

1 This is the peer reviewed version of the following article:  
2  
3

4 Gregory AS, Ritz K, McGrath SP, Quinton JN, Goulding KWT, Jones RJA,  
5 Harris JA, Bol R, Wallace P, Pilgrim ES, Whitmore AP (2015) A review of  
6 the impacts of degradation threats on soil properties in the UK. Soil Use and  
7 Management 31, 1-15.  
8  
9

10 Which has been published in final form at doi: [10.1111/sum.12212](https://doi.org/10.1111/sum.12212)  
11  
12  
13

14 This article may be used for non-commercial purposes in accordance with  
15 [Wiley Terms and Conditions for Self-Archiving](#).  
16  
17

18 **A review of the impacts of degradation threats on soil properties**  
19 **in the UK**

20

21 A. S. GREGORY <sup>1</sup>, K. RITZ <sup>2</sup>, S. P. MCGRATH <sup>1</sup>, J. N. QUINTON <sup>3</sup>, K. W. T. GOULDING <sup>1</sup>, R. J. A.  
22 JONES <sup>4</sup>, J. A. HARRIS <sup>4</sup>, R. BOL <sup>5</sup>, P. WALLACE <sup>6</sup>, E. S. PILGRIM <sup>7</sup> & A. P. WHITMORE <sup>1</sup>

23

24 <sup>1</sup> *Department of Sustainable Soils and Grassland Systems, Rothamsted Research, Harpenden,*  
25 *Hertfordshire, AL5 2JQ, UK*

26 <sup>2</sup> *Division of Agricultural and Environmental Sciences, University of Nottingham, Sutton*  
27 *Bonington Campus, Loughborough, Leicestershire, LE12 5RD, UK*

28 <sup>3</sup> *Lancaster Environment Centre, Lancaster University, Lancaster, LA1 4YQ, UK*

29 <sup>4</sup> *School of Energy, Environment and Agrifood, Cranfield University, Cranfield,*  
30 *Bedfordshire, MK43 0AL, UK*

31 <sup>5</sup> *Terrestrial Biogeochemistry Group, Institute of Bio- and Geosciences IBG-3: Agrosphere,*  
32 *Forschungszentrum Jülich GmbH, 52425 Jülich, Germany*

33 <sup>6</sup> *Phil Wallace Ltd, Westland, Martlesham Heath, Ipswich, Suffolk, IP5 3SU, UK*

34 <sup>7</sup> *University of Exeter, Amory Building, Rennes Drive, Exeter, EX4 4RJ, UK*

35

36 Correspondence: A. S. Gregory. E-mail: andy.gregory@rothamsted.ac.uk

37

38 Running Title: Degradation threats to soil properties in the UK

39 **Abstract**

40 National governments are becoming increasingly aware of the importance of their soil  
41 resources and are shaping strategies accordingly. Implicit in any such strategy is that  
42 degradation threats and their potential effect on important soil properties and functions are  
43 defined and understood. In this paper we aimed to review the principal degradation threats on  
44 important soil properties in the UK, seeking quantitative data where possible. Soil erosion  
45 results in the removal of important topsoil and, with it, nutrients, C and porosity. A decline in  
46 soil organic matter principally affects soil biological and microbiological properties, but also  
47 impacts on soil physical properties because of the link with soil structure. Soil contamination  
48 affects soil chemical properties, affecting nutrient availability and degrading microbial  
49 properties, whilst soil compaction degrades the soil pore network. Soil sealing removes the  
50 link between the soil and most of the ‘spheres’, significantly affecting hydrological and  
51 microbial functions, and soils on re-developed brownfield sites are typically degraded in most  
52 soil properties. Having synthesized the literature on the impact on soil properties, we discuss  
53 potential subsequent impacts on the important soil functions, including food and fibre  
54 production, storage of water and C, support for biodiversity, and protection of cultural and  
55 archaeological heritage. Looking forward, we suggest a twin approach of field-based  
56 monitoring supported by controlled laboratory experimentation to improve our mechanistic  
57 understanding of soils. This would enable us to better predict future impacts of degradation  
58 processes, including climate change, on soil properties and functions so that we may manage  
59 soil resources sustainably.

60

61 **Keywords:** Soil erosion, soil organic matter, soil contamination, soil compaction, soil  
62 functions, climate change

## 63 **Introduction**

64 National governments are becoming increasingly aware of the importance of their soil  
65 resources and have begun to shape policies to recognise this. In the UK, for example, there  
66 have been soil strategies and policy documents in England (HMG, 2009b; HMG, 2011b),  
67 Scotland (Dobbie *et al.*, 2011) and Wales (WAG, 2006). All have a similar central aim,  
68 namely the ambition to manage soils sustainably and tackle potential degradation threats so  
69 that their ability to provide essential services is protected or enhanced. Soil degradation in  
70 England has been estimated to have cost the economy at least £150M - £250M each year  
71 (HMG, 2011b).

72 Implicit in any such strategy is that the principal degradation threats and their effect on  
73 important soil properties are defined and understood. If this can be achieved then, by  
74 extension, we may better-understand the likely impact on soil functions – the essential  
75 services that we rely on soils to perform – and we can begin to define policies to protect  
76 them. Evidence-gathering is an initial stage in the process of developing and refining policies  
77 (HMG, 2011a).

78 In this paper we aimed to identify and review the principal degradation threats on important  
79 soil properties in the UK, seeking quantitative data where possible. We summarize the main  
80 findings and discuss the likely subsequent impacts on soil functions and also the potential  
81 impacts of predicted changes in climate in the UK.

82

## 83 **Methodology**

### 84 *Degradation threats*

85 In examining which degradation threats were important in the context of the UK, we  
86 consulted the report of the European Environmental Assessment of Soil for Monitoring  
87 (ENVASSO) project (Huber *et al.*, 2008), which aimed to establish a soil monitoring system

88 in support of a proposed European Union-wide Soil Framework Directive (EC, 2006). In the  
89 report of Huber *et al.* (2008), nine key threats to soil were identified: soil erosion, decline in  
90 soil organic matter (SOM), soil contamination, soil sealing, soil compaction, decline in soil  
91 biodiversity, soil salinisation, landslides and desertification. In addition, the report identified  
92 three further ‘cross-cutting issues’ which exist as threats to soil: climate change, land use  
93 change and brownfield development. Similar threats to soils have been identified in the UK  
94 previously (e.g. SG, 2009; HMG, 2011b).

95 From this list, we focused on soil erosion, decline in SOM, soil contamination, soil  
96 compaction, soil sealing, and brownfield development, as we believe these to be of the  
97 greatest relevance to soils in the UK. It is our view that the decline in soil biodiversity does  
98 not exist as a specific independent threat to soil, but that instead it arises as a result of some  
99 of the other threats identified. Similarly, land use change imparts some of the other threats  
100 identified on the soil. Therefore these two threats were covered in the context of the other  
101 threats. We review soil salinisation and landslides only briefly, as we consider these to be less  
102 important, and extremely localized in the UK. Desertification is not a threat currently to UK  
103 soils and is not reviewed. Finally we discuss climate change separately in terms of what the  
104 likely impacts might be on degradation threats and soil properties. The degradation threats  
105 considered and brief definitions are given in Table 1.

106

### 107 *Literature review*

108 A literature review of peer-reviewed publications was conducted using the web-based ISI  
109 Web of Knowledge <sup>SM</sup> search engine (Thomson Reuter, New York, USA), supplemented by  
110 other relevant published evidence (e.g. reports). We took each degradation threat as a search  
111 term in turn with ‘soil’ and ‘UK’ and sought data, predominantly from the 2000-2015 period,  
112 on the impacts on important soil physical, biological and chemical properties in the UK. In

113 particular we focused on general properties likely to be of direct relevance for the ability of  
114 the soil to carry out its principal functions, including food and fibre production, water and air  
115 filtration, and biodiversity support. We synthesized the most relevant information in our  
116 review below.

117

## 118 **The impacts of degradation threats on soil properties in the UK**

119

### 120 *Soil erosion*

121 Although soil erosion can be natural, current concerns relate to accelerated erosion where the  
122 rate has increased significantly through human activities, and greatly exceeds current  
123 estimates of soil formation (0.3-1.4 Mg ha<sup>-1</sup> year<sup>-1</sup> in Europe) (Verheijen *et al.*, 2009). Most  
124 erosion is by water, with light-textured soils particularly susceptible (Quinton & Catt, 2004),  
125 although wind erosion has been observed on arable soils in eastern England, albeit it is very  
126 difficult to quantify (Bullock, 1987), and peaty soils can erode at daily rates of up to 5.6 kg  
127 ha<sup>-1</sup> when dry (Foulds & Warburton, 2007).

128 Mean annual erosion rates in England measured directly or interpreted from aerial  
129 photography on mostly arable sites are typically up to 10 Mg ha<sup>-1</sup>, but can be as high as 66  
130 Mg ha<sup>-1</sup> whilst annual tillage erosion in the UK can reach 5 Mg ha<sup>-1</sup> (van Oost *et al.*, 2009).  
131 Under grassland, 52% of the 399 upland sites in England and Wales surveyed by McHugh *et*  
132 *al.* (2002) in 1999 had suffered erosion and an estimated 89 000 m<sup>3</sup> of soil had been lost over  
133 an unspecified time, less than 1% of which was deposited in the same field site. Improved  
134 lowland grasslands typically have lower annual rates of erosion, ranging from 0.5-1.2 Mg ha<sup>-1</sup>  
135 <sup>1</sup>, (Whitmore *et al.*, 2004; Bilotta *et al.*, 2010).

136 Structural damage of the soil surface, caused by raindrops, running water and deposited  
137 material, reduces infiltration and increases surface runoff (Dexter, 1997; Whitmore *et al.*,

138 2004; Pilgrim *et al.*, 2010). The direct loss of soil C by water erosion (Lal, 2003; van Oost *et*  
139 *al.*, 2007) has been estimated to be 0.20-0.76 Tg annually in England and Wales (Quinton *et*  
140 *al.*, 2006). Plant nutrients can be lost in eroded topsoil (Pimentel *et al.*, 1995; Quinton *et al.*,  
141 2001; Palmer & Smith, 2013), although few published studies have examined N and P losses  
142 in detail (Kronvang, 1990; Chambers *et al.*, 2000).

143

#### 144 *Decline in soil organic matter*

145 In common with other temperate-zone countries, there has been a decline in SOM in some  
146 soils in the UK over a long period, predominantly as a result of changes in land use.  
147 Historically land has changed from native woodland to grazing land, and then on to annual  
148 arable systems. Since the 1940s, the area covered by permanent grassland has reduced and in  
149 arable systems there has been a reduction in the use of manures and an increase in cultivation  
150 depth (Bellamy *et al.*, 2005). These have all served to both reduce organic inputs and increase  
151 decomposition of existing SOM. Topsoil horizons (up to 0.30 m depth) are those most  
152 affected by SOM decline as the topsoil is the main zone affected by land use, although there  
153 is increased awareness of potential impacts of land use on subsoil SOM (e.g. Gregory *et al.*,  
154 2014). SOM contents under arable systems are much lower than those under grass and  
155 woodland in the UK (Chapman *et al.*, 2013; Gregory *et al.*, 2014). The SOM changes as the  
156 soil adjusts to a new equilibrium of plant inputs, which can take several decades (Jenkinson *et*  
157 *al.*, 2008; Johnston *et al.*, 2009). Occasionally land is taken out of arable cultivation and  
158 SOM can recover, though at a much slower rate (Johnston, 1986; Poulton *et al.*, 2003; Smith  
159 *et al.*, 2007). There is conflicting evidence as to whether SOM and C stocks have declined  
160 significantly in the UK over the last 30 years where there has been no change in land use  
161 (Bellamy *et al.*, 2005; Reynolds *et al.*, 2013; Chapman *et al.*, 2013), and the current estimate  
162 of the total soil organic C stock down to 1 m depth in the whole of the UK is 5260 Tg

163 (Bradley *et al.*, 2005; Gregory *et al.*, 2014). Instead there is much evidence as to the effects of  
164 SOM decline on soil properties, particularly physical properties.  
165 Specific decreases in aggregate stability of 10-40% with a 1% decrease in SOM content have  
166 been recorded in the UK and similar locations (Williams, 1971; Tisdall & Oades, 1980;  
167 Tisdall & Oades, 1982; Riley *et al.*, 2008), as well as a decrease in the resilience of soil to  
168 physical stresses, such as compaction (Watts & Dexter, 1997; Gregory *et al.*, 2009). This can  
169 lead to an undesirable domination of coarser clods (Riley *et al.*, 2008), a decrease in friability  
170 (Watts & Dexter, 1998), and a reduction in porosity (Riley *et al.*, 2008). SOM decline can  
171 reduce soil water retention (Kibblewhite *et al.*, 2008; Johnston *et al.*, 2009) by up to 10% for  
172 a difference in SOM content from 7% to 3% (Gregory *et al.*, 2009). Arable soils of low SOM  
173 content are susceptible to slumping when wetted due to aggregate instability leading to lower  
174 infiltration and greater surface runoff (Whitmore *et al.*, 2004).

