrews et al.,**  
462 **2002).**

463 Burger and Kelting (Burger and Kelting 1999) suggested that good indicators should have the  
464 following features:

- 465 • possess an available baseline against which to compare change;
- 466 • provide a sensitive and timely measure of a soil's ability to function;
- 467 • be applicable over large areas but specific enough to be sensitive;
- 468 • be capable of providing a continuous assessment;
- 469 • be inexpensive, easy to use, collect, and calculate;
- 470 • discriminate between natural changes and those induced by management;
- 471 • be highly correlated to long-term response; and
- 472 • be responsive to corrective measures.

473 The increase in the value of basic data by using it to estimate more expensive and laborious to  
474 obtain data were named by Bouma (Bouma 1989) as pedotransfer functions (PTFs) and defined  
475 as translating data we have into what we need. Computer programs such as Soilpar (Acutis and  
476 Donatelli 2003) and Rosetta (Schaap et al. 2001) were developed to estimate the soil hydraulic  
477 properties from surrogate soil data such as soil texture, bulk density, organic carbon, soil pH,  
478 and cation exchange capacity. Pedotransfer functions were the basis for the development of soil  
479 interference systems (SINFERS) that take measurements known with a level of certainty and  
480 infer data that is not known with minimal inaccuracy using logically linked predictive functions  
481 (pedotransfer functions) (McBratney et al. 2002).

## 482 **Risk Based Approach to Soil Quality**

483 Regulatory bodies are increasingly using risk based approaches to environmental decision  
484 making (Pollard et al. 2002). Such risk based decision making does, to some extent, include  
485 soil quality, however this is predominantly in the assessment and management of soil  
486 contamination, just one part of soil quality. Although use of risk based methods have not been  
487 extensively used to assess other aspects of soil quality, the methods and decision making  
488 processes have potential for wider application in soil quality assessment.

489 In such current soil contamination risk based assessment the effect of contaminants on humans  
490 and ecosystems is investigated, rather than using the total contaminant concentration in the soil  
491 (Madejón et al. 2006). The source- pathway- receptor pollutant linkage is used in environmental  
492 risk assessment and used extensively in the assessment of risks from contaminated land  
493 (Nathanail and Bardos 2004). In assessment of risk from contaminated land a potential for risk  
494 exists if there is a source of contaminants, a receptor sensitive to the contaminant at the level of  
495 exposure present, and a pathway linking the two. A potential risk is said to exist, only if all three  
496 (source, pathway and receptor) elements are present (Hardisty and Özdemiroğlu 2005).

497 Definition of a soil's quality in terms of the source- pathway- receptor linkage allows potential for  
498 assessment in terms of the risk posed to or from soil to other environmental mediums, and  
499 allows the inclusion of soils often multiple functions. Although a function of soil is to act as an  
500 environmental filter (European Commission (EC) 2006b; Larson and Pierce 1991; Loveland and  
501 Thompson 2002) soil has the ability to act as a source, a pathway and a receptor to  
502 contaminants. All three aspects being affected by indicators of properties regularly used to  
503 determine soil quality, the linkage, processes and properties are detailed in table 4.

504 **Table 4 Interaction between risk linkage, soil process, and soil properties**

505 A contaminant is a substance that is not naturally present in the environment or is present in  
506 concentrations with the potential to adversely alter an environment (Saunier and Meganck  
507 2009). Soil can act as a primary source of contamination, that is a direct flux, or a secondary  
508 source by the release of contaminants that have previously affected the soil. The potential of  
509 soil to act as a source is highly variable due to the heterogeneous nature of the soil both with  
510 regard to controlling soil properties but also the chemicals present and their concentration. The  
511 nature of soils being dynamic means that there is a flux of chemicals across soil depths (i.e.  
512 movement from topsoil to sub soil and the opposite) and spatially. There are constant changes  
513 in the soil state due to natural leaching processes and interactions/ fluxes between soil water,  
514 soil gas and the organic and mineral components of soil.

