

1 Technologies for increasing carbon storage in soil to mitigate climate change

2 AP Whitmore¹, GJD Kirk² and BG Rawlins³

3 ¹*Rothamsted Research, Harpenden, Hertfordshire. AL5 2JQ*

4 ²*Cranfield University, Cranfield, Bedford MK43 0AL*

5 ³*British Geological Survey, Keyworth, Nottingham, NG12 5GG*

6 **Abstract**

7 Means to enhance storage of carbon in soil or avoid its loss from soil are discussed and examined
8 from the viewpoint of policy. In particular, technologies that have until now received little attention are
9 assessed. The main means by which soil carbon might be increased are first listed. These are: (i)
10 increasing the rate of input of organic matter; (ii) decreasing the rate of its decomposition by biological
11 or chemical means; (iii) increasing the rate of its stabilisation by physico-chemical protection within
12 aggregates and organo-mineral complexes; and (iv) increasing the depth or more correctly the total
13 soil volume sequestering carbon at maximum rate.

14 Immediate gains in carbon storage might be made by switching to more perennial crops, especially
15 grasses that as a result of breeding put more carbon into soil. In the longer term, targets for research
16 such as understanding the role of enzymes in carbon turnover and the exploitation of the capacity in
17 subsoils are suggested. Increased fixation of CO₂ as inorganic carbonate in soils by application of
18 silicate wastes may have some role.

19 **Introduction**

20 The UK Department for Environment, Food and Rural Affairs (Defra) sets soils policy for the England
21 and Wales and since the Millennium Assessment (2001), has adopted an Ecosystem Services
22 approach which is exemplified by the UK National Ecosystem Assessment (Anon, 2011) and has fed
23 into policy through the Natural Environment White Paper (Anon, 2011). Safeguarding Our Soils, A
24 Strategy for England (Defra, 2009) stresses the role that storage of carbon in soil can play in helping
25 to combat climate change and meeting the UK Government's emission reduction targets and carbon
26 budgets in England, introduced by the Climate Change Act 2008. Of particular importance is the
27 ability of soils to regulate carbon in the environment through storage or other means in the soil and
28 the wider value of soil organic carbon (SOC) on soil quality and the role it plays in the provision of
29 habitat for biodiversity. Safeguarding our soils also points out, however, the need that policy-makers
30 have for a robust evidence base with which to inform policy. Although there have been several recent
31 reviews of existing science and methodologies for increasing levels of carbon in soil, here we

32 consider less tried and tested technologies for their potential to retain carbon that would otherwise
33 increase atmospheric CO₂. Despite the use of UK data, many of the conclusions reached here are
34 relevant to policy-makers world-wide who are grappling with issues surrounding soil carbon and most
35 issues discussed are relevant to policy-makers in NW Europe.

36 There are two major components to the global carbon cycle: (i) a geological cycle which acts over
37 epochs but cycles very large amounts of carbon because of the time and spatial scales involved, and
38 (ii) a biological cycle that operates over much shorter periods of time. Humanity's current problems
39 and confusion with carbon stem from exploitation of the geological carbon and attempts to fix this by
40 manipulating the biological cycle. Because the two operate at different timescales there are huge
41 amounts of carbon to exploit from geological reserves but little capacity to fix this within the biology.
42 Nevertheless, the biological cycle does have some capacity and it is also worth noting that the two
43 cycles are not entirely distinct: the *soil* carbon cycle and chemical cycles sit somewhat in between
44 since soil C is derived from the annual biological cycling of plants on the one hand but is capable of
45 long-term physico-chemical preservation in soil for thousands of years in some instances.

46 Although there is some interest in means to stimulate the uptake of inorganic carbon dioxide directly
47 from the atmosphere, most carbon enters the soil through the plant

48 In this review we consider some novel ways in which policy might be used to steer interventions in
49 these short-term natural cycles in order to weigh the balance in favour of increased net input or
50 storage of carbon in soil. The principal factors that determine C sequestration in the soil are:

51

- 52 1. the rate of input of organic matter;
- 53 2. the rate of its decomposition by biological or chemical means;
- 54 3. the rate of its stabilisation by physico-chemical protection within aggregates and organo-
55 mineral complexes; and
- 56 4. the depth or more correctly the total soil volume sequestering carbon at maximum rate.