175 The quantity and quality of SOM, as the primary food source, largely controls the soil  
176 microbial biomass (Fierer *et al.*, 2009) and biodiversity (Orwin *et al.*, 2006; Wardle *et al.*,  
177 2006). Loss of SOM can reduce the exchange of important nutrients such as N, P and S  
178 (Johnston *et al.*, 2009). SOM loss from 5% to 2% over a 60 year period at Rothamsted  
179 resulted in a 90% decrease in microbial biomass, but no significant effect on microbial  
180 diversity (Hirsch *et al.*, 2009) or substrate utilization (Wu *et al.*, 2012). Lower fungal biomass  
181 (Gregory *et al.*, 2009) and fungal-to-bacterial biomass ratios (Bardgett *et al.*, 1996, 2007)  
182 have been found soils of low SOM content compared with undisturbed and botanically-rich  
183 grassland soils in the UK.

184 SOM also plays a key role in the ability of soils to buffer the effects of potentially-toxic  
185 substances, in part by chelation and adsorption (Chander & Brookes, 1993; Hund-Rinke &  
186 Kördel, 2003; Griffiths *et al.*, 2005, 2008; Kuan *et al.*, 2007). Loss of SOM can, hence,  
187 release toxic elements (ROTAP, 2009).



188

189 *Soil contamination*

190 Soil contamination may result from point or diffuse sources. Impacts of the latter are hard to  
191 predict as it can be affected by factors such as the weather, and soils far away from the source  
192 may be affected. Contamination mainly affects soil biological and chemical properties,  
193 although some contaminants (e.g. salts) may destabilize soil structure and affect soil physical  
194 properties.

195 Contamination that decreases soil pH, such as N deposition (NEGTAP, 2001; ROTAP,  
196 2009), reduces nutrient availability, even at moderate levels (pH 5-7), and increases the risk  
197 of nutrient leaching (Pearson & Stewart, 1993; Jefferies & Maron, 1997; Degryse *et al.*,  
198 2007). Soil pH is one of the main determinants of soil biodiversity and functioning (Fierer &  
199 Jackson, 2006; Smolders *et al.*, 2009; Griffiths *et al.*, 2011). Some keystone soil taxa  
200 including *Lumbricidae* (earthworms), *Collembola* (springtails), and N-fixing bacteria are  
201 particularly sensitive to metals (Emmett *et al.*, 2010). Contamination can affect the health of  
202 soil invertebrates in general (Spurgeon & Hopkin, 1996). Addition of Cu to UK soils  
203 (equivalent to 500 mg kg<sup>-1</sup>) decreased both microbial respiration rates by up to 80% initially,  
204 and microbial biomass itself (Griffiths *et al.*, 2001; Kuan *et al.*, 2007; Gregory *et al.*, 2009).  
205 The effects may not be linear (Hirsch *et al.*, 1993; Giller *et al.*, 2009) as different groups  
206 dominate at different points as toxicity changes. Additions of Cu and Zn increase the  
207 metabolic quotient (Rost *et al.*, 2001) which is an indicator of microbial stress (Chander &  
208 Joergensen, 2001; Chander *et al.*, 2002). Metals added in association with sewage sludge may  
209 be more toxic than metals added as inorganic salts (Chaudri *et al.*, 2008). As a result,  
210 contamination can decrease OM mineralization (Giller *et al.*, 1998; Dai *et al.*, 2004; Emmett  
211 *et al.*, 2010), N fixation (McGrath, 1998; Broos, 2004) and the catabolic diversity of soils,  
212 measured by the soil's ability to degrade a range of compounds (Wenderoth & Reber, 1999;

213 Girvan *et al.*, 2005). Urban soils, often have lower biodiversity (Fountain & Hopkin, 2004;  
214 Styers *et al.*, 2010), presumably due to contamination.

215

### 216 *Soil compaction*

217 Compaction is mainly associated with trafficking in arable soils and livestock in grassland  
218 soils. Whereas clay soils are better-able to recover, sandy soils are particularly vulnerable  
219 (Gregory *et al.*, 2009). Subsoil compaction is particularly insidious because it is rarely  
220 detected. Recent reviews have summarized comprehensively the causes, effects (some of  
221 which are discussed below) and management of soil compaction in the UK (Clarke *et al.*,  
222 2007; Batey, 2009).

223 Soil compaction degrades soil physical quality (Dexter, 1988; Whitmore & Whalley, 2009).  
224 Increases in bulk density (of up to 0.18 Mg m<sup>-3</sup>, Ball *et al.*, 2008) and soil strength (of up to 3  
225 MPa, Gregory *et al.*, 2007; Whalley *et al.*, 2008), and decreases in friability (by up to 50%,  
226 Watts & Dexter, 1998), soil porosity (by 10-25%, Mooney & Nipattasuk, 2003; Gregory *et al.*  
227 *et al.*, 2009; Matthews *et al.*, 2010) and water-holding capacity (Gregory *et al.*, 2009) have been  
228 reported in UK soils. Compaction preferentially affects macropores (Breland & Hansen,  
229 1996; Richard *et al.*, 2001) and can change the alignment of pores from vertical to parallel  
230 with respect to the soil surface (Servadio *et al.*, 2005). This affects infiltration rates  
231 (Heathwaite *et al.*, 1990; Kibblewhite *et al.*, 2008; Batey, 2009) and hence increases the risk  
232 of overland flow, flooding and erosion (Dexter, 1988). Decreases in the saturated hydraulic  
233 conductivity of soil by up to three orders of magnitude have been reported (Mooney &  
234 Nipattasuk, 2003; Matthews *et al.*, 2010). Compaction in grassland soils is less severe than in  
235 arable soil (Palmer & Smith, 2013), although it is much less understood (Bilotta *et al.*, 2007).  
236 Compaction may have little effect on microorganisms as they inhabit small pores which are  
237 less affected (Breland & Hansen, 1996; Jensen *et al.*, 1996; Kohler *et al.*, 2005; Shestak &

238 Busse, 2005; Gregory *et al.*, 2007). However, microbial functions may be affected. Breland  
239 & Hansen (1996) reported reductions of up to 18% in N mineralization with compaction,  
240 ascribed to increased physical protection of SOM and microbial biomass in the smaller pores  
241 inaccessible to grazing nematodes created by compaction. Denitrification and NH<sub>3</sub>  
242 volatilization may increase with compaction, causing N loss (Batey & Killham, 1986). Ball *et*  
243 *al.* (2008) found N<sub>2</sub>O emissions increased by up to 4 mg N m<sup>-2</sup> hour<sup>-1</sup> following compaction –  
244 twice that of the uncompacted control. In contrast, compaction may affect soil  
245 macroorganisms. Reductions in *Collembola* (Heisler & Kaiser, 1995; Schrader & Lingnau,  
246 1997), *Arthropoda* (arthropods) (Aritajate *et al.*, 1977a, 1977b), *Enchytraeidae* (potworms)  
247 (Schrader *et al.*, 1997; Rohrig *et al.*, 1998), and both surface-dwelling (Pearce, 1984;  
248 Radford *et al.*, 2001) and deep-burrowing *Lumbricidae* species (Rushton, 1986; Kretzschmar,  
249 1991) have been reported.

250

### 251 *Soil sealing*

252 Soil sealing is associated with the main urban areas of the UK under the greatest pressure for  
253 housing and infrastructure. In 2011, 82% of the population of England lived in urban areas  
254 (ONS, 2012, 2013). Whilst there is little direct evidence of the impacts on soil properties in  
255 the UK, general impacts from a European perspective have been discussed (e.g. Huber *et al.*,  
256 2008; Scalenghe & Marsan, 2009; Virto *et al.*, 2015). Sealing interrupts or removes  
257 completely the contact between the soil and other system components such as the biosphere,  
258 atmosphere and hydrosphere (Huber *et al.*, 2008) with significant and irreversible impacts on  
259 the ability of soil to transmit water and gas (Virto *et al.*, 2015). Declines in SOM (Wei *et al.*,  
260 2014) and microbial biomass and respiration (Piotrowska-Dlugosz & Charzyński, 2015) have  
261 also been reported.

262

263 *Brownfield development*

264 The impact from brownfield development on soil properties is wide-ranging as determined by  
265 the specific prior engineering project. In the extreme case where brownfield development  
266 results in a non-green after-use, the soil is removed permanently and hence all soil functions  
267 will be lost. However, common brownfield developments in the UK include the restoration to  
268 a green after-use of mineral workings, landfill sites and underground infrastructure networks.  
269 In these cases, how the soil was removed, stored and reinstated prior to, during and following  
270 the lifetime of the industrial use will have a large impact on the success of the green after-use  
271 and the properties and functions of the soil.

272 The removal and storage of soil often has deleterious effects on soil physical properties,  
273 including compaction and loss of structure (HMG, 1996). Soil structure can be damaged with  
274 low porosity, up to 15% lower aggregate stability (Malik & Scullion, 1998), and domination  
275 of smaller (<2 mm) aggregates (Edgerton *et al.*, 1995; Gregory & Vickers, 2003, 2007). The  
276 nutrient status of the soil may be reduced due to leaching during storage and waterlogging if  
277 compacted (HMG, 1996). SOM can also be lost (Johnson *et al.*, 1988; Bentham *et al.*, 1992;  
278 Malik & Scullion, 1998; Wick *et al.*, 2009). These effects can persist when the soil is  
279 reinstated.

280 The high compaction and shearing forces imparted during lifting, moving and replacement of  
281 soil have immediate and significant effects on the biological community (Harris *et al.*, 1989,  
282 1993). The soil microbial biomass can decrease by 50% immediately upon removal (Harris *et*  
283 *al.*, 1989) and by 95% following storage if conditions become anaerobic (Harris & Birch,  
284 1990). *Lumbricidae* are severely affected, and their populations may take decades to recover  
285 even after the soil is reinstated. Fungi and complex organisms are disproportionately affected  
286 by engineering operations, because of their physical, multicellular structure. The observed

287 slow recovery of microbial biomass in brownfield soils is linked to the reduced soil physical  
288 quality (Edgeron *et al.*, 1995; Harris, 2003).

289

#### 290 *Other degradation threats*

291 Salinisation, the excess of water-soluble salts in soils by natural or human-enhanced means  
292 (Huber *et al.*, 2008), is limited to those UK soils most susceptible to seawater flooding, or  
293 naturally-occurring localised acid sulphate soils such as in East Anglia (Dent, 1985;  
294 Kibblewhite *et al.*, 2008). Salts have a deleterious effect on soil structure and often result in a  
295 release of pollutants (Du Laing *et al.*, 2009). Though more commonly associated with  
296 Mediterranean areas in Europe, particularly mountainous areas (e.g. Ferrara *et al.*, 2015;  
297 Virto *et al.*, 2015), landslides do occur in localized areas of the UK (Foster *et al.*, 2013),  
298 including coastal cliffs (Bowman & Take, 2015) and upland areas (Gunn *et al.*, 2013;  
299 Johnson & Warburton, 2015). The result of landslides is often the loss of the entire soil  
300 material and hence all properties and functions from a site. As vulnerable sites tend to be in  
301 the uplands or by the coast, there can be a significant impact on amenity and agricultural uses  
302 (Bowman & Take, 2015). Correspondingly, the soil at the deposition site is buried, severely  
303 impairing its functioning.

304

## 305 **Discussion**

306

### 307 *The impacts of degradation threats on soil properties in the UK*

308 From the review above, we see that the main degradation threats to soils in the UK affect a  
309 wide range of properties within the three main types: physical, biological and chemical. Soil  
310 erosion results in the removal of important topsoil and any contained nutrients, C and  
311 porosity. A decline in SOM principally affects soil biological and microbiological properties,

312 SOM being the primary food source, but also impacts on soil physical properties because of  
313 the effect of SOM on soil structure development and stabilization. Soil contamination affects  
314 soil chemical properties, affecting nutrient availability and degrading microbial properties,  
315 whilst soil compaction degrades soil physical properties, especially soil porosity. Soil sealing  
316 removes the link between the soil and most of the ‘spheres’ and can significantly affect soil  
317 hydrological and microbial functions, but may not necessarily affect other soil properties. By  
318 contrast, soils on re-developed brownfield sites are typically degraded in physical, chemical  
319 and biological properties. From our review it is apparent that the potential or actual effect of  
320 some degradation threats on soils in the UK are well-documented, including soil erosion,  
321 decline in SOM, soil contamination and soil compaction. By contrast, the impact of soil  
322 sealing and brownfield development on soils in the UK appears to be understood less. These  
323 areas might need to be research priorities in the future if the UK population (particularly in  
324 urban areas) continues to increase.