515 Soils functioning as a source can occur when water travels through the soil matrix, combined  
516 with carbon dioxide to form a weak carbonic acid, acting as a pathway. As the weak carbonic  
517 acid moves through soil, small amounts of naturally occurring minerals and man-made  
518 chemicals held within the soil matrix are dissolved and held in solution, a process known as  
519 leaching (Neung-Hwan and Richter 2004). Potential receptors can include ground and surface  
520 waters, drinking water, humans, animals, services, industrial processes, and household  
521 appliances. Calcium and magnesium leached from the soil is a cause of “hard water” making  
522 soaps and detergents less effective and effecting water-using appliances (Boyd 2000). In small  
523 doses fluoride, iron, and copper can be beneficial to human health but in larger doses can be  
524 harmful (Bogden and Klevay 2000). Elements such as lead, arsenic, and mercury are of  
525 concern to human health (Alloway 1994). Although carbonic acid is the main leaching agent in  
526 natural systems leaching is dependent on the type, quantity and characteristics of the leaching  
527 agent; there are many natural and anthropogenic lixiviation agents including sulphuric acid, and  
528 humic or fulvic acids (Johnson et al. 1979). Alternative leaching agents have been researched  
529 extensively in the remediation of contaminated soils (Dirilgen et al. 2010; Johnson et al. 1979).  
530 Common soil properties that determine the rate and quantity that material is leached from soils  
531 include the cation exchange capacity (C.E.C.), crop/ plant cover, soil texture, soil permeability,  
532 soil organic matter, soil pH. Leaching is also dependent on climatic factors such as temperature  
533 and precipitation. Due to the number of controlling factors and the large variability in these  
534 properties soils have a resultant highly variable susceptibility to leaching,

535 In addition, soil can act as a source of contaminants through pathways such as the ingestion of  
536 plant or animal products that have assimilated contaminants from the soil, with humans or  
537 animal health as receptors (Collins et al. 2006; Earl and Kearney 2000; Michaud et al. 1991;  
538 Sjöström et al. 2008). Soil properties which affect the bioavailability of contaminants include soil  
539 pH, soil texture, soil C.E.C., soil organic matter, porosity, bulk density, water content, hydraulic  
540 conductivity, and soil temperature (Chiou et al. 2001; Hung and Mackay 1997; Massas et al.  
541 2002; Ryan et al. 1988; Topp et al. 1986; Trapp and Matthies 1995; Travis and Arms 1988).  
542 Plants can modify the rhizosphere by production of organic acids and therefore may exclude or  
543 accumulate contaminants selectively (Glick 2004).

544 There is also potential for the ingestion of contaminated soil directly by humans (especially  
545 children) and animals (Beyer and Connor, E. E. Gerould, S. 1994; Calabrese et al. 1997). In this  
546 case the soil would be a source and a pathway to the receptor. In this case a physiologically  
547 based extraction test (PBET) can relate bioavailability to soil properties such as pH, C.E.C., Fe-  
548 and Mn-oxide content, particle size distribution, and total organic and inorganic C, water  
549 content, bulk density, porosity (Stewart et al. 2003a; Stewart et al. 2003b; Thompson et al.  
550 1992). The atmosphere can act as a pathway of contaminants from a soil source where there is  
551 a vapour transfer of contaminants to a receptor of humans, animals or buildings (Cowherd et al.  
552 1985; Jury et al. 1990; Little et al. 1992). Soil vapour transfer is influenced by climatic and  
553 meteorological factors as well as soil properties of total porosity unsaturated zone, water filled  
554 porosity unsaturated zone, organic carbon fraction, soil dry bulk density, soil permeability,  
555 moisture content, soil texture as well as soil temperature (Evans et al. 2001; Fischer et al.  
556 1996). Besides vapour transfer of contaminants other soil to atmosphere transfers exist such as  
557 radon. Radon-222 is a natural radioactive gas that is produced from the decay of radium  
558 ( $^{226}\text{Ra}$ ), itself produced from the decay of uranium, found naturally in small, but hererogenous,  
559 quantities in all soils and rock (Appleton 2007). Exposure to radon indoors is the largest  
560 contributor to radiation exposure and has been linked to lung cancer (Darby et al. 1998; Miles  
561 and Appleton 2005). Soil gas has been identified as the main source of indoor radon (Nazaroff  
562 and Sextro 1989). Radon potential is the result of a combination of the properties of the soil,  
563 and the underlying geology such as the radium concentration and its distribution in the soil, the  
564 soil porosity, permeability, moisture content and also meteorological variables (Winkler et al.  
565 2001).