57

58 In this analysis a distinction has been made between physical methods of reducing decomposition (3)
59 of organic matter which tend to halt turnover, and methods which act on the chemical and biological
60 processes (2) because these latter tend to slow decomposition down rather than stop it altogether.

61 For previous reviews of this topic see Smith *et al.* (2000), Powlson *et al.* (2011) and Stockmann *et al.*
62 (2013).

63 **Increasing the rate of input of organic matter to soils**

64 *Agroforestry and intercropping*

65 Forest and woodland ecosystems contain more carbon than pasture or arable (Bolin *et al.*, 2000).

66 Although levels of soil carbon in the soils of the most productive pastoral systems can approach the

67 levels found in forest soils (Bolin *et al.*, 2000), arable soils usually contain much less C than either
68 forest or pasture (Bolin *et al.*, 2000). Mixed systems, that is to say trees and arable (known as
69 silvoarable or agroforestry systems) or trees and grass (known as silvopastoral systems) have been
70 proposed as a means to extend the benefits of forest to farmed land. Because different species use
71 resources differently, they can be complementary with one another, often yielding more and
72 consuming less than corresponding sole crops. It has been suggested recently that agroforestry and
73 intercropped systems increase the store of carbon in land managed for production (Nair *et al.*,
74 2009a,b). Nair *et al.* (2009b) report a range of soil C sequestration data with modest values of around
75 1 Mg C ha⁻¹. Gupta *et al.* (2009) found 3 Mg increase in one year and a 6 Mg ha⁻¹ increase during six
76 years, with little difference in loamy sand and sandy clay soils. Agroforestry and silvopastoral systems
77 contain more carbon in soil than cropland, but almost all the evidence comes from work in tropical and
78 sub-tropical soils with little work in temperate systems (Jose, 2009). Even in these studies, few
79 woodland controls exist so it is not clear if the resource-use complementarity referred to above leads
80 to extra carbon storage relative to sole species. Quinckenstein *et al.*, 2009; and Montagnini & Nair
81 (2004) who reviewed C sequestration in soils under temperate agroforestry systems cite a figure of
82 63-76 Mg C ha⁻¹ but the source of these values is unclear. There is a need to assess the potential of
83 temperate agroforestry systems for increasing soil C

84 Mixed tree and crop systems will stimulate the nitrogen cycle as well as the carbon cycle and a 25%
85 increase in emissions of N₂O has been found on a loamy soil in China (e.g. Guo *et al.*, 2009).
86 Verchot *et al.* (2008), however, found no increase in N₂O emitted on a sandy soil in the Amazon, nor
87 was CH₄ oxidation capacity of the soil affected. Results from the UK are lacking. If intercropped
88 systems are to be widely adopted in the UK, for whatever reason, the potential for increased N₂O
89 emissions needs to be assessed. Leaching of dissolved organic carbon (DOC) can often be high in
90 forest systems (e.g. Kalbitz *et al.*, 2004), but there is no evidence to show a change in DOC
91 production and loss in agroforestry or silvopastoral systems.

92 Intercropping field crops might improve C storage relative to monoculture controls too. Bolin *et al.*
93 (2000) quote data suggesting that temperate grasslands store 236 C Mg ha⁻¹ as a global average.
94 Sequestration rates of 65-70 Mg ha⁻¹ in 100 years have been quoted (Abberton *et al.*, 2007). On the
95 other hand Skinner *et al.*, (2006) found that soil C either remained the same with species mixtures or
96 declined during two years after sowing into a soil that had previously supported winter wheat. The
97 potential for soil carbon storage in intercropped soils does not appear to have been widely
98 investigated.