325 The spatial arrangement of degradation threats to soils in the UK is complex and beyond the  
326 scope of this review. However we may offer some initial simplistic thoughts. Erosion is  
327 associated with overland flow on wet soils or wind in dry soils. Therefore in the UK upland  
328 soils in the north and west that experience considerable rainfall and arable soils of low  
329 porosity may be more prone to suffer from soil erosion by water whereas light-textured arable  
330 soils may be more prone to wind erosion, such as those in the south and east of the UK.  
331 Intuitively, soils with a greater amount of SOM have more potential to lose SOM than soils  
332 of lesser SOM. As SOM is to a large extent dictated by land use, soils under grassland, semi-  
333 natural or natural vegetation may be candidates to experience a loss of SOM, particularly if  
334 the input from vegetation changes in some way. Grassland dominates soils in the west and  
335 north of the UK, whilst the main areas of semi-natural or natural vegetation are in the  
336 uplands. However, it is important to reiterate that there is currently no definitive evidence for

337 significant changes to SOM levels in UK soils (Bellamy *et al.*, 2005; Reynolds *et al.*, 2013;  
338 Chapman *et al.*, 2013; Gregory *et al.*, 2014). Although compaction is often perceived to be a  
339 degradation associated exclusively with trafficking of arable soils, grassland soils can become  
340 compacted from the impact of livestock, and hence compaction can potentially affect many  
341 agricultural soils in the UK. The impacts are likely to be more severe in tramlines and where  
342 livestock congregate (e.g. feeding and watering troughs) in arable and grassland systems,  
343 respectively. Soil sealing and brownfield development are primarily urban-based  
344 degradations and hence will mainly threaten soils within and surrounding the main urban  
345 areas in the UK, particularly in the cities in England. Soil contamination could also affect the  
346 same soils close to urban and industrial areas, but other contaminants, particular airborne  
347 ones, could diffuse to affect soils distant from the source. Continued development and  
348 exploitation of soil and land use spatial databases (e.g. Mackney *et al.*, 1983; Proctor *et al.*,  
349 1998; Morton *et al.*, 2011) should help to identify soils at risk from particular degradation  
350 threats. This kind of approach can then be used to review current land management practices  
351 in order to minimize degradation impacts.

352

### 353 *Implications for soil functions in the UK*

354 Having synthesized the literature on the impact of degradation threats on soil properties in the  
355 UK we may then discuss the likely impacts on important soil functions – the tasks or services  
356 we ask of soil. These functions typically include food and fibre production, storage of water  
357 and C, water and air filtration, support for infrastructure, and support for biodiversity,  
358 habitats, cultural and archaeological heritage (HMG, 2011b). We discuss briefly some  
359 potential impacts of changes in soil properties arising from degradation threats on soil  
360 functions.

361 Loss of topsoil affects crop yields. A review of 24 studies in the UK found that yields  
362 decreased by 4% per 10 cm depth of soil loss, equivalent to a soil loss of around 100 Mg ha<sup>-1</sup>  
363 (Bakker *et al.*, 2004). Erosion on lowland grasslands, which ranges from 0.5-1.2 Mg ha<sup>-1</sup>, can  
364 be important locally for growth and silage quality (Bilotta *et al.*, 2010). Erosion removes soil  
365 habitat space, thus impacting on biodiversity support and water storage functions. Amenity  
366 use is also affected by erosion (Rodway-Dyer & Walling, 2010).

367 Degradation of soil physical properties, particularly the decrease in porosity from compaction  
368 and the destabilization of structure from loss of SOM, affect a range of soil functions. Water  
369 storage and flood regulation functions are degraded with a loss in porosity (Dexter, 1997;  
370 Whitmore *et al.*, 2004; Pilgrim *et al.*, 2010). Plant growth can decline as a result of  
371 compaction-imposed loss of porosity, particularly if a dense plough pan develops (van den  
372 Akker, 1997). Compaction impairs root penetration (Batey, 2009) and root development  
373 (Whalley *et al.*, 1995). Specific declines in crop yield have been reported in the UK (Douglas  
374 *et al.*, 1992; Gregory *et al.*, 2007), which can be up to 3 Mg ha<sup>-1</sup> for each 0.1 Mg m<sup>-3</sup> increase  
375 in bulk density (Whalley *et al.*, 1995) or each 1 MPa increase in strength (Whalley *et al.*,  
376 2006, 2008). Gregory *et al.* (2007) reported yield declines of up to 3 Mg ha<sup>-1</sup> in a heavily  
377 compacted loamy soil. Compaction can also increase the susceptibility of a crop to soil-borne  
378 diseases and fungi (Batey, 2009). In arable systems however some compaction is beneficial  
379 to achieve good seed-soil contact (Dexter, 1988) and to lessen the risk of lodging (Scott *et al.*,  
380 2005).

381 A decline in soil physical quality has implications for biodiversity support. Plant species  
382 differ in their ability to grow in compacted soil (Godefroid & Koedam, 2004a, 2004b) and  
383 compacted grassland soils may be less biodiverse than uncompacted soils (Roovers *et al.*,  
384 2004). Some evidence exists as to a link between compacted soil and a reduction in soil-  
385 pupating larvae of *Lepidoptera* (butterflies and moths) (Roach & Campbell, 1983). Gilroy *et*



386 *al.* (2008) reported a negative correlation between soil strength and the abundance of  
387 *Motacilla flava* (yellow wagtail) in eastern England, perhaps related to the effect on soil-  
388 dwelling prey. Other British grassland species, including *Turdus philomelos* (song thrush),  
389 *Sturnus vulgaris* (starling) and some waders, may be similarly affected (Clarke *et al.*, 2007).  
390 The quality of soil-turf systems for amenity is impaired by compaction and trafficking  
391 (Marjamaki & Pietola, 2007; Han *et al.*, 2008), although compaction is desired in special  
392 cases, such as cricket pitches (Baker *et al.*, 1998). Compaction may affect the preservation of  
393 cultural artefacts and archaeology in the soil (Blum, 1993).

394 Although the quantitative evidence for critical thresholds is slight (Korschens *et al.*, 1998;  
395 Loveland & Webb, 2003; Reynolds *et al.*, 2007), there is a widely-held belief that soil cannot  
396 function optimally without an adequate level of SOM (van Camp *et al.*, 2004). Often declines  
397 in SOM and structural development are hard to separate. Robinson & Woodrun (2008)  
398 reported an inverse relationship between SOM content and surface runoff due to crusting in  
399 agricultural soils on chalk in southern England. Declines in SOM have been associated with  
400 increased erosion (Fullen, 1991) and clay dispersion (Watts & Dexter; 1998). Other functions  
401 can also be affected. Correlations have been made between SOM and the abundance of  
402 *Diptera* (flies) and aerially-active *Coleoptera* (beetles) in arable soils in England (Gilroy *et*  
403 *al.*, 2008) and *Culicoides impunctatus* (highland midge) in Scotland (Blackwell *et al.*, 1999).  
404 A link between SOM loss and the release of toxic elements in soils has also been found  
405 (ROTAP, 2009).

406 Changes in soil chemical properties, chiefly pH arising from agricultural inputs or  
407 contaminants, affect many functions. Metals and metalloids can accumulate in topsoil from  
408 either the atmosphere or the use of fertilizers, agrochemicals, manures or waste materials on  
409 land which, if released in toxic concentrations, particularly under acidifying conditions, can  
410 severely impair plant growth and food quality (Pearson & Stewart, 1993; Blake *et al.*, 1994;

411 Blake & Goulding, 2002; Millennium Ecosystem Assessment, 2005; Degryse *et al.*, 2007;  
412 Atkinson *et al.*, 2012). Some metals and metalloids are phytotoxic and decrease yields at high  
413 concentrations (e.g. Zn, Cu, Cr, and As), whereas ‘passage poisons’ affect animal and  
414 humans consuming food with little effect on yields (e.g. Cd, Mo, Se and possibly Co)  
415 (McGrath & Zhao, 2015). The UK has substantial areas that are As-contaminated (Appleton  
416 *et al.*, 2012). Acidification can cause plant nutrient imbalances (Phoenix *et al.*, 2004),  
417 increased risk of nutrient leaching (Pearson & Stewart, 1993; Jefferies & Maron, 1997;  
418 Degryse *et al.*, 2007) and increased susceptibility of plants to stressors, including diseases and  
419 pests (Power *et al.*, 1998; Carroll *et al.*, 1999). Acid grassland can be toxic to grazing.  
420 Above-ground biomass may be significantly reduced near urban areas due, in part, to the  
421 proximity of contaminant sources (Ander *et al.*, 2013). Ground-level O<sub>3</sub> may also potentially  
422 reduce grass (Gonzalez *et al.*, 1999) and arable crop yields by up to 15% in the UK, in part by  
423 the effect on the ability of plants to respond to drought and to sequester C (ROTAP, 2009).  
424 Excess salt levels are toxic to most plant species, but the resulting halophytic ecosystems are  
425 often of great biodiversity value however (e.g. salt marsh, Watts *et al.*, 2003). Indeed, soil pH  
426 is one of the main determinants of plant biodiversity (Buneman *et al.*, 2006; Cookson *et al.*,  
427 2006; Rousk *et al.*, 2009).

428 At a fundamental level, where soil sealing removes the link between soils and the other  
429 ‘spheres’, functions such as supporting vegetation growth, C sequestration, filtering water  
430 and air and supporting biodiversity are significantly or irreversibly reduced (Huber *et al.*,  
431 2008; Scalenghe & Marsan, 2009). Also the degradations in soil properties arising from  
432 brownfield development cause problems for re-creating functioning soils. Restoration to a  
433 desired post-operation land use, such as species-rich grassland, may require intervention  
434 (Carrington & Diaz, 2011). However, modern restoration techniques can successfully

435 recreate habitats of high nature conservation value (Tarrant *et al.*, 2013), and indeed soils  
436 with poor structure or nutrient status may help in this regard (HMG, 1996).

437 It is therefore apparent that if potential soil degradation threats are realized, a range of  
438 important soil functions may be affected, through their effects on measured soil properties.  
439 The studies reviewed above largely focus on functions of immediate current economic value  
440 (e.g. crop yields and water resource management), and were often empirical observations  
441 rather than mechanistic studies linked to soil properties. Extrapolation of knowledge between  
442 soil properties and soil functions is challenging as a result (HMG, 2011b) even though similar  
443 processes may be at work. A related issue is the potential or otherwise for soils to be truly  
444 multi-functional. There are obvious trade-offs: agricultural monoculture might be at odds  
445 with supporting biodiversity, for instance. In the future, a more mechanistic understanding of  
446 the response of soil functions to degradation processes, through measured changes in soil  
447 properties, would help in this regard.

448 It is important to note that degradation processes do not necessarily have irreversible effects  
449 on soil functions. Land management practices can be revised to reduce or even remove the  
450 degradation threat to improve soil properties and functions. Examples in agriculture include  
451 cultivation when the soil is brittle rather than plastic, and reduced tyre pressures on  
452 machinery to reduce compaction (Batey, 2009), and cultivation perpendicular to (rather than  
453 up-and-down) the slope to reduce erosion (Quinton & Catt, 2004). Farmers may also prevent  
454 SOM loss by incorporating residues or adding organic materials. On non-agricultural land,  
455 degradation threats such as contamination, sealing and brownfield site development can  
456 probably only be mitigated by policy.

457

458 *The effects of climate change on soils in the UK*

459 It is predicted that the UK will experience hotter, drier summers and warmer, wetter winters  
460 than currently, with an increased occurrence of low frequency-high magnitude events such as  
461 heat waves and intense storms (HMG, 2009a, 2009b; Lowe *et al.*, 2009). Climate change is  
462 likely to affect all the degradation threats, and hence soil properties. We briefly summarize  
463 some important implications with reference to observations in the literature and modelling.  
464 Whilst it may be possible to look at evidence from regions currently experiencing the kind of  
465 climate predicted for the UK, such soils have likely developed over millennia under stable  
466 conditions and hence may not necessarily be analogous to how UK soils will respond to rapid  
467 climate change.

468 Soils on the margins of stability are likely to be most vulnerable to drier summers, such as  
469 those in eastern England which already experience low rainfall, or peat soils which can suffer  
470 irreversible shrinkage upon drying. Prolonged drying can increase soil hydrophobicity  
471 (McHale *et al.*, 2005) and strength (Whitmore & Whalley, 2009). Rapid drying can increase  
472 the mobility of cationic metals (Simpson *et al.*, 2010) which can reduce the buffering  
473 capacity (Park *et al.*, 2010). The likely effect on SOM is unknown: warming may increase  
474 microbial activity (Cox *et al.*, 2002; Carney *et al.*, 2007), or net primary productivity (Smith  
475 *et al.*, 2007; Johnston *et al.*, 2009), resulting in either a net loss or gain in soil C, respectively.  
476 Some models predict significant loss of soil C across much of the UK up to 2080 (Smith *et al.*  
477 *et al.*, 2005). Suseela & Dukes (2013) suggested a seasonality effect on SOM with decreased  
478 respiration during the growing season and increased respiration in the non-growing season.  
479 Global warming is predicted to cause a sea level rise of between 3-9 cm between 2010 and  
480 2030 (Lowe *et al.*, 2009), which will increase the risk of flooding and salinisation in low-  
481 lying coastal soils of the UK.