566 Soil, as mentioned above, has the potential to act as a pathway. An example of this is the  
567 creation of soil particulate matter by the process of wind erosion (Cave et al. 2009; Macleod et  
568 al. 2006). The particulate matter can carry contaminants to receptors such as humans or other  
569 organisms. Soil properties affecting wind erosion include soil erodible fraction, soil crust, soil  
570 roughness, soil texture, and bulk density, plant factors that can affect wind erosion include  
571 growing crops and flat and standing residues in addition to climatic factors (Fryrear et al. 1998;  
572 Fryrear et al. 2000). Another example is the soil migration, plant uptake and volatilisation of

573 radio-selenium material through from contaminated groundwater, dependent on the soil redox  
574 status (Ashworth and Shaw 2006).

575 Soils can also be a receptor, especially when they are perceived as a product, or a media that  
576 needs to be protected from pollution. Sources of soil contamination are diverse and can be  
577 defined as point source or non point source (Rawlins et al. 2005). Point sources are those  
578 where the source of pollution is clearly identifiable and can be traced back to the specific source  
579 such as leakages from underground storage tanks (Naidu et al. 2006a). Point source pollution is  
580 typically associated with acute pollution incidents and the assessment of this falls under the  
581 remit of traditional contaminated land investigation. With an increase in environmental  
582 legislation and environmental awareness since the 1970s and 1980s point source pollution has  
583 come under increasingly strict control. There has consequently been an increasing emphasis on  
584 non point source pollution. The historic definition of soil quality has related to non-point or  
585 diffuse pollution and its effects on the ability of soil to function. The effects of anthropogenic  
586 contamination can be assessed through monitoring of soil quality indicators over time. Non  
587 point source pollution of soils is where there is no obvious single point source of discharge and  
588 the contamination is widespread in nature (Naidu et al. 2006b). This type of contamination,  
589 when compared to point source contamination, can typically be described as chronic pollution  
590 and can be associated with a decline in soil quality. Non point contamination sources that have  
591 the potential to effect upon soils ability to function can include aerial transport and deposition of  
592 contaminants from a number of anthropogenic activities such as transport and heavy industry  
593 (Facchinelli et al. 2001) fertiliser and pesticide application (Mostaghimi et al. 2001; Torbert et al.  
594 2002), and use of soil amendments (Voulvoulis and Lester 2006). The susceptibility of soils to  
595 act as a receptor to contaminants depends not only on the presence of point or diffuse sources  
596 of pollution and the concentration of contaminants but on a number of soil properties and other  
597 factors. Susceptibility of soils to act as a receptor can be defined as the potential of soils to be  
598 effected by contaminants, this either by limiting build up of contaminants, by buffering  
599 contaminants, or degrading them (Glazovskaya 1990; Karlen et al. 2001).

## 600 **Discussion**

601 The range of definitions of soil quality has developed since its initial inception by Alexander  
602 (Alexander 1971), notably by the inclusion of consideration of the soil function. Since the initial  
603 activity however, development has slowed and there have been a number of challenges to the  
604 definition of soil quality. Recent concerns are due to the failure of soil quality assessment to  
605 integrate simultaneous soil functions which often require contradictory soil properties and  
606 management (Letey et al. 2003; Sojka and Upchurch 1999; Sojka et al. 2003).

607 Soil quality should not be defined solely by the ability of soils to perform a single function (Sojka  
608 and Upchurch 1999). It should include the potential to perform the multiple functions that are  
609 desired of it, by humans, ecosystems and to be able to successfully provide ecosystem  
610 services. It should also encompass that the soil can act as a source or pathway to other  
611 environmental media or soil functions.