99 *Perennial in place of annual crops*

100 The development of perennial crops in place of current annual ones such as wheat through plant
101 breeding may lead to gains in soil C (Royal Society, 2009a). In general, perennial plants store more C
102 than annuals as the annual cycle of cultivation does little to maintain storage. Perennial crops are in

103 the ground all year long and intercept more of the sun's radiation as a result (e.g. Glover et al., 2010).
104 It follows that a change from arable to perennial grassland is likely to lead to a significant increase in
105 soil C (Guo & Gifford, 2002). By implication therefore, a change from annual to perennial grain crops
106 should also lead to an increase in SOC. Because they live longer, many perennials invest in deep,
107 extensive root systems which are efficient in scavenging for nutrients and water as well as putting
108 carbon in to soil. The amount of C retained by soils is influenced greatly by management practices,
109 with those that lead to reduced soil disturbance and for increased crop persistency having the
110 greatest benefits on C sequestration. Moreover, perennial vegetation may receive fewer passes with
111 machinery, so consuming less energy because perennial systems are more diverse and receive fewer
112 sprays that consume fossil fuels in their manufacture. However to date there are no perennial crop
113 species that produce adequate grain yields. The Royal Society (2009a) estimates that it will be at
114 least 10 years before the development of commercial varieties.

115 *Improved grasses*

116 The key plant traits likely to influence C sequestration (root depth, structure and architecture; litter
117 composition and amount) are reasonably well established and genetic variation is beginning to be
118 characterized for many of them. Some early progress has been made with regard to mapping of
119 genes in perennial ryegrass for C sequestration, with effective C return in litter (Abberton *et al.*, 2007).
120 Key questions to be resolved are the extent to which investment of photosynthate below ground is at
121 the expense of above-ground productivity, and how much of the additional below-ground carbon can
122 be stored in subsoils for the long term.

123 *Roots, exudation and priming effects*

124 Although roots obviously put carbon directly belowground, root turnover can be appreciable and the
125 roots of many plants exude large amounts of carbon-containing polymeric compounds into soil over
126 the course of a growing season. Grazing enhances rhizodeposition thus temporarily changing the
127 balance between root and shoot production (Hamillton III et al, 2008). Plants are themselves also
128 subject to grazing by animals whose droppings or carcasses (in the case of wild animals) usually return
129 carbon to soil eventually. Grazing can occur both above and below-ground since many insects have
130 a larval stage in the soil. Clearly, total input to soil depends on the balance between the reduction in
131 photosynthesis due to grazing and the temporary diversion of carbon into soil.

132 Plants send varying amounts of carbon belowground and a large part of the belowground C is exuded
133 from roots into the rhizosphere. Jones *et al.* (2009) estimate net rhizodeposition at around 11% of the
134 net fixed C or 27% of C allocated to roots. This would correspond to 400–600 kg C ha⁻¹ during the
135 vegetative period of grasses and cereals. However below-ground C allocation and exudation vary
136 between and within plant species, and with light conditions, soil moisture and nutrient conditions,
137 grazing and other variables. Soil microbes and fungi also release carbon compounds into the

138 environment. While bacteria are relatively well studied, far less is known about soil fungi (de Boer,
139 2005). In the vast majority of cases, however, the ultimate source of the carbon that is processed and
140 exuded by the soil microbes is derived originally from plants and photosynthesis.

141 Some authors suggest that inputs of fresh plant-derived carbon and other root-induced changes in the
142 soil increase the turnover of existing Soil Organic Matter (SOM, Paterson *et al.*, 2009; Kuzyakov,
143 2010). Such 'priming' effects are not well understood, and they are not allowed for in most current
144 models (Wutzler & Reichstein, 2008; Blagodatsky *et al.*, 2010). However, artefacts may account for
145 many of these observations. Fontaine *et al.* (2007) working with *ex situ* cores found turnover of old
146 SOM in subsoil was stimulated by addition of fresh organic matter but Salome *et al.* (2009), who
147 carefully reproduced subsoil conditions, found no priming in soils from below 30cm. While it is
148 possible that some observed instances of priming are the result of artefacts there is nonetheless
149 considerable interest in this area (Stockmann *et al.*, 2013)

150 **Decreasing the rate of decomposition of organic matter in soils**

151 In this section we review recent advances in the understanding of certain biological and chemical
152 controls on the rate of decomposition of organic matter (OM) in soils, largely drawn from observation
153 in the natural environment. In this respect the research is at a preliminary stage, so it is not yet
154 possible to draw conclusions about practical soil management interventions based on it.