482 The wet winter experienced in the UK in 2000-2001 provided some insight into future  
483 rainfall patterns (ADAS, 2002). Soils suffered from prolonged waterlogging, rill erosion,

484 losses of NO<sub>3</sub> (in drainage water), S (in SO<sub>4</sub>) and P (in sediment), and precipitation of Fe and  
485 Mn (ADAS, 2002). Waterlogging causes anaerobism and has been found to reduce N, P and  
486 K nutrient uptake rates to less than 10% of control soils, and to increase the concentration of  
487 potentially-harmful compounds including C<sub>2</sub>H<sub>4</sub> (up to 6 μL L<sup>-1</sup>) and Mn (up to 0.5 mg kg<sup>-1</sup>)  
488 (Drew & Sisworo, 1979). McTiernan *et al.* (2001) reported 70-300% greater losses of  
489 dissolved organic C from seasonally-waterlogged soil compared to drained grassland,  
490 although Scholefield *et al.* (1993) found increased NO<sub>3</sub> leaching in drained soil at the same  
491 site. Unger *et al.* (2009) found that flooding reduced total microbial biomass, Gram-positive  
492 bacteria and mycorrhizal fungi by up to 50%. Milan (2012) reported lasting effects of high-  
493 magnitude flooding in an upland catchment in the UK where soil adjacent to the river was  
494 lost together with its vegetation. The overall increase in flood frequency in the UK may be as  
495 high as 50% at the current 50-year return period in some catchments (Kay *et al.*, 2006). The  
496 full effects of significant flooding in southern England in the winter of 2013-2014 have yet to  
497 be assessed.

498 Changes in soil properties arising from climate change will affect important soil functions,  
499 particularly food and fibre yields. With increased drying, rainfed agriculture could become  
500 risky for some important crops in the UK such as potato (Daccache *et al.*, 2012). Following  
501 the wet winter in the UK in 2000-2001, yields of winter wheat (12% decline), barley (7.5%  
502 decline), spring oilseed rape crop, sugar beet and potato were significantly reduced (ADAS,  
503 2002). Rounsevell & Brignall (1994) concluded that machinery working days would be  
504 reduced should autumnal precipitation increase in England by 15%, which is entirely  
505 possible. Flooding makes it difficult to get livestock onto the land (Tyson *et al.*, 1992) and  
506 animals grazing floodplains are at risk of being lost in floodwater (Blackwell & Maltby,  
507 2006). Whilst the greater atmospheric CO<sub>2</sub> may enhance yields of temperate plants (Long *et al.*  
508 *et al.*, 2004) it could come at a cost of reduced plant protein content (Cotrufo *et al.*, 1998;

509 DaMatta *et al.*, 2010), if N becomes limited in the soil (Gill *et al.*, 2002). Further impacts on  
510 soil functions may be apparent. Increased concentrations of CO<sub>2</sub> may reduce plant  
511 transpiration (Korner, 2000) which could reduce the ability of the soil to store additional  
512 rainfall. Substantially reduced flows in wetlands may reduce their water regulatory capacity  
513 (Sutherland *et al.*, 2008). Waterlogging causes reducing conditions in soils which could  
514 impact on buffering and contaminant filtering (Du Laing *et al.*, 2009; Lair *et al.*, 2009). The  
515 impact of climate change on soil biodiversity remains unclear, although it will reflect changes  
516 in general soil conditions and vegetative growth. Resilience in biodiverse habitats at the  
517 larger scale may mask changes at fine scales (Fridley *et al.*, 2011). A link between climate,  
518 shrink-swell cycles in clay soils, and subsidence claims from properties damaged in the UK  
519 has been reported (Harrison *et al.*, 2012), and it is predicted that the magnitude and frequency  
520 of landslides in the UK will increase in the future (Pritchard *et al.*, 2014). There is conflicting  
521 evidence as to whether waterlogging and anaerobism will help to preserve (Caple, 1996;  
522 Raiswell, 2001) or degrade (Douteralo *et al.*, 2010) archaeological materials in soils.  
523 It would appear that soils will need to be carefully managed in the future to minimize any  
524 exacerbating effects of climate change on the range of degradations that they currently  
525 experience.

526

## 527 **Conclusions**

528 With the UK as an example, we have summarized some key data on the impact of  
529 degradation threats on soil properties, and have sought to link changes in soil properties to  
530 important soil functions. The key next stage will be to continue to add to the database with  
531 field-based monitoring of broad changes to soil properties following degradation supported  
532 by controlled laboratory experimentation to improve understanding of the mechanisms  
533 involved. Outputs from such an approach, together with refinement of soil and land use

534 spatial databases, should aid the development of models capable of extrapolating up to the  
535 national scale in order to link soil degradations to soil functions. We may also be able to  
536 predict any effect that climate change is likely to have. Armed with this, we may revise our  
537 policies so that soils are truly managed sustainably.

538

### 539 **Acknowledgements**

540 This review was funded by the UK Government Department for Environment, Food and  
541 Rural Affairs (Project SP1601 ‘Soil functions, quality and degradation – studies in support of  
542 the implementation of the Soil Strategy for England’). Rothamsted Research uses facilities  
543 funded by the UK Biotechnology and Biological Sciences Research Council.

544

### 545 **References**

546 ADAS 2002. The wet autumn of 2000: implications for agriculture. Project CC0372 final  
547 report. Department for Environment, Food and Rural Affairs, London, UK.

548 Ander, E. L., Johnson, C. C., Cave, M. R., Palumbo-Roe, B., Nathanail, C. P. & Lark, R. M.  
549 2013. Methodology for the determination of normal contaminants in English soil  
550 background concentrations of. *Science of the Total Environment*, **454**, 604-618.

551 Appleton, J. D., Cave, M. R. & Wragg, J. 2012. Anthropogenic and geogenic impacts on  
552 arsenic bioaccessibility in UK topsoils. *Science of the Total Environment*, **435**, 21-29.

553 Aritajat, U., Madge, D. S. & Gooderham, P. T. 1977a. Effects of compaction of agricultural  
554 soils on soil fauna. 1. Field investigations. *Pedobiologia*, **17**, 262-282.

555 Aritajat, U., Madge, D. S. & Gooderham, P. T. 1977b. Effects of compaction of agricultural  
556 soils on soil fauna. 2. Laboratory investigations. *Pedobiologia*, **17**, 283-291.

557 Atkinson, N. R., Young, S. D., Tye, A. M., Breward, N. & Bailey, E. H. 2012. Does returning  
558 sites of historic peri-urban waste disposal to vegetable production pose a risk to

559 human health? - A case study near Manchester, UK. *Soil Use and Management*, **28**,  
560 559-570.

561 Baker, S. W., Cook, A. & Adams, W. A. 1998. Soil characteristics of first-class cricket  
562 pitches and their influence on playing performance. *Journal of Turfgrass Science*, **74**,  
563 63-77.

564 Bakker, M. M., Govers, G. & Rounsevell, M. D. A. 2004. The crop productivity-erosion  
565 relationship: an analysis based on experimental work. *Catena*, **57**, 55-76.

566 Ball, B. C., Crichton, I. & Horgan, G. W. 2008. Dynamics of upward and downward N<sub>2</sub>O and  
567 CO<sub>2</sub> fluxes in ploughed or no-tilled soils in relation to water-filled pore space,  
568 compaction and crop presence. *Soil & Tillage Research*, **101**, 20-30.

569 Bardgett, R. D., Hobbs, P. J. & Frostegard, A. 1996. Changes in soil fungal:bacterial biomass  
570 ratios following reductions in the intensity of management of an upland grassland.  
571 *Biology and Fertility of Soils*, **22**, 261-264.

572 Bardgett, R. D., Smith, R. S., Shiel, R. S., Tallowin, J. R. B., Mortimer, S. R., Brown, V. K.,  
573 Pilgrim, E. S., Millward, D., Lawson, C., Harrison, K. A., Edwards, A. E., Hobbs, P.  
574 J., Sanderson, R., Harris, S. J., Beaumont, D. A., Murray, A. M. & Quirk, H. 2007.  
575 Diversification of grassland through the manipulation of plant-soil interactions.  
576 Project BD1451 objective 1 final report. Department for Environment, Food and  
577 Rural Affairs.

578 Batey, T. 2009. Soil compaction and soil management - a review. *Soil Use and Management*,  
579 **25**, 335-345.

580 Batey, T. & Killham, K. 1986. Field evidence on nitrogen losses by denitrification. *Soil Use*  
581 *and Management*, **2**, 83-86.

582 Bellamy, P. H., Loveland, P. J., Bradley, R. I., Lark, R. M. & Kirk, G. J. D. 2005. Carbon  
583 losses from all soils across England and Wales 1978-2003. *Nature*, **437**, 245-248.



- 584 Bentham, H., Harris, J. A., Birch, P. & Short, K. C. 1992. Habitat classification and soil  
585 restoration assessment using analysis of soil microbiological and physicochemical  
586 characteristics. *Journal of Applied Ecology*, **29**, 711-718.
- 587 Bilotta, G. S., Brazier, R. E. & Haygarth, P. M. 2007. The impacts of grazing animals on the  
588 quality of soils, vegetation, and surface waters in intensively managed grasslands.  
589 *Advances in Agronomy*, **94**, 237-280.
- 590 Bilotta, G. S., Krueger, T., Brazier, R. E., Butler, P., Freer, J., Hawkins, J. M. B., Haygarth,  
591 P. M., Macleod, C. J. A. & Quinton, J. N. 2010. Assessing catchment-scale erosion  
592 and yields of suspended solids from improved temperate grassland. *Journal of*  
593 *Environmental Monitoring*, **12**, 731-739.
- 594 Blackwell, A., Lock, K. A., Marshall, B., Boag, B. & Gordon, S. C. 1999. The spatial  
595 distribution of larvae of *Culicoides impunctatus* biting midges. *Medical and*  
596 *Veterinary Entomology*, **13**, 362-371.
- 597 Blackwell, M. S. A. & Maltby, E. (eds) 2006. *Ecoflood Guidelines: How to Use Floodplains*  
598 *for Flood Risk Reduction*, Office for Official Publications of the European  
599 Communities, Luxembourg.
- 600 Blake, L. & Goulding, K. W. T. 2002. Effects of atmospheric deposition, soil pH and  
601 acidification on heavy metal contents in soils and vegetation of semi-natural  
602 ecosystems at Rothamsted Experimental Station, UK. *Plant and Soil*, **240**, 235-251.
- 603 Blake, L., Johnston, A. E. & Goulding, K. W. T. 1994. Mobilization of aluminum in soil by  
604 acid deposition and its uptake by grass cut for hay - a chemical time bomb. *Soil Use*  
605 *and Management*, **10**, 51-55.
- 606 Blum, W. E. H. 1993. Soil protection concept of the Council of Europe and integrated soil  
607 research. In: *Integrated Soil and Sediment Research: A Basis for Proper Protection*.

608 (eds H. J. P. Eijsackers & T. Hamers), Kluwer Academic Publishers, Dordrecht, The  
609 Netherlands, pp. 37-47.

610 Bowman, E. T. & Take, W. A. 2015. The runout of chalk cliff collapses in England and  
611 France - case studies and physical model experiments. *Landslides*, **12**, 225-239.

612 Bradley, R. I., Milne, R., Bell, J., Lilly, A., Jordan, C. & Higgins, A. 2005. A soil carbon and  
613 land use database for the United Kingdom. *Soil Use and Management*, **21**, 363-369.

614 Breland, T. A. & Hansen, S. 1996. Nitrogen mineralization and microbial biomass as affected  
615 by soil compaction. *Soil Biology & Biochemistry*, **28**, 655-663.

616 Broos, K., Uyttebroek, M., Mertens, J. & Smolders, E. 2004. A survey of symbiotic nitrogen  
617 fixation by white clover grown on metal contaminated soils. *Soil Biology &  
618 Biochemistry*, **36**, 633-640.

619 Bullock, P. 1987. Soil erosion in the UK - an appraisal. *Journal of the Royal Agricultural  
620 Society of England*, **148**, 144-157.

621 Bunemann, E. K., Schwenke, G. D. & van Zwieten, L. 2006. Impact of agricultural inputs on  
622 soil organisms - a review. *Australian Journal of Soil Research*, **44**, 379-406.

623 Burghardt, W., Banko, G., Hoeke, S., Hursthouse, A., de L'Escaille, T., Ledin, S., Marsan, F.  
624 A., Sauer, D., Stahr, K., Amann, E., Quast, J., Nерger, M., Schneider, J. & Kuehn, K.  
625 2004. Sealing soils, soils in urban areas, land use and land use planning. Report of  
626 Task Group 5, Volume VI: Research, sealing and cross-cutting issues. In: *Reports of  
627 the Technical Working Groups Established under the Thematic Strategy for Soil  
628 Protection*. EUR 21319 EN/6. (eds.) L. Van-Camp, B. Bujarrabal, A.-R. Gentile, R. J.  
629 A. Jones, L. Montanarella, C. Olazabal & S.-K. Selvaradjou, Office for Official  
630 Publications of the European Communities, Luxembourg, pp. 61-107.