612 Such a multiple functional soil quality definition takes into account the growing need for  
613 assessment of soil quality to incorporate the multiple and possibly conflicting functions of soils  
614 (Letey et al. 2003). Therefore soil quality assessment should be improved to meet changes in  
615 attitudes to soil and the environment being more than just a resource.

616 Soil quality assessment, taking into account the multiple functions that soil provides, normally  
617 utilises a selection of indicators specific to the soil functions of interest (Ditzler and Tugel 2002).  
618 To that extent, dynamic indicator systems, whether selected using expert opinion or other  
619 methods such as principal component analysis, can create a good data set for assessment of  
620 soil quality. However even then, such methods cannot effectively compare soil quality between  
621 different soils of different functions. In addition, they often require indicators which are  
622 expensive and difficult or laborious to collect data for. Although there may be conflicting  
623 functions that soil is required to carry out, there is a notion that this does not happen in many  
624 circumstances and that simultaneity of soils functions can take place. While soils function may  
625 determine ideal values for soil properties, there is overlap between the soil properties necessary  
626 for the assessment of the ability to carry out a specific function and these properties can be  
627 included in a minimum dataset.

628 Following a risk based approach such methods could be used initially to rank sites according to  
629 a specified soil function, but could not allow for the identification and prioritisation of areas for  
630 further investigation required for cross functional improvements. To improve such a screening  
631 step, cross functional indicators could be developed to enable ranking and prioritisation across  
632 different soil functions to inform further detailed investigation and risk assessment. The use of  
633 soil indicators in soil protection and soil quality assessment in legal frameworks is currently  
634 limited across Europe. The European environment agency has mapped soil quality of some  
635 southern European states, using indices based on soil parent material, soil depth, soil texture  
636 and the slope of the land surface. The indicator system appears to focus on desertification,  
637 where the soil has lost part of its capability to support human communities and ecosystems  
638 (European Environment Agency 2009). The UK Environment Agency undertook research into  
639 soil quality indicators, and suggested using total above-ground biomass production, total below-  
640 ground soil organic carbon, topsoil pH, buffering capacity, keystone species, soil microbial  
641 diversity, soil surface condition, extent and depth of ploughing, area of land taken for mineral  
642 workings (Loveland and Thompson 2002; Merrington et al. 2006). In a review of this work in  
643 2006, the minimum data set was revised to soil organic carbon, total nitrogen, Olsen P,  
644 available and total copper (Cu), nickel (Ni) and zinc (Zn), bulk density, and pH. This minimum  
645 dataset has a bias toward soils chemical factors.

646 The cross functional indicators should collect information on soils chemical, physical and  
647 biological properties and the associated factors that determine soils quality. Specific indicators  
648 used would depend on the method of data collection, sampling strategy, available resources,  
649 desired decision making output, and scale of application. Assessment must take place if a  
650 desired level of data quality will be met for indicators selected to allow adequate evaluation of  
651 the soil quality. However independent of factors controlling the amount of information collected  
652 there is a minimum dataset that will be required for assessment of soil quality. The minimum  
653 dataset is likely to include pH, soil texture, organic carbon, infiltration rate, root presence, plant  
654 cover, soil odour, soil organism presence and diversity, soil colour, evidence of anthropogenic  
655 disruption (i.e. presence of construction material, coal/ soot) and penetrability. In addition  
656 important information about landuse and habitat will provide useful information. This information



657 will likely provide more useful information when investigated spatially and not necessarily at a  
658 site specific level. The scale at which these indicators would be applied depends on the spatial  
659 variation of soil properties, and research into this should be undertaken in the design stage of  
660 the system. Such method should be built upon significant experience of the use of screening  
661 tools in environmental and other applications.