155 *SOC turnover*

156 Studies of decomposition of organic matter in peatlands have shown inhibition of the enzymes
157 responsible by phenolic compounds (Freeman *et al.*, 2001; Zibilske & Bradford, 2006; Toberman *et*
158 *al.*, 2008; Sinsabaugh, 2010; Benoit & Starkey 1968a,b). These studies point to a particular role of
159 phenolic compounds in the carbon cycle with three key features: (i) few enzymes degrade these
160 abundant materials and those enzymes that do are inhibited almost completely by certain conditions
161 or a combination of conditions found in peat; (ii) phenolic compounds inhibit other enzymes,
162 particularly those that decompose organic matter in soil; and (iii) many phenolic compounds bind
163 other OM especially proteins and enzymes, this in itself has two further effects: (a) it reduces the
164 availability of OM for decomposition and (b) it removes other enzymes such as hydrolases that effect
165 that decomposition.

166 The surprising conclusion from this review of research is that a key oxidation step in the
167 decomposition of organic matter in soil is susceptible to inhibition by a specific class of phenolic
168 compounds. Carbon accumulation in peat soils may be the result of restricted oxidase and peroxidase
169 activity that remove these phenols, which in turn is the result of a lack of oxygen but does not result
170 from any general impact of the lack of oxygen on the soil microflora as a whole. If so, organic matter
171 decomposition in soil might be reduced by the application of inhibitors or anti-oxidants.

172 Aerts *et al.* (1999) have exploited the ability of phenol-containing substances to bind proteins by
173 ensuring their presence in the rumen of sheep by adding polyphenol-containing (tannin) forage
174 residues to the animals' diet. Aerts *et al.* (1999) attribute the beneficial effects on the animals to the
175 ability of the tannins to bind both proteins in the feed and the enzymes responsible for degradation
176 under the anaerobic conditions in the rumen. Proteins, especially then survive long enough to reach
177 other parts of the animals' guts where they can be absorbed, so improving the effectiveness of the
178 nutrition. Intriguingly, this raises the possibility that tannin-rich diets might lead to the introduction of
179 tannins to soil via manure and so reduce the turnover of organic carbon in soil.

180 In separate work, Rimmer (2006) proposed the more general hypothesis that the decomposition of
181 plant residues in soil is effected by free radicals and that anti-oxidants such as quinines which are
182 common in soil, moderate this activity by quenching the free radicals. Thus, observed SOC turnover
183 would be the balance between these components. Phenols and polyphenols are anti-oxidants.
184 Rimmer & Smith (2009) have found anti-oxidants in soil and have related the anti-oxidant capacity of
185 soils to the total soil carbon content but did not find evidence that the anti-oxidant capacity of the soil
186 was derived from plant litter. Additionally they found that anti-oxidant capacity decreased with depth
187 in the soil (Rimmer & Smith, 2009). There has been little further uptake of these ideas in the scientific
188 literature and the key experiments where anti-oxidants are deliberately introduced into soil or removed
189 appear to be lacking. Organic amendments naturally containing large amounts of anti-oxidants were
190 found to decompose more slowly during an initial 7 day period than amendments without anti-oxidants
191 (Rimmer *et al.*, 2013)

192 *Biochar*

193 Biochar – the porous carbonaceous solid produced by thermochemical conversion of organic
194 materials in an oxygen depleted atmosphere has been reviewed recently by Shackley & Sohi (2009)
195 and will not be repeated here. Essentially these authors conclude the residence time of biochar in soil
196 is often in the order of millennia as opposed to a few tens of years for other soil organic carbon. They
197 review benefits to yield and possible mechanisms for this but also the risks associated with adding
198 biochar to soil. These include a liming benefit but also the potential addition of long-lived toxins along
199 with the char.