- 631 Caple, C. 1996. Parameters for monitoring anoxic environments. In: *Preserving*  
632 *Archaeological Remains 'in situ'*. (ed M. Corfield), Museum of London  
633 Archaeological Service, London, UK, pp. 113-122.
- 634 Carney, K. M., Hungate, B. A., Drake, B. G. & Megonigal, J. P. 2007. Altered soil microbial  
635 community at elevated CO<sub>2</sub> leads to loss of soil carbon. *Proceedings of the National*  
636 *Academy of Sciences of the United States of America*, **104**, 4990-4995.
- 637 Carrington, L. P. & Diaz, A. 2011. An investigation into the effect of soil and vegetation on  
638 the successful creation of a hay meadow on a clay-capped landfill. *Restoration*  
639 *Ecology*, **19**, 93-100.
- 640 Carroll, J. A., Caporn, S. J. M., Cawley, L., Read, D. J. & Lee, J. A. 1999. The effect of  
641 increased deposition of atmospheric nitrogen on *Calluna vulgaris* in upland Britain.  
642 *New Phytologist*, **141**, 423-431.
- 643 Chambers, B. J., Garwood, T. W. D. & Unwin, R. J. 2000. Controlling soil water erosion and  
644 phosphorus losses from arable land in England and Wales. *Journal of Environmental*  
645 *Quality*, **29**, 145-150.
- 646 Chander, K. & Brookes, P. C. 1993. Residual effects of zinc, copper and nickel in sewage  
647 sludge on microbial biomass in a sandy loam. *Soil Biology & Biochemistry*, **25**, 1231-  
648 1239.
- 649 Chander, K. & Joergensen, R. G. 2001. Decomposition of C-14 glucose in two soils with  
650 different amounts of heavy metal contamination. *Soil Biology & Biochemistry*, **33**,  
651 1811-1816.
- 652 Chander, K., Klein, T., Eberhardt, U. & Joergensen, R. G. 2002. Decomposition of carbon-  
653 14-labelled wheat straw in repeatedly fumigated and non-fumigated soils with  
654 different levels of heavy metal contamination. *Biology and Fertility of Soils*, **35**, 86-  
655 91.

656 Chapman, S. J., Bell, J. S., Campbell, C. D., Hudson, G., Lilly, A., Nolan, A. J., Robertson,  
657 A. H. J., Potts, J. M. & Towers, W. 2013. Comparison of soil carbon stocks in  
658 Scottish soils between 1978 and 2009. *European Journal of Soil Science*, **64**, 455-465.

659 Chaudri, A., McGrath, S., Gibbs, P., Chambers, B., Carlton-Smith, C., Bacon, J., Campbell,  
660 C. & Aitken, M. 2008. Population size of indigenous *Rhizobium leguminosarum*  
661 biovar *trifolii* in long-term field experiments with sewage sludge cake, metal-  
662 amended liquid sludge or metal salts: Effects of zinc, copper and cadmium. *Soil*  
663 *Biology & Biochemistry*, **40**, 1670-1680.

664 Clarke, M. A., Creamer, R. E., Deeks, L. K., Gowing, D. J. G., Holman, I. P., Jones, R. J. A.,  
665 Palmer, R. C., Potts, S. G., Rickson, R. J., Ritz, K., Smith, J., Thompson, T. R. E.,  
666 Truckell, I. G., Vickery, J., Whalley, W. R., Whelan, M. J. & Woodcock, B. A. 2007.  
667 Scoping study to assess soil compaction affecting upland and lowland grassland in  
668 England and Wales. Project BD2304 final report. Department for Environment, Food  
669 and Rural Affairs, London, UK.

670 Cookson, W. R., Marschner, P., Clark, I. M., Milton, N., Smirk, M. N., Murphy, D. V.,  
671 Osman, M., Stockdale, E. A. & Hirsch, P. R. 2006. The influence of season,  
672 agricultural management, and soil properties on gross nitrogen transformations and  
673 bacterial community structure. *Australian Journal of Soil Research*, **44**, 453-465.

674 Cotrufo, M. F., Ineson, P. & Scott, A. 1998. Elevated CO<sub>2</sub> reduces the nitrogen concentration  
675 of plant tissues. *Global Change Biology*, **4**, 43-54.

676 Cox, J. W., Chittleborough, D. J., Brown, H. J., Pitman, A. & Varcoe, J. C. R. 2002. Seasonal  
677 changes in hydrochemistry along a toposequence of texture-contrast soils. *Australian*  
678 *Journal of Soil Research*, **40**, 581-604.

679 Cruden, D. M. & Varnes, D. J. 1996. Landslide types and processes. In: *Landslides:*  
680 *Investigation and Mitigation*. Special Report 247, Transportation Research Board,

681 National Research Council. (eds.) A. K. Turner & R. L. Schuster, National Academy  
682 Press, Washington DC, USA, pp. 36-75.

683 Daccache, A., Keay, C., Jones, R. J. A., Weatherhead, E. K., Stalham, M. A. & Knox, J. W.  
684 2012. Climate change and land suitability for potato production in England and  
685 Wales: impacts and adaptation. *Journal of Agricultural Science*, **150**, 161-177.

686 Dai, J., Becquer, T., Rouiller, J. H., Reversat, G., Bernhard-Reversat, F. & Lavelle, P. 2004.  
687 Influence of heavy metals on C and N mineralisation and microbial biomass in Zn-,  
688 Pb-, Cu-, and Cd-contaminated soils. *Applied Soil Ecology*, **25**, 99-109.

689 DaMatta, F. M., Grandis, A., Arenque, B. C. & Buckeridge, M. S. 2010. Impacts of climate  
690 changes on crop physiology and food quality. *Food Research International*, **43**, 1814-  
691 1823.

692 Degryse, F., Vlassak, V., Smolders, E. & Merckx, R. 2007. Mobilization of Cd upon  
693 acidification of agricultural soils: column study and field modelling. *European  
694 Journal of Soil Science*, **58**, 152-165.

695 Dent, D. 1985. An introduction to acid sulphate soils and their occurrence in East Anglia.  
696 *Seesoil (Journal of the South East England Soils Discussion Group)*, **2**, 37-51.

697 Dexter, A. R. 1988. Advances in characterization of soil structure. *Soil & Tillage Research*,  
698 **11**, 199-238.

699 Dexter, A. R. 1997. Physical properties of tilled soils. *Soil & Tillage Research*, **43**, 41-63.

700 Dobbie, K. E., Bruneau, P. M. C. & Towers, W. (eds) 2011. *The State of Scotland's Soil*,  
701 Natural Scotland, Edinburgh, UK. pp. 187.

702 Douglas, J. T., Koppi, A. J. & Moran, C. J. 1992. Changes in soil structure induced by wheel  
703 traffic and growth of perennial grass. *Soil & Tillage Research*, **23**, 61-72.

704 Douterelo, I., Goulder, R. & Lillie, M. 2010. Soil microbial community response to land-  
705 management and depth, related to the degradation of organic matter in English

706 wetlands: Implications for the *in situ* preservation of archaeological remains. *Applied*  
707 *Soil Ecology*, **44**, 219-227.

708 Drew, M. C. & Sisworo, E. J. 1979. Development of waterlogging damage in young barley  
709 plants in relation to plant nutrient status and changes in soil properties. *New*  
710 *Phytologist*, **82**, 301-314.

711 Du Laing, G., Rinklebe, J., Vandecasteele, B., Meers, E. & Tack, F. M. G. 2009. Trace metal  
712 behaviour in estuarine and riverine floodplain soils and sediments: A review. *Science*  
713 *of the Total Environment*, **407**, 3972-3985.

714 EC 2006. *Communication of 22 September 2006 from the Commission to the Council, the*  
715 *European Parliament, the European Economic and Social Committee and the*  
716 *Committee of the Regions: Thematic Strategy for Soil Protection*. COM 2006, 231  
717 final, European Commission, Brussels, Belgium, pp. 12.

718 Edgerton, D. L., Harris, J. A., Birch, P. & Bullock, P. 1995. Linear relationship between  
719 aggregate stability and microbial biomass in three restored soils. *Soil Biology &*  
720 *Biochemistry*, **27**, 1499-1501.

721 Emmett, B. A., Reynolds, B., Chamberlain, P. M., Rowe, E., Spurgeon, D., Brittain, S. A.,  
722 Frogbrook, Z., Hughes, S., Lawlor, A. J., Poskitt, J., Potter, E., Robinson, D. A.,  
723 Scott, A., Wood, C. & Woods, C. 2010. Countryside Survey: Soils Report from 2007.  
724 Technical Report No. 9/07 (CEH Project Number: C03259). Natural Environment  
725 Research Council/Centre for Ecology & Hydrology. Wallingford, Oxon., UK.

726 Ferrara, C., Barone, P. M. & Salvati, L. 2015. Unravelling landslide risk: soil susceptibility,  
727 agro-forest systems and the socio-economic profile of rural communities in Italy. *Soil*  
728 *Use and Management*, **31**, 290-298.

- 729 Fierer, N. & Jackson, R. B. 2006. The diversity and biogeography of soil bacterial  
730 communities. *Proceedings of the National Academy of Sciences of the United States*  
731 *of America*, **103**, 626-631.
- 732 Fierer, N., Strickland, M. S., Liptzin, D., Bradford, M. A. & Cleveland, C. C. 2009. Global  
733 patterns in belowground communities. *Ecology Letters*, **12**, 1238-1249.
- 734 Foster, C., Pennington, C. V. L., Culshaw, M. G. & Lawrie, K. 2012. The national landslide  
735 database of Great Britain: development, evolution and applications. *Environmental*  
736 *Earth Sciences*, **66**, 941-953.
- 737 Foulds, S. A. & Warburton, J. 2007. Wind erosion of blanket peat during a short period of  
738 surface desiccation (North Pennines, Northern England). *Earth Surface Processes and*  
739 *Landforms*, **32**, 481-488.
- 740 Fountain, M. T. & Hopkin, S. P. 2004. Biodiversity of Collembola in urban soils and the use  
741 of *Folsomia candida* to assess soil 'quality'. *Ecotoxicology*, **13**, 555-572.
- 742 Fridley, J. D., Grime, J. P., Askew, A. P., Moser, B. & Stevens, C. J. 2011. Soil heterogeneity  
743 buffers community response to climate change in species-rich grassland. *Global*  
744 *Change Biology*, **17**, 2002-2011.
- 745 Fullen, M. A. 1991. Soil organic matter and erosion processes on arable loamy sand soils in  
746 the West Midlands of England, UK. *Soil Technology*, **4**, 19-31.
- 747 Gill, R. A., Polley, H. W., Johnson, H. B., Anderson, L. J., Maherali, H. & Jackson, R. B.  
748 2002. Nonlinear grassland responses to past and future atmospheric CO<sub>2</sub>. *Nature*, **417**,  
749 279-282.
- 750 Giller, K. E., Witter, E. & McGrath, S. P. 1998. Toxicity of heavy metals to microorganisms  
751 and microbial processes in agricultural soils: a review. *Soil Biology & Biochemistry*,  
752 **30**, 1389-1414.

- 753 Giller, K. E., Witter, E. & McGrath, S. P. 2009. Heavy metals and soil microbes. *Soil Biology*  
754 *& Biochemistry*, **41**, 2031-2037.
- 755 Gilroy, J. J., Anderson, G. Q. A., Grice, P. V., Vickery, J. A., Bray, I., Watts, P. N. &  
756 Sutherland, W. J. 2008. Could soil degradation contribute to farmland bird declines?  
757 Links between soil penetrability and the abundance of yellow wagtails *Motacilla flava*  
758 in arable fields. *Biological Conservation*, **141**, 3116-3126.
- 759 Girvan, M. S., Campbell, C. D., Killham, K., Prosser, J. I. & Glover, L. A. 2005. Bacterial  
760 diversity promotes community stability and functional resilience after perturbation.  
761 *Environmental Microbiology*, **7**, 301-313.
- 762 Godefroid, S. & Koedam, N. 2004a. Interspecific variation in soil compaction sensitivity  
763 among forest floor species. *Biological Conservation*, **119**, 207-217.
- 764 Godefroid, S. & Koedam, N. 2004b. The impact of forest paths upon adjacent vegetation:  
765 effects of the path surfacing material on the species composition and soil compaction.  
766 *Biological Conservation*, **119**, 405-419.
- 767 Gonzalez, R. C., Calleja, C. A., Arias, M. T. G., Fernandez, M. C. G. & Garcia, B. M. 1999.  
768 Decontamination of poultry meats: II. Physical treatments and the situation in the EU.  
769 *Alimentaria*, **36**, 103-111.
- 770 Gregory, A. S. & Vickers, A. W. 2003. Effects of amendments on soil structural development  
771 in a clay soil-forming material used as a cap for landfill restoration. *Soil Use and*  
772 *Management*, **19**, 273-276.
- 773 Gregory, A. S. & Vickers, A. W. 2007. Short-term soil development in a clay soil-forming  
774 material used as a landfill restoration cap: a case study. *Land Contamination &*  
775 *Reclamation*, **15**, 289-300.
- 776 Gregory, A. S., Watts, C. W., Whalley, W. R., Kuan, H. L., Griffiths, B. S., Hallett, P. D. &  
777 Whitmore, A. P. 2007. Physical resilience of soil to field compaction and the



778 interactions with plant growth and microbial community structure. *European Journal*  
779 *of Soil Science*, **58**, 1221-1232.

780 Gregory, A. S., Watts, C. W., Griffiths, B. S., Hallett, P. D., Kuan, H. L. & Whitmore, A. P.  
781 2009. The effect of long-term soil management on the physical and biological  
782 resilience of a range of arable and grassland soils in England. *Geoderma*, **153**, 172-  
783 185.

784 Gregory, A. S., Kirk, G. J. D., Keay, C. A., Rawlins, B. G., Wallace, P. & Whitmore, A. P.  
785 2014. An assessment of subsoil organic carbon stocks in England and Wales. *Soil Use*  
786 *and Management*, **30**, 10-22.