662 Detailed environmental assessment is often informed by the use of screening tools. Screening  
663 tools are generally designed to gather a large amount of information quickly and at a low cost.  
664 Screening tools are used extensively in many areas including healthcare, product development,  
665 international development, and environmental quality (Calantone et al. 1999; Department for  
666 International Development (DFID) 2003; Elmore et al. 2005). Screening tools used in the  
667 environment include flood risk (Department of Communities and Local Government (DCLG)  
668 2006), site prioritisation and regulation (Environment Agency 2009), contaminated land  
669 (Environmental Protection Agency 1996; Pollard et al. 2004), air quality (Department of the  
670 Environment (DoE) 1997), water quality (Alvarez-Guerra et al. 2009), environmental fate  
671 (Duarte-Davidson and Jones 1996; Wilson et al. 1996) and chemical risk (Pan et al. 2009).  
672 Similarly, the development of a ranking and prioritisation method for soil quality assessment has  
673 the potential to help toward implementing current and future soil regulation, for example the soil  
674 thematic strategy (European Commission (EC) 2006b) and the likely requirements of the SFD  
675 (European Commission (EC) 2006c; Van-Camp et al. 2004). The development of cross  
676 functional soil indicators could facilitate direct comparison of soils and as such allow  
677 prioritisation of soils flagged for further attention. Such indicators should be standard for every  
678 soil assessed, allowing expert knowledge of the methodologies by personnel carrying out  
679 multiple assessments with a resulting decreased level of error. The output of such assessment  
680 should still provide all the information incorporated and not just be a single index figure of soil  
681 quality. It should aim to provide evidence collated into a number of indices; that could be used  
682 by specialists to inform further decision making.

683 The selection of cross functional soil indicators, development of their indices and methods for  
684 interpreting them are all very challenging tasks. The use of Pedotransfer functions as predictive

685 functions of certain soil properties when determining soil quality indicators could support  
686 efficient assessment of soil quality (Bouma 1989; Jana et al. 2007). For example, soil name,  
687 topsoil textural class, land use, and mean temperature are often used to facilitate the estimation  
688 of the topsoil organic carbon (Daroussin and King 1999). A compiled cross functional soil  
689 indicator dataset could also be complemented by data from other sources to make estimates of  
690 other soil properties. Use of soil inference systems can be used to make estimates of  
691 expensive, difficult to obtain or unavailable indicators from the less expensive and easier to  
692 obtain broad soil indicators (McBratney et al. 2002).

693 In addition, previous soil quality assessment methodologies have not assessed soil organisms  
694 in the same detail as soil physical and chemical properties. The presence and types of soil  
695 organisms can facilitate cross functional screening indicators and their use has great potential in  
696 soil quality assessment and remediation (Héry et al. 2008; Singer et al. 2001). Such as  
697 approach is in accordance with other environmental quality assessments that incorporate  
698 ecological risk in their frameworks (Ashton et al. 2008).

699 The system of prioritisation of soils using measurement of cross functional indicators suggested  
700 in this paper does not aim to replace current methodologies that are required for risk  
701 assessment. It is not an alternative to the Triad approach that requires the simultaneous and  
702 integrated deployment of chemical, toxicological and ecological lines of evidence for risk  
703 assessment (Chapman 1986; Rutgers et al. 2001). On the contrary, the results of this  
704 screening step aim to support the weight of evidence approach (Burton et al. 2002; Chapman et  
705 al. 2002; Interdepartmental Group on Health Risks from Chemicals 2002) by identifying areas of  
706 concern, focusing risk assessment investigations to reach a conclusion about an environmental  
707 system or stressor.

708 Such a screening option has also the potential to facilitate long term soil quality monitoring  
709 programmes. Although soil surveys have been carried out, these generally are not repeated in  
710 time and therefore qualify as inventories rather than monitoring programs (Department for Food  
711 and Rural Affairs (DEFRA). 2003). Monitoring programs currently generally rely on repeat visits  
712 to a number of preselected sites e.g. Countryside Survey (Carey et al. 2008) and the