200 *Wetlands*

201 Grip (drain) blocking in peat soils is hypothesised to reduce carbon losses through reduced
202 decomposition and reduced loss of dissolved organic carbon. Billett *et al.* (2010) suggest that current
203 rates of accumulation of carbon in UK peatlands (56 to 72 g C m⁻² yr⁻¹) are at the low end of rates
204 seen during the last 150 years. However, losses of methane may increase and the tradeoff between
205 reduced emissions of CO₂ and adverse effects of emission of CH₄ are currently being assessed for
206 the UK (Defra, 2012). Consequently, it is too early to assess restoration of upland peat as a

207 technology for reducing overall Green House Gas (GHG) emissions even if it is highly likely to
208 increase stores of carbon.

209

210 Managed realignment of coastal defences is also a possible means to increase carbon storage if the
211 deposited sediments contain carbon eroded with soil. Here it appears that a balance must be struck
212 with the emission of N₂O from denitrification and that the ideal is the establishment of saline rather
213 than non-saline marshes (Andrews *et al.*, 2006)

214 *Tillage*

215 Powlson *et al.* (2011, 2012) have reviewed the scope for increasing soil carbon by reducing tillage
216 and adding organic materials to soil. In general this work agreed with earlier studies as to the
217 quantities of carbon involved but differed somewhat in interpretation. Direct drilling probably allows
218 soil to increase in SOC by about 0.3 t ha⁻¹ yr⁻¹ although the data available for UK conditions is not
219 sufficient to say if this figure is statistically greater than zero. Most soils in the UK that are not
220 ploughed are in some kind of rotational tillage. Here the risk is that even if there is a gain in carbon
221 stored during the non-inversion rotation, on ploughing this gain will be lost (Conant *et al.*, 2007).
222 Powlson *et al.* (2011, 2012) also consider the addition of organic waste materials to soil such as
223 manure or straw. Here the result is less equivocal as regards a change in soil organic carbon status
224 but with regard to climate change Powlson *et al.* (2011) also caution that the original use of a material
225 must be considered before its addition to soil can be considered as carbon sequestration in the
226 service of mitigation of climate change. If the material is simply diverted from one soil to another then
227 this can hardly be interpreted as genuine sequestration

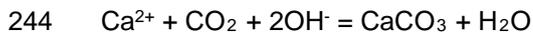
228 **Enhanced mineral weathering in soils to sequester CO₂**

229 One of the methods proposed to 'geo-engineer' the global climate is to accelerate the weathering of
230 silicate rocks on land to form carbonate rocks, thereby fixing CO₂ from the atmosphere (Royal
231 Society, 2009b). Conversion of silicates to carbonates is the main natural control on atmospheric CO₂
232 on Earth on geological timescales. The proposal is to accelerate it by applying finely-divided silicate
233 rocks (e.g. olivine) to soils, with the carbonate so fixed being stored in the soil as mineral carbonate
234 and, ultimately, exported in drainage waters to rivers and the deep ocean. The ecological
235 consequences of this for the land surface and seas are highly uncertain. In addition, the potential for
236 this method and its immediate consequences for soils are unknown.

237 The literature on this at the planetary or national scale is thin (Schuiling & Krijgsman, 2006; Hartmann
238 & Kempe, 2008). However there is plenty of information on rates of mineral weathering in soils (e.g.
239 Moulton *et al.*, 2000; Andrews & Schlesinger, 2001; and references therein) and the fate of lime (e.g.
240 Kirk *et al.*, 2010 and references therein). The conclusions from this literature review are as follows.

241 *Large-scale application of silicates to sequester carbon*

242 The removal of CO₂ from the atmosphere by precipitation as mineral carbonates (either Ca or Mg or
243 both) can be summarised with the reaction



245 i.e. the reaction requires sources of (a) CO₂, (b) Ca²⁺ or Mg²⁺ cations and (c) base, i.e. Brønsted
246 base, capable of neutralizing H⁺ ions. Soils are a good source of CO₂ for this purpose because CO₂
247 fixed from the atmosphere by plants is released into the soil through the decomposition of plant
248 exudates and residues. As a result the CO₂ pressure in the soil air is typically five to 50 times that in
249 the bulk atmosphere.