787 Griffiths, B. S., Bonkowski, M., Roy, J. & Ritz, K. 2001. Functional stability, substrate  
788 utilisation and biological indicators of soils following environmental impacts. *Applied*  
789 *Soil Ecology*, **16**, 49-61.

790 Griffiths, B. S., Hallett, P. D., Kuan, H. L., Pitkin, Y. & Aitken, M. N. 2005. Biological and  
791 physical resilience of soil amended with heavy metal-contaminated sewage sludge.  
792 *European Journal of Soil Science*, **56**, 197-205.

793 Griffiths, B. S., Hallett, P. D., Kuan, H. L., Gregory, A. S., Watts, C. W. & Whitmore, A. P.  
794 2008. Functional resilience of soil microbial communities depends on both soil  
795 structure and microbial community composition. *Biology and Fertility of Soils*, **44**,  
796 745-754.

797 Griffiths, R. I., Thomson, B. C., James, P., Bell, T., Bailey, M. & Whiteley, A. S. 2011. The  
798 bacterial biogeography of British soils. *Environmental Microbiology*, **13**, 1642-1654.

799 Gunn, D. A., Chambers, J. E., Hobbs, P. R. N., Ford, J. R., Wilkinson, P. B., Jenkins, G. O. &  
800 Merritt, A. 2013. Rapid observations to guide the design of systems for long-term  
801 monitoring of a complex landslide in the Upper Lias clays of North Yorkshire, UK.  
802 *Quarterly Journal of Engineering Geology and Hydrogeology*, **46**, 323-336.

- 803 Han, L. B., Song, G. L. & Zhang, X. 2008. Preliminary observations on physiological  
804 responses of three turfgrass species to traffic stress. *Horttechnology*, **18**, 139-143.
- 805 Harris, J. A. 2003. Measurements of the soil microbial community for estimating the success  
806 of restoration. *European Journal of Soil Science*, **54**, 801-808.
- 807 Harris, J. A. & Birch, P. 1990. The effects of heavy civil engineering and stockpiling on the  
808 soil microbial community. *Microbiology in Civil Engineering*, **59**, 274-287.
- 809 Harris, J. A., Birch, P. & Short, K. C. 1989. Changes in the microbial community and  
810 physico-chemical characteristics of topsoils stockpiled during opencast mining. *Soil*  
811 *Use and Management*, **5**, 161-168.
- 812 Harris, J. A., Birch, P. & Short, K. C. 1993. Changes in the microbial community during the  
813 construction and subsequent storage of soil stockpiles: A strategist theory  
814 interpretation. *Restoration Ecology*, **1**, 88-100.
- 815 Harrison, A. M., Plim, J. F. M., Harrison, M., Jones, L. D. & Culshaw, M. G. 2012. The  
816 relationship between shrink-swell occurrence and climate in south-east England.  
817 *Proceedings of the Geologists Association*, **123**, 556-575.
- 818 Heathwaite, A. L., Burt, T. P. & Trudgill, S. T. 1990. The effect of land use on nitrogen,  
819 phosphorus and suspended sediment delivery to streams in a small catchment in  
820 southwest England. In: *Vegetation and Erosion. Processes and Environments*. (ed J.  
821 B. Thornes), John Wiley, Chichester, UK, pp. 161-178.
- 822 Heisler, C. & Kaiser, E. A. 1995. Influence of agricultural traffic and crop management on  
823 collembola and microbial biomass in arable soil. *Biology and Fertility of Soils*, **19**,  
824 159-165.
- 825 Hirsch, P. R., Jones, M. J., McGrath, S. P. & Giller, K. E. 1993. Heavy metals from past  
826 applications of sewage sludge decrease the genetic diversity of *Rhizobium*

827 leguminosarum biovar trifolii populations. *Soil Biology & Biochemistry*, **25**, 1485-  
828 1490.

829 Hirsch, P. R., Gilliam, L. M., Sohi, S. P., Williams, J. K., Clark, I. M. & Murray, P. J. 2009.  
830 Starving the soil of plant inputs for 50 years reduces abundance but not diversity of  
831 soil bacterial communities. *Soil Biology & Biochemistry*, **41**, 2021-2024.

832 HMG 1996. *Minerals Planning Guidance 7: Reclamation of Mineral Workings*. Her  
833 Majesty's Government. Office of the Deputy Prime Minister. The Stationery Office.  
834 London, UK. pp. 53.

835 HMG 2009a. *Adapting to Climate Change: UK Climate Projections*. Her Majesty's  
836 Government. Department for Environment, Food and Rural Affairs. Defra. London,  
837 UK. pp. 43.

838 HMG 2009b. *Safeguarding our Soils: A Strategy for England*. Her Majesty's Government.  
839 Department for Environment, Food and Rural Affairs. Defra. London, UK. pp. 42.

840 HMG 2011a. *Defra's Evidence Investment Strategy: 2010-2013 and beyond. 2011 Update*.  
841 Her Majesty's Government. Department for Environment, Food and Rural Affairs.  
842 London, UK. pp. 51.

843 HMG 2011b. *The Natural Choice: Securing the Value of Nature*. Her Majesty's Government.  
844 Department for Environment, Food and Rural Affairs. The Stationery Office.  
845 Norwich, UK. pp. 78.

846 Huber, S., Prokop, G., Arrouays, D., Banko, G., Bispo, A., Jones, R. J. A., Kibblewhite, M.  
847 G., Lexer, W., Möller, A., Rickson, R. J., Shishkov, T., Stephens, M., Toth, G., van  
848 den Akker, J. J. H., Varallyay, G., Verheijen, F. G. A. & Jones, A. R. (eds) 2008.  
849 *Environmental Assessment of Soil for Monitoring: Volume I Indicators & Criteria*.  
850 *EUR 23490 EN/1.*, Office for the Official Publications of the European Communities,  
851 Luxembourg.

852 Hund-Rinke, K. & Kördel, W. 2003. Underlying issues in bioaccessibility and bioavailability:  
853 experimental methods. *Ecotoxicology and Environmental Safety*, **56**, 52-62.

854 ISO 2006. *ISO11074:2005 Soil quality: Vocabulary*, International Organization for  
855 Standardization, Geneva, Switzerland.

856 Jefferies, R. L. & Maron, J. L. 1997. The embarrassment of riches: Atmospheric deposition  
857 of nitrogen and community and ecosystem processes. *Trends in Ecology & Evolution*,  
858 **12**, 74-78.

859 Jenkinson, D. S., Poulton, P. R. & Bryant, C. 2008. The turnover of organic carbon in  
860 subsoils. Part 1. Natural and bomb radiocarbon in soil profiles from the Rothamsted  
861 long-term field experiments. *European Journal of Soil Science*, **59**, 391-399.

862 Jensen, L. S., McQueen, D. J. & Shepherd, T. G. 1996. Effects of soil compaction on N-  
863 mineralization and microbial-C and -N .1. Field measurements. *Soil & Tillage*  
864 *Research*, **38**, 175-188.

865 Johnson, D. B., Williamson, J. C. & Bailey, A. J. 1988. Response of soil micro-organisms to  
866 stockpiling and land restoration. In: *A Seminar on Land Restoration Techniques: Ten*  
867 *Years of Research- What Next? Newcastle upon Tyne, UK. 18-20 July 1988*. British  
868 Coal Opencast Executive, Mansfield, UK, pp. 95-108.

869 Johnson, R. M. & Warburton, J. 2015. Sediment erosion dynamics of a gullied debris slide: a  
870 medium-term record. *Catena*, **127**, 152-169.

871 Johnston, A. E. 1986. Soil organic matter, effects on soils and crops. *Soil Use and*  
872 *Management*, **2**, 97-105.

873 Johnston, A. E., Poulton, P. R. & Coleman, K. 2009. Soil organic matter: its importance in  
874 sustainable agriculture and carbon dioxide fluxes. *Advances in Agronomy*, **101**, 1-57.

875 Kay, A. L., Jones, R. G. & Reynard, N. S. 2006. RCM rainfall for UK flood frequency  
876 estimation. II. Climate change results. *Journal of Hydrology*, **318**, 163-172.

877 Kibblewhite, M. G., Jones, R. J. A., Baritz, R., Huber, S., Arrouays, D., Micheli, E. &  
878 Stephens, M. 2008. ENVASSO Final Report Part I: Scientific and Technical  
879 Activities. ENVASSO Project (Contract 022713) coordinated by Cranfield  
880 University, UK, for Scientific Support to Policy, European Commission 6th  
881 Framework Research Programme.

882 Kohler, F., Hamelin, J., Gillet, F., Gobat, J. M. & Buttler, A. 2005. Soil microbial community  
883 changes in wooded mountain pastures due to simulated effects of cattle grazing. *Plant  
884 and Soil*, **278**, 327-340.

885 Korner, C. 2000. Biosphere responses to CO<sub>2</sub> enrichment. *Ecological Applications*, **10**, 1590-  
886 1619.

887 Korschens, M., Weigel, A. & Schulz, E. 1998. Turnover of soil organic matter (SOM) and  
888 long-term balances - tools for evaluating sustainable productivity of soils. *Zeitschrift  
889 fur Pflanzenernahrung und Bodenkunde*, **161**, 409-424.

890 Kretzschmar, A. 1991. Burrowing ability of the earthworm *Aporrectodea longa* limited by  
891 soil compaction and water potential. *Biology and Fertility of Soils*, **11**, 48-51.

892 Kronvang, B. 1990. Sediment-associated phosphorus transport from two intensively farmed  
893 catchment areas. In: *Soil Erosion on Agricultural Land*. eds J. Boardman, L. D. L.  
894 Foster & J. A. Dearing), John Wiley, Chichester, UK, pp. 313-330.

895 Kuan, H. L., Hallett, P. D., Griffiths, B. S., Gregory, A. S., Watts, C. W. & Whitmore, A. P.  
896 2007. The biological and physical stability and resilience of a selection of Scottish  
897 soils to stresses. *European Journal of Soil Science*, **58**, 811-821.

898 Lair, G. J., Zehetner, F., Fiebig, M., Gerzabek, M. H., van Gestel, C. A. M., Hein, T.,  
899 Hohensinner, S., Hsu, P., Jones, K. C., Jordan, G., Koelmans, A. A., Poot, A.,  
900 Slijkerman, D. M. E., Totsche, K. U., Bondar-Kunze, E. & Barth, J. A. C. 2009. How  
901 do long-term development and periodical changes of river-floodplain systems affect

902 the fate of contaminants? Results from European rivers. *Environmental Pollution*,  
903 **157**, 3336-3346.

904 Lal, R. 2003. Soil erosion and the global carbon budget. *Environment International*, **29**, 437-  
905 450.

906 Long, S. P., Ainsworth, E. A., Rogers, A. & Ort, D. R. 2004. Rising atmospheric carbon  
907 dioxide: plants face the future. *Annual Review of Plant Biology*, **55**, 591-628.

908 Loveland, P. & Webb, J. 2003. Is there a critical level of organic matter in the agricultural  
909 soils of temperate regions: a review. *Soil & Tillage Research*, **70**, 1-18.

910 Lowe, J. A., Howard, T. P., Pardaens, A., Tinker, J., Holt, J., Wakelin, S., Milne, G., Leake,  
911 J., Wolf, J., Horsburgh, K., Reeder, T., Jenkins, G., Ridley, J., Dye, S. & Bradley, S.  
912 2009. UK Climate Projections Science Report: Marine and Coastal Projections. Met  
913 Office Hadley Centre, Exeter, UK.

914 Mackney, D., Hodgson, J. M., Hollis, J. M. & Staines, S. J. 1983. *The 1:250000 National Soil*  
915 *Map of England and Wales*. Soil Survey of England and Wales, Harpenden, UK.

916 Malik, A. & Scullion, J. 1998. Soil development on restored opencast coal sites with  
917 particular reference to organic matter and aggregate stability. *Soil Use and*  
918 *Management*, **14**, 234-239.

919 Marjamaki, T. & Pietola, L. 2007. Root growth dynamics in golf greens with different  
920 compression intensities and winter survival. *Agricultural and Food Science*, **16**, 66-  
921 76.

922 Matthews, G. P., Laudone, G. M., Gregory, A. S., Bird, N. R. A., Matthews, A. G. d. G. &  
923 Whalley, W. R. 2010. Measurement and simulation of the effect of compaction on the  
924 pore structure and saturated hydraulic conductivity of grassland and arable soil. *Water*  
925 *Resources Research*, **46**, W05501.