713 Environmental Change Network (Environmental Change Network 2009). Existing monitoring  
714 and inventory programs, especially those carried out before 1990, have largely omitted urban  
715 soils due to the emphasis of the programs use on mineral extraction, wanting to exclude  
716 anthropogenic pollution (Johnson and Ander 2008). There are also issues with difficulty of  
717 accessing sites, and the heterogeneity of the urban environment. A prioritisation method that  
718 repeats surveys over time has the potential to be used to monitor soils and to provide data for  
719 areas where lacking from other programs, however will not replace existing monitoring  
720 programs. Such methods have the potential to fill in gaps in existing monitoring regimes and  
721 inform the need for further function specific assessment, potentially providing useful information  
722 to meet current and future regulations relating to soil and their protection. Methodologies to  
723 assess the impacts of land management practices and pollution on soil need to be developed,  
724 with this leading to practices preventing and managing degradation of soils. Broad cross  
725 functional indicators might be more appropriate for such use.

726 Soils do not have a static state and properties can vary significantly both spatially over small  
727 distances, and over time. Due to the dynamic state of the system a single measurement in  
728 space or time can be problematic in evaluation. There is a need to assess the dynamics of soil  
729 quality associated with varying soil properties and intrinsic cycles and trends associated with the  
730 spatial and temporal variability of soil properties and soil quality, which can be evaluated using  
731 methods such as control charts (Larson and Peirce 1994). There is a need to relate clearly how  
732 the dynamic state of soils influences its ability to function, and ultimately the soil quality. Use of  
733 suggested cross functional soil quality indicators could allow repeat measurements can be  
734 affordably collected. Collection of repeat indicator measurements can allow determination of  
735 how spatial and temporal variability of soil properties can influence soil quality. It is with this  
736 knowledge that it can be adequately determined if soil quality is changing due to natural  
737 variation or is in fact subject to decline.

738 Screening methodologies could be developed with the potential to act as the basis for collection  
739 of soil characteristics by non specialists, allowing for even more cost effective, relatively quick,  
740 easy screening of soil characteristics. Use of a larger group of personnel makes regular

741 repeated measurements of soils more feasible than solely using experts; however it would  
742 require considerable organisation and commitment from participants to provide more than just  
743 one off data. This could however be accomplished using keen specialist groups.

744 In general, based on the review undertaken in this work, further research is required to develop  
745 an effective methodology/ framework for soil quality assessment under emerging regulatory  
746 requirements. As discussed, research is needed to better establish the spatial and temporal  
747 variation in soil properties this allowing the scale of application of soil quality assessment  
748 methods to be determined. There is a clear need to establish the relationship between soil  
749 organisms, soil properties and soil quality; this has the potential benefit of identifying organisms/  
750 species that can be used as holistic bioindicators of soil quality or of more specific threats for  
751 example soil contamination. There is an ongoing need to establish linkages between soil  
752 indicators, effectively allowing further development of pedotransfer functions allowing the most  
753 resource efficient establishment of soil properties. Development of a method for assessment of  
754 the collected information needs to build upon the significant application of environmental risk  
755 assessment and screening decision making; research will need to draw upon expert knowledge  
756 of the soil system and interactions between the biological, chemical and physical factors.  
757 Methodology development will need considerable calibration with existing datasets and field  
758 testing in a range of situations from severely degraded sites to those considered pristine.

759 As well as soil regulation, screening and prioritisation of sites could have the ability to fit well  
760 with the modern needs of environmental protection and policy, complimenting the recent move  
761 to a holistic approach to environmental appraisal.

## 762 **Conclusion**

763 There are a number of new and emerging regulations which aim to protect soils and prevent soil  
764 degradation. Soil degradation is often seen as closely related to, and effecting, soil quality. In  
765 order to protect soils from a decline in soil quality and ultimately from soil degradation it was  
766 necessary to improve the understanding of the terms soil and soil quality and to review how soil  
767 quality is assessed.

768 This paper has reflected that assessment of soil quality that has integrated soils function has  
769 not achieved consensus in the scientific community. Assessment of soil quality with respect to  
770 its function can rely on expensive and time consuming methods. The use of different indicators  
771 chosen dependent on the soil function is potentially challenging with regard to comparison of  
772 quality between soils with different functions. A method to evaluate and prioritise further  
773 investigation and risk assessment could be developed that uses cross functional indicators.  
774 Use of cross functional indicators could prove a more effective method to assess soils ability to  
775 meet the multiple and often conflicting requirements of it. The use of indicators in this way  
776 should significantly contribute to the knowledge based approach to soil monitoring and inform  
777 soil protection and sustainable use.

778 A standardised methodology for the assessment and comparison of many soils with different  
779 and multiple soil functions requires the development of set of a broad soil indicators. Indicators  
780 that are selected for inclusion in a site identification and prioritisation method should be cross-  
781 functional, that is applicable to many soil functions. Soil quality indicators currently in use in  
782 existing soil quality assessment tools and monitoring programmes should be assessed for their  
783 ability to act as cross-functional indicators and inclusion in Pedotransfer functions.

784 The use of screening methods using broad soil indicators that do not rely upon specific soil  
785 functions has the ability to fit well with the modern needs of monitoring within soil regulation, as  
786 well as general environmental protection and policy. It has the potential to provide information to  
787 assist in compliance with legislation requiring monitoring or identification of geographical  
788 risk/priority areas such as the proposed EU Soil Framework Directive and the EU Soil Thematic  
789 Strategy. Such methods could highlight areas requiring further attention and threat dependent  
790 assessment for example detailed identification of areas requiring special protection from  
791 erosion, organic matter decline, compaction, salinisation, landslides, and acidification, using  
792 indicators specific to the threat in question. There have been problems reaching agreement on  
793 the content of the proposed Soil Framework Directive partly because of the different methods  
794 used in European member states and the requirement to identify risk/priority areas requiring  
795 special protection from erosion, organic matter decline, compaction, salinisation, landslides and

796 acidification. A systematic approach to identification of areas of concern could help with this  
797 requirement and allow progress to be made on development of the directive.

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802 **Table 1 Definitions of soil in legislation and literature**

Soil Definition	Jurisdiction	Reference
The upper layer of the earth's crust, as far as this layer fulfils the soil functions, and including its liquid components (soil solution) and gaseous components (soil air), except groundwater and beds of bodies of water	Germany	Federal Ministry for the Environment Nature Conservation and Nuclear Safety 1998
The solid part of the earth including liquid and gaseous compounds and organisms therein	Netherlands	VROM (The Netherlands Ministry of Housing, Physical Planning and the Environment) 1986
Soil is the zone where plants take root, the foundation for terrestrial life and the basis for a large amount of economic production and varies in depth from a few centimetres to several meters	UK	Environment Agency 2004
Solid part of the earth, including the groundwater and the other components and organisms that are present in it	Belgium – Flanders	Public Waste Agency of Flanders (OVAM) 2007
Soil is generally defined as the top layer of the earth's crust, formed by mineral particles, organic matter, water, air and living organisms	EU	European Commission (EC) 2006b
The top layer of the Earth's crust situated between the bedrock and the surface. The soil is composed of mineral particles, organic matter, water, air and living organisms	EU	Council of the European Union 2009
(i)The unconsolidated mineral or organic material on the immediate surface of the earth that serves as a natural medium for the growth of land plants.  (ii)The unconsolidated mineral or organic matter on the surface of the earth that has been subjected to and shows effects of genetic and environmental factors of: climate (including water and temperature effects), and macro- and microorganisms, conditioned by relief, acting on parent material over a period of time. A product-soil differs from the material from which it is derived in many physical, chemical, biological, and morphological properties and characteristics	N/A	Soil Science Glossary Terms Committee 2008
(i)A dynamic natural body composed of mineral and organic solids, gases, liquids, and living organisms  (ii)The collection of natural bodies occupying parts of the Earth's surface that is capable of supporting plant growth and that has properties resulting from the integrated effects of climate and living organisms acting upon parent material, as conditioned by topography, over periods of time	N/A	Brady and Weil 2008



804 **Table 2 Examples of main contaminated land legislation in EU member states**