- 926 McGrath, S. P. 1998. Phytoextraction for soil remediation. In: *Plants That Hyperaccumulate*  
927 *Heavy Metals: Their Role in Phytoremediation, Microbiology, Archaeology, Mineral*  
928 *Exploration and Phytomining*. (ed R. R. Brooks), CABI, Wallingford, UK, pp. 261-  
929 287.
- 930 McGrath, S.P. & Zhao, F.J. 2015. Concentrations of metals and metalloids in soils that have  
931 the potential to lead to exceedance of maximum limit concentrations of contaminants  
932 in food and feed. *Soil Use and Management*, **in press**.
- 933 McHale, G., Newton, M. I. & Shirtcliffe, N. J. 2005. Water-repellent soil and its relationship  
934 to granularity, surface roughness and hydrophobicity: a materials science view.  
935 *European Journal of Soil Science*, **56**, 445-452.
- 936 McHugh, M., Harrod, T. & Morgan, R. 2002. The extent of soil erosion in upland England  
937 and Wales. *Earth Surface Processes and Landforms*, **27**, 99-107.
- 938 McTiernan, K. B., Jarvis, S. C., Scholefield, D. & Hayes, M. H. B. 2001. Dissolved organic  
939 carbon losses from grazed grasslands under different management regimes. *Water*  
940 *Research*, **35**, 2565-2569.
- 941 Met Office 2015. *What is climate change?* [Online] Available at:  
942 <http://www.metoffice.gov.uk/climate-guide/climate-change>; accessed 01/05/2015.
- 943 Milan, D. J. 2012. Geomorphic impact and system recovery following an extreme flood in an  
944 upland stream: Thinhope Burn, northern England, UK. *Geomorphology*, **138**, 319-  
945 328.
- 946 Millennium Ecosystem Assessment 2005. *Ecosystems and Human Well-Being: Current*  
947 *States and Trends*, Island Press, Washington DC, USA.
- 948 Mooney, S. J. & Nipattasuk, W. 2003. Quantification of the effects of soil compaction on  
949 water flow using dye tracers and image analysis. *Soil Use and Management*, **19**, 356-  
950 363.

951 Morton, D., Rowland, C., Wood, C., Meek, L., Marston, C., Smith, G., Wadsworth, R. &  
952 Simpson, I. C. 2011. *Final Report for LCM2007 - the new UK Land Cover Map*.  
953 Countryside Survey Technical Report No. 11/07. CEH Project No. C03259. Natural  
954 Environment Research Council/Centre for Ecology & Hydrology, Wallingford, Oxon,  
955 UK. pp. 112.

956 NEG-TAP 2001. *Transboundary Air Pollution: Acidification, Eutrophication and Ground-*  
957 *Level Ozone in the UK*. National Expert Group on Transboundary Air Pollution at  
958 CEH Edinburgh on behalf of the UK Department for Environment, Food and Rural  
959 Affairs, Scottish Executive, the National Assembly for Wales / Cynulliad  
960 Cenedlaethol Cymru, Department of the Environment for Northern Ireland. [Online]  
961 Available at: [http://uk-air.defra.gov.uk/library/reports?report\\_id=109](http://uk-air.defra.gov.uk/library/reports?report_id=109); accessed:  
962 01/01/2014.

963 ONS 2012. *2011 Census. Population and Household Estimates for England and Wales*.  
964 Office for National Statistics. pp. 36. [Online] Available at:  
965 [http://www.ons.gov.uk/ons/dcp171778\\_270487.pdf](http://www.ons.gov.uk/ons/dcp171778_270487.pdf); accessed 24/07/2014.

966 ONS 2013. *2011 Census Analysis. Comparing Rural and Urban Areas of England and*  
967 *Wales*. Office for National Statistics. pp. 43. [Online] Available at:  
968 [http://www.ons.gov.uk/ons/rel/census/2011-census-analysis/rural-urban-](http://www.ons.gov.uk/ons/rel/census/2011-census-analysis/rural-urban-analysis/comparing-rural-and-urban-areas-of-england-and-wales.html)  
969 [analysis/comparing-rural-and-urban-areas-of-england-and-wales.html](http://www.ons.gov.uk/ons/rel/census/2011-census-analysis/rural-urban-analysis/comparing-rural-and-urban-areas-of-england-and-wales.html); accessed  
970 24/07/2014.

971 Orwin, K. H., Wardle, D. A. & Greenfield, L. G. 2006. Ecological consequences of carbon  
972 substrate identity and diversity in a laboratory study. *Ecology*, **87**, 580-593.

973 Palmer, R. C. & Smith, R. P. 2013. Soil structural degradation in SW England and its impact  
974 on surface-water runoff generation. *Soil Use and Management*, **29**, 567-575.



- 975 Park, J., Duan, L., Kim, B., Mitchell, M. J. & Shibata, H. 2010. Potential effects of climate  
976 change and variability on watershed biogeochemical processes and water quality in  
977 Northeast Asia. *Environment International*, **36**, 212-225.
- 978 Pearson, J. & Stewart, G. R. 1993. The deposition of atmospheric ammonia and its effects on  
979 plants. *New Phytologist*, **125**, 283-305.
- 980 Phoenix, G. K., Booth, R. E., Leake, J. R., Read, D. J., Grime, J. P. & Lee, J. A. 2004.  
981 Simulated pollutant nitrogen deposition increases P demand and enhances root-  
982 surface phosphatase activities of three plant functional types in a calcareous grassland.  
983 *New Phytologist*, **161**, 279-289.
- 984 Pearce, T. G. 1984. Earthworm populations in soils disturbed by trampling. *Biological*  
985 *Conservation*, **29**, 241-252.
- 986 Pilgrim, E. S., Macleod, C. J. A., Blackwell, M. S. A., Bol, R., Hogan, D. V., Chadwick, D.  
987 R., Cardenas, L., Misselbrook, T. H., Haygarth, P. M., Brazier, R. E., Hobbs, P.,  
988 Hodgson, C., Jarvis, S., Dungait, J., Murray, P. J. & Firbank, L. G. 2010. Interactions  
989 among agricultural production and other ecosystem services delivered from European  
990 temperate grassland systems. *Advances in Agronomy*, **109**, 117-154.
- 991 Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., Ncnair, M., Crist, S.,  
992 Shpritz, L., Fitton, L., Saffouri, R. & Blair, R. 1995. Environmental and economic  
993 costs of soil erosion and conservation benefits. *Science*, **267**, 1117-1123.
- 994 Piotrowska-Dlugosz, A. & Charzyński, P. 2015. The impact of the soil sealing degree on  
995 microbial biomass, enzymatic activity, and physicochemical properties in the Ekranic  
996 Technosols of Toruń (Poland). *Journal of Soils and Sediments*, **15**, 47-59.
- 997 Poulton, P. R., Pye, E., Hargreaves, P. R. & Jenkinson, D. S. 2003. Accumulation of carbon  
998 and nitrogen by old arable land reverting to woodland. *Global Change Biology*, **9**,  
999 942-955.

- 1000 Power, S. A., Ashmore, M. R. & Cousins, D. A. 1998. Impacts and fate of experimentally  
1001 enhanced nitrogen deposition on a British lowland heath. *Environmental Pollution*,  
1002 **102**, 27-34.
- 1003 Pritchard, O. G., Hallett, S. H. & Farewell, T. S. 2014. Soil impacts on UK infrastructure:  
1004 current and future climate. *Proceedings of the Institution of Civil Engineers-*  
1005 *Engineering Sustainability*, **167**, 170-184.
- 1006 Proctor, M. E., Siddons, P. A., Jones, R. J. A., Bellamy, P. H. & Keay, C. A. 1998. LandIS - a  
1007 land information system for the UK. In: *Land Information Systems: Developments for*  
1008 *Planning the Sustainable Use of Land Resources*. European Soil Bureau Research  
1009 Report No. 4. EUR 17729 EN (eds. H. J. Heineke, W. Eckelmann, A. J. Thomasson,  
1010 R. J. A. Jones, L. Montanarella & B. Buckley), Office for Official Publications of the  
1011 European Communities, Luxembourg, pp. 219–233.
- 1012 Quinton, J. N. & Catt, J. A. 2004. The effects of minimal tillage and contour cultivation on  
1013 surface runoff, soil loss and crop yield in the long-term Woburn Erosion Reference  
1014 Experiment on sandy soil at Woburn, England. *Soil Use and Management*, **20**, 343-  
1015 349.
- 1016 Quinton, J. N., Catt, J. A. & Hess, T. M. 2001. The selective removal of phosphorus from  
1017 soil: Is event size important? *Journal of Environmental Quality*, **30**, 538-545.
- 1018 Quinton, J. N., Catt, J. A., Wood, G. A. & Steer, J. 2006. Soil carbon losses by water erosion:  
1019 Experimentation and modeling at field and national scales in the UK. *Agriculture*  
1020 *Ecosystems & Environment*, **112**, 87-102.
- 1021 Radford, B. J., Wilson-Rummenie, A. C., Simpson, G. B., Bell, K. L. & Ferguson, M. A.  
1022 2001. Compacted soil affects soil macrofauna populations in a semi-arid environment  
1023 in central Queensland. *Soil Biology & Biochemistry*, **33**, 1869-1872.

- 1024 Raiswell, R. 2001. Defining the burial environment. In: *Handbook of Archaeological*  
1025 *Sciences*. eds D. R. Brothwell & A. M. Pollard), John Wiley & Sons Ltd, Chichester,  
1026 UK, pp. 595-603.
- 1027 Reynolds, W. D., Drury, C. F., Yang, X. M., Fox, C. A., Tan, C. S. & Zhang, T. Q. 2007.  
1028 Land management effects on the near-surface physical quality of a clay loam soil. *Soil*  
1029 *& Tillage Research*, **96**, 316-330.
- 1030 Reynolds, B., Chamberlain, P. M., Poskitt, J., Woods, C., Scott, W. A., Rowe, E. C.,  
1031 Robinson, D. A., Frogbrook, Z. L., Keith, A. M., Henrys, P. A., Black, H. I. J. &  
1032 Emmett, B. A. 2013. Countryside survey: national "soil change" 1978-2007 for  
1033 topsoils in Great Britain - acidity, carbon, and total nitrogen status. *Vadose Zone*  
1034 *Journal*, **12**, 0114.
- 1035 Richard, G., Cousin, I., Sillon, J. F., Bruand, A. & Guerif, J. 2001. Effect of compaction on  
1036 the porosity of a silty soil: influence on unsaturated hydraulic properties. *European*  
1037 *Journal of Soil Science*, **52**, 49-58.
- 1038 Riley, H., Pommeresche, R., Eltun, R., Hansen, S. & Korsath, A. 2008. Soil structure,  
1039 organic matter and earthworm activity in a comparison of cropping systems with  
1040 contrasting tillage, rotations, fertilizer levels and manure use. *Agriculture Ecosystems*  
1041 *& Environment*, **124**, 275-284.
- 1042 Roach, S. H. & Campbell, R. B. 1983. Effects of soil compaction on bollworm (Lepidoptera:  
1043 Noctuidae) moth emergence. *Environmental Entomology*, **12**, 1882-1886.
- 1044 Robinson, D. A. & Woodun, J. K. 2008. An experimental study of crust development on  
1045 chalk downland soils and their impact on runoff and erosion. *European Journal of*  
1046 *Soil Science*, **59**, 784-798.

- 1047 Rodway-Dyer, S. J. & Walling, D. E. 2010. The use of Cs-137 to establish longer-term soil  
1048 erosion rates on footpaths in the UK. *Journal of Environmental Management*, **91**,  
1049 1952-1962.
- 1050 Rohrig, R., Langmaack, M., Schrader, S. & Larink, O. 1998. Tillage systems and soil  
1051 compaction - their impact on abundance and vertical distribution of Enchytraeidae.  
1052 *Soil & Tillage Research*, **46**, 117-127.
- 1053 Roovers, P., Baeten, S. & Hermy, M. 2004. Plant species variation across path ecotones in a  
1054 variety of common vegetation types. *Plant Ecology*, **170**, 107–119.
- 1055 Rost, U., Joergensen, R. G. & Chander, K. 2001. Effects of Zn enriched sewage sludge on  
1056 microbial activities and biomass in soil. *Soil Biology & Biochemistry*, **33**, 633-638.
- 1057 ROTAP 2009. *Review of Transboundary Air Pollution. Acidification, Eutrophication,*  
1058 *Ground Level Ozone and Heavy Metals in the UK*. Complete ROTAP Report. Centre  
1059 for Ecology and Hydrology, Penicuik, UK. [Online] Available at:  
1060 <http://www.rotap.ceh.ac.uk>; accessed 01/01/2014.
- 1061 Rounsevell, M. D. A. & Brignall, A. P. 1994. The potential effects of climate change on  
1062 autumn soil tillage opportunities in England and Wales. *Soil & Tillage Research*, **32**,  
1063 275-289.
- 1064 Rousk, J., Brookes, P. C. & Baath, E. 2009. Contrasting soil pH effects on fungal and  
1065 bacterial growth suggest functional redundancy in carbon mineralization. *Applied and*  
1066 *Environmental Microbiology*, **75**, 1589-1596.
- 1067 Rushton, S. P. 1986. The effects of soil compaction on *Lumbricus terrestris* and its possible  
1068 implications for populations on land reclaimed from open-cast coal mining.  
1069 *Pedobiologia*, **29**, 85-90.
- 1070 Scalenghe, R. & Marsan, F. A. 2009. The anthropogenic sealing of soils in urban areas.  
1071 *Landscape and Urban Planning*, **90**, 1-10.

- 1072 Scholefield, D., Tyson, K. C., Garwood, E. A., Armstrong, A. C., Hawkins, J. & Stone, A. C.  
1073 1993. Nitrate leaching from grazed grassland lysimeters: effects of fertilizer input,  
1074 field drainage, age of sward and patterns of weather. *Journal of Soil Science*, **44**, 601-  
1075 613.
- 1076 Schrader, S. & Lingnau, M. 1997. Influence of soil tillage and soil compaction on  
1077 microarthropods in agricultural land. *Pedobiologia*, **41**, 202-209.
- 1078 Schrader, S., Langmaack, M. & Helming, K. 1997. Impact of Collembola and enchytraeidae  
1079 on soil surface roughness and properties. *Biology and Fertility of Soils*, **25**, 396-400.
- 1080 Scott, D. I., Tams, A. R., Berry, P. M. & Mooney, S. J. 2005. The effects of wheel-induced  
1081 soil compaction on anchorage strength and resistance to root lodging of winter barley  
1082 (*Hordeum vulgare* L.). *Soil & Tillage Research*, **82**, 147-160.
- 1083 Servadio, P., Marsili, A., Vignozzi, N., Pellegrini, S. & Pagliai, M. 2005. Effects on some  
1084 soil qualities in central Italy following the passage of four wheel drive tractor fitted  
1085 with single and dual tires. *Soil & Tillage Research*, **84**, 87-100.
- 1086 SG 2009. *The Scottish Soil Framework*, The Scottish Government, Edinburgh, UK, pp. 64.
- 1087 Shestak, C. J. & Busse, M. D. 2005. Compaction alters physical but not biological indices of  
1088 soil health. *Soil Science Society of America Journal*, **69**, 236-246.
- 1089 Simpson, S. L., Fitzpatrick, R. W., Shand, P., Angel, B. M., Spadaro, D. A. & Mosley, L.  
1090 2010. Climate-driven mobilisation of acid and metals from acid sulfate soils. *Marine  
1091 and Freshwater Research*, **61**, 129-138.
- 1092 Smith, J., Smith, P., Wattenbach, M., Zaehle, S., Hiederer, R., Jones, R. J. A., Montanarella,  
1093 L., Rounsevell, M. D. A., Reginster, I. & Ewert, F. 2005. Projected changes in  
1094 mineral soil carbon of European croplands and grasslands, 1990-2080. *Global Change  
1095 Biology*, **11**, 2141-2152.

1096 Smith, P., Chapman, S. J., Scott, W. A., Black, H. I. J., Wattenbach, M., Milne, R., Campbell,  
1097 C. D., Lilly, A., Ostle, N., Levy, P. E., Lumsdon, D. G., Millard, P., Towers, W.,  
1098 Zaehle, S. & Smith, J. U. 2007. Climate change cannot be entirely responsible for soil  
1099 carbon loss observed in England and Wales, 1978-2003. *Global Change Biology*, **13**,  
1100 2605-2609.

1101 Smolders, E., Oorts, K., van Sprang, P., Schoeters, I., Janssen, C. R., McGrath, S. P. &  
1102 McLaughlin, M. J. 2009. Toxicity of trace metals in soil as affected by soil type and  
1103 aging after contamination: using calibrated bioavailability models to set ecological  
1104 soil standards. *Environmental Toxicology and Chemistry*, **28**, 1633-1642.

1105 Spurgeon, D. J. & Hopkin, S. P. 1996. Effects of metal-contaminated soils on the growth,  
1106 sexual development, and early cocoon production of the earthworm *Eisenia fetida*,  
1107 with particular reference to zinc. *Ecotoxicology and Environmental Safety*, **35**, 86-95.

1108 Styers, D. M., Chappelka, A. H., Marzen, L. J. & Somers, G. L. 2010. Developing a land-  
1109 cover classification to select indicators of forest ecosystem health in a rapidly  
1110 urbanizing landscape. *Landscape and Urban Planning*, **94**, 158-165.

1111 Suseela, V. & Dukes, J. S. 2013. The responses of soil and rhizosphere respiration to  
1112 simulated climatic changes vary by season. *Ecology*, **94**, 403-413.

1113 Sutherland, W. J., Bailey, M. J., Bainbridge, I. P., Brereton, T., Dick, J. T. A., Drewitt, J.,  
1114 Dulvy, N. K., Dusic, N. R., Freckleton, R. P., Gaston, K. J., Gilder, P. M., Green, R.  
1115 E., Heathwaite, A. L., Johnson, S. M., Macdonald, D. W., Mitchell, R., Osborn, D.,  
1116 Owen, R. P., Pretty, J., Prior, S. V., Prosser, H., Pullin, A. S., Rose, P., Stott, A., Tew,  
1117 T., Thomas, C. D., Thompson, D. B. A., Vickery, J. A., Walker, M., Walmsley, C.,  
1118 Warrington, S., Watkinson, A. R., Williams, R. J., Woodroffe, R. & Woodroof, H. J.  
1119 2008. Future novel threats and opportunities facing UK biodiversity identified by  
1120 horizon scanning. *Journal of Applied Ecology*, **45**, 821-833.

- 1121 Tarrant, S., Ollerton, J., Rahman, M. L., Tarrant, J. & McCollin, D. 2013. Grassland  
1122 Restoration on Landfill Sites in the East Midlands, United Kingdom: An Evaluation  
1123 of Floral Resources and Pollinating Insects. *Restoration Ecology*, **21**, 560-568.
- 1124 Tisdall, J. M. & Oades, J. M. 1980. The effect of crop rotation on aggregation in a red brown  
1125 earth. *Australian Journal of Soil Research*, **18**, 423-433.
- 1126 Tisdall, J. M. & Oades, J. M. 1982. Organic matter and water-stable aggregates in soils.  
1127 *Journal of Soil Science*, **33**, 141-163.
- 1128 Tyson, K. C., Garwood, E. A., Armstrong, A. C. & Scholefield, D. 1992. Effects of field  
1129 drainage on the growth of herbage and the liveweight gain of grazing beef cattle.  
1130 *Grass and Forage Science*, **47**, 290-301.
- 1131 Unger, I. M., Kennedy, A. C. & Muzika, R. M. 2009. Flooding effects on soil microbial  
1132 communities. *Applied Soil Ecology*, **42**, 1-8.
- 1133 van Camp, N., vande Walle, I., Mertens, J., De Neve, S., Samson, R., Lust, N., Lemeur, R.,  
1134 Boeckx, P., Lootens, P., Beheydt, D., Mestdagh, I., Sleutel, S., Verbeeck, H., van  
1135 Cleemput, O., Hofman, G. & Carlier, L. 2004. Inventory-based carbon stock of  
1136 Flemish forests: comparison of European biomass expansion factors. *Annals of Forest  
1137 Science*, **61**, 677-682.
- 1138 van den Akker, J. J. H. 1997. Construction of a wheel-load bearing capacity map of the  
1139 Netherlands. In: *Proceedings of the 14th International Soil Tillage Research  
1140 Organization Conference, Pulawy, Poland, 27 July - 01 August 1997. Bibliotheca  
1141 Fragmenta Agronomica*. pp. 15-18.
- 1142 van Oost, K., Quine, T. A., Govers, G., De Gryze, S., Six, J., Harden, J. W., Ritchie, J. C.,  
1143 McCarty, G. W., Heckrath, G., Kosmas, C., Giraldez, J. V., da Silva, J. R. M. &  
1144 Merckx, R. 2007. The impact of agricultural soil erosion on the global carbon cycle.  
1145 *Science*, **318**, 626-629.

- 1146 van Oost, K., Cerdan, O. & Quine, T. A. 2009. Accelerated sediment fluxes by water and  
1147 tillage erosion on European agricultural land. *Earth Surface Processes and*  
1148 *Landforms*, **34**, 1625-1634.
- 1149 Verheijen, F.G.A., Jones, R.J.A., Rickson, R.J. & Smith, C.J. 2009. Tolerable versus actual  
1150 soil erosion rates in Europe. *Earth Science Reviews*, **94**, 23-38.
- 1151 Virto, I., Imaz, M. J., Fernández-Ugalde, O., Gartzia-Bengoetxea, N., Enrique, A. &  
1152 Bescansa, P. 2015. Soil degradation and soil quality in Western Europe: current  
1153 situation and future perspectives. *Sustainability*, **7**, 313-365.
- 1154 WAG 2006. *Environment Strategy for Wales*, Welsh Assembly Government, Cardiff, UK,  
1155 pp. 70.
- 1156 Wardle, D. A., Yeates, G. W., Barker, G. M. & Bonner, K. I. 2006. The influence of plant  
1157 litter diversity on decomposer abundance and diversity. *Soil Biology & Biochemistry*,  
1158 **38**, 1052-1062.
- 1159 Watts, C. W. & Dexter, A. R. 1997. The influence of organic matter in reducing the  
1160 destabilization of soil by simulated tillage. *Soil & Tillage Research*, **42**, 253-275.
- 1161 Watts, C. W. & Dexter, A. R. 1998. Soil friability: theory, measurement and the effects of  
1162 management and organic carbon content. *European Journal of Soil Science*, **49**, 73-  
1163 84.
- 1164 Watts, C. W., Tolhurst, T. J., Black, K. S. & Whitmore, A. P. 2003. In situ measurements of  
1165 erosion shear stress and geotechnical shear strength of the intertidal sediments of the  
1166 experimental managed realignment scheme at Tollesbury, Essex, UK. *Estuarine*  
1167 *Coastal and Shelf Science*, **58**, 611-620.
- 1168 Wei, Z., Wu, S., Yan, X. & Zhou, S. 2014. Density and stability of soil organic carbon  
1169 beneath impervious surfaces in urban areas. *PLoS One*, **9**, e109380.



- 1170 Wenderoth, D. F. & Reber, H. H. 1999. Correlation between structural diversity and catabolic  
1171 versatility of metal-affected prototrophic bacteria in soil. *Soil Biology &*  
1172 *Biochemistry*, **31**, 345-352.
- 1173 Whalley, W. R., Dumitru, E. & Dexter, A. R. 1995. Biological effects of soil compaction.  
1174 *Soil & Tillage Research*, **35**, 53-68.
- 1175 Whalley, W. R., Clark, L. J., Gowing, D. J. G., Cope, R. E., Lodge, R. J. & Leeds-Harrison,  
1176 P. B. 2006. Does soil strength play a role in wheat yield losses caused by soil drying?  
1177 *Plant and Soil*, **280**, 279-290.
- 1178 Whalley, W. R., Watts, C. W., Gregory, A. S., Mooney, S. J., Clark, L. J. & Whitmore, A. P.  
1179 2008. The effect of soil strength on the yield of wheat. *Plant and Soil*, **306**, 237-247.
- 1180 Whitmore, A. P. & Whalley, W. R. 2009. Physical effects of soil drying on roots and crop  
1181 growth. *Journal of Experimental Botany*, **60**, 2845-2857.
- 1182 Whitmore, A. P., Rickson, R. J., Watts, C. W. & Clarke, M. A. 2004. Critical levels of soil  
1183 organic carbon in surface soils in relation to soil stability, function and infiltration.  
1184 Project SP0519 final report. Department for Environment, Food and Rural Affairs,  
1185 London, UK.
- 1186 Wick, A. F., Stahl, P. D., Ingram, L. J. & Vicklund, L. 2009. Soil aggregation and organic  
1187 carbon in short-term stockpiles. *Soil Use and Management*, **25**, 311-319.
- 1188 Williams, R. J. B. 1971. Relationships between the composition of soils and physical  
1189 measurements made on them. In: *Rothamsted Experimental Station. Report for 1970.*  
1190 *Part 2.* Rothamsted Experimental Station, Harpenden, UK, pp. 5-35.
- 1191 Wu, Y., Kemmitt, S., White, R. P., Xu, J. & Brookes, P. C. 2012. Carbon dynamics in a 60  
1192 year fallowed loamy-sand soil compared to that in a 60 year permanent arable or  
1193 permanent grassland UK soil. *Plant and Soil*, **352**, 51-63.

1194 **Table 1** The eight degradation threats identified as important for soils in the UK. The  
 1195 descriptions are those of Huber *et al.* (2008), unless stated otherwise.

Degradation threat	Brief description
Soil erosion	The accelerated loss of soil as a result of anthropogenic activity in excess of accepted rates of natural soil formation.
Decline in soil organic matter	The negative imbalance between the build-up of soil organic matter and rates of decomposition, leading to an overall decline in soil organic matter content and/or quality.
Soil contamination	The presence of a substance or agent in the soil as a result of human activity emitted from moving sources, from sources with a large area, or from many sources (diffuse) (ISO, 2006), or where intensive industrial activities, inadequate waste disposal, mining, military activities or accidents introduce excessive amounts of contaminants (local).
Soil compaction	The densification and distortion of soil by which total and air-filled porosity are reduced.
Soil sealing	The destruction or covering of soil by buildings, constructions and layers or other bodies of artificial material which may be very slowly permeable to water (Burghardt <i>et al.</i> , 2004).
Brownfield development	The further development of developed land previously used for commercial or industrial purposes, including restoration of green after-uses.
Soil salinisation	The excessive increase of water-soluble salts in soil through natural processes and human interventions.
Landslides	The movement of a mass of rock, debris, artificial fill or soil

---

down a slope under the force of gravity (Cruden & Varnes, 1996).

Climate change

The large-scale, long-term shift in the planet's weather patterns or average temperatures (Met Office, 2015).

---

1196