<b>State</b>	<b>Act</b>	<b>Reference</b>
Belgium – Franders	Soil Remediation Decree, 2006	Public Waste Agency of Flanders (OVAM) 2007
Belgium-Brussels	Ordonnance du 5 mars 2009 relative à la gestion et à l'assainissement des sols pollués	Brussels Ministre de l'Environnement 2009
Belgium-Walloon	Décret du 5 décembre 2008 relatif à la gestion des sols	Gouvernements de communauté et de région-Region Wallonne 2009
Germany	Federal Soil Protection Law, 1998	Federal Ministry for the Environment Nature Conservation and Nuclear Safety 1998
Italy	Ministerial Decree 471 on the remediation of polluted sites, 1999	Governo Italiano 1999
Netherlands	Soil Protection Act, 1987 (Amended 2008)	VROM (The Netherlands Ministry of Housing, Physical Planning and the Environment) 1986
Spain	Royal Decree on contaminated soils, 2005	Spanish Central Government 2005
Sweden	Environmental Code, 1999	Swedish Ministry of the Environment 1999
UK- England	Contaminated Land (England) Regulations 2006	UK Government 2006
UK- N. Ireland	The Waste and Contaminated Land (1997 Order) (Commencement No. 6) Order (Northern Ireland) 2002	Northern Ireland Executive 2002
UK- Scotland	The Contaminated Land (Scotland) Regulations 2005	The Scottish Government 2005
UK- Wales	Contaminated Land (Wales) Regulations 2006	National Assembly for Wales 2006

805 **Table 3 Development of the definition of soil quality**

<b>Soil Quality Definition</b>	<b>Year</b>	<b>Reference</b>
The sustained capability of a soil to accept, store and recycle water, nutrients and energy	1984	Anderson and Gregorich 1984
The state of existence of soil relative to a standard, or in terms of a degree of excellence	1991	Larson and Pierce 1991
The capacity of a soil to function, within ecosystem and land use boundaries, to sustain productivity, maintain environmental	1994	Doran and Parkin 1994

quality, and promote plant and animal health		
Ability of soil to perform or function according to its potential, and changes over time due to human use and management or to unusual events.	1995	Mausbach and Tugel 1995
The capacity of a specific kind of soil to function, within natural or managed ecosystem boundaries, to sustain plant and animal productivity, maintain or enhance water and air quality, and support human health and habitation	1997	Karlen et al. 1997a
Encompassing an indefinite (open) set of tangible or dispositional attributes of the soil. These attributes may be substituted for or supplemented by other attributes without needing to change the term. Therefore it is a vessel to contain what is assigned to it. The attributes assigned to the term will differ among soil and the various demands, because the term is influenced by value judgements	2000	Patzel et al. 2000

806 **Table 4 Interaction between risk linkage, soil process, and soil properties**

Linkage	Process	Soil Properties
Source	Leaching	Cation exchange capacity, crop/ plant cover, soil texture, soil permeability, soil organic matter, soil pH
	Ingestion of plant or animal products	pH, soil texture, cation exchange capacity, soil organic matter, porosity, bulk density, water content, hydraulic conductivity, soil temperature
	Direct ingestion	pH, cation exchange capacity, Fe- and Mn oxide content, particle size distribution, total organic and inorganic carbon, water content, bulk density, porosity
	Vapour transfer	Total porosity of the unsaturated zone, water filled porosity unsaturated zone, organic carbon fraction, soil dry bulk density, soil permeability, moisture content, soil texture, soil temperature
	Radon Exposure	Radium concentration and its distribution in the soil, soil porosity, permeability, moisture content
Pathway	Wind erosion	Soil erodible fraction, soil crust, soil roughness, soil texture, bulk density, crop/ plant cover
	Migration, plant uptake and volatilisation of radio selenium	Soil redox status
Receptor	Point or diffuse source pollution (natural and anthropogenic)	Buffering capacity, soil microbes, pH and redox conditions, occurrence of carbonates, Fe- and Al- hydroxides, inorganic substances capable of chemisorptions, content and composition of organic substances, clay content and mineralogy, hydrolytic acidity, cation exchange capacity, amount of exchangeable bases and exchangeable Al, soil texture

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