250 The planetary-scale carbon sequestration sought by geo-engineers requires silicate applications in
251 excess of acidifying processes so that the base in the silicates is transformed to carbonates on land
252 or ultimately in the deep ocean. Precipitation of carbonates in the soil as a result of large additions of
253 silicate base might occur, depending on rates of carbonate precipitation versus rates of HCO₃⁻
254 leaching. But large-scale carbonate precipitation in soils is probably not desirable given its likely
255 effects on soil conditions and plant growth. So the aim would be to generate increases in the flux of
256 HCO₃⁻ through soils, rivers and into the sea. If the carbonate remains dissolved in the sea, rather than
257 precipitating, then two moles of CO₂ are stored per mol of Ca silicate weathered, or four moles of
258 CO₂ in the case of Mg silicates.

259 Transfer of carbonate out of the soil requires that the soil pH be raised to the point where leaching of
260 the bicarbonate anion HCO₃⁻ with metal cations M⁺ is significant. Typically this means pHs greater
261 than neutral. Similar reasoning explains the well-known phenomenon that the neutralizing effect of
262 lime applied to the soil surface is only transferred to the subsoil when there is an excess of CaCO₃ in
263 the surface. Russell (1973) reports that soils containing free CaCO₃ in temperate regions may lose
264 Ca²⁺ with HCO₃⁻ in leachate at rates of the order of 2.5 kg CaCO₃ ha⁻¹ y⁻¹, based on measurements
265 in lysimeters. Calcareous soils at Rothamsted lose 300–400 kg CaCO₃ ha⁻¹ y⁻¹. Soils without free
266 CaCO₃ will also leach Ca²⁺ + HCO₃⁻. But the lower the pH and the less the saturation of the soil
267 exchange complex with Ca²⁺, the lower will be the loss. In arable land with heavy dressings of
268 ammoniacal fertilizers, loss of Ca²⁺ with NO₃⁻ will be much greater than its loss with HCO₃⁻.

269 A further issue is how to maximise the rate of dissolution of silicates, favoured by low pH, whilst
270 maximising the leaching of M⁺ + HCO₃⁻, favoured by high pH. Manning and Renforth (2013) give data
271 on the thermodynamics of dissolution of the most widely distributed Ca and Mg silicates in acid and
272 neutral solutions, and conclude that rates of dissolution will in general be far slower than rates of CO₂
273 generation in plant and soil organic matter turnover. Based on the activation energies given by
274 Manning and Renforth (50–80 kJ mol⁻¹), rates of dissolution are likely to be limited by surface
275 processes rather than by diffusion away from the dissolving surface (for which activation energies are
276 typically in the range 15–30 kJ mol⁻¹ – Glasstone *et al.*, 1941). On the same basis, calcite (CaCO₃)

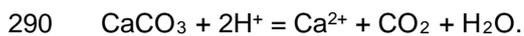
277 dissolution is much faster, and likely to be limited by diffusion and the degree of saturation of the soil
278 solution (Nye & Ameloko, 1987).

279 Also unknown are the ecological consequences of large silicate applications at the site of application.
280 Of concern are the consequences for (a) plant growth, e.g. via deficiencies of P and micronutrients at
281 high pH in calcifuge plants; (b) soil structure and sealing of the soil by SiO₂ precipitation; and (c) the
282 turnover of soil organic matter and leaching of dissolved organic carbon. Equally we know little about
283 the consequences of increased HCO₃⁻ fluxes downstream in rivers, local seas, and the deep ocean.

284 *Replacement of agricultural lime with silicates*

285 In theory, there is a significant potential for avoiding carbon emissions by replacing current agricultural
286 lime applications with ground silicates, assuming the C costs of production and transport are the
287 same.

288 Liming to balance acidity produced in nitrogen transformations, crop off-take, acid deposition etc.
289 releases 1 mol of CO₂ to the atmosphere per 2 mol of acid (i.e. H⁺) neutralised.



291 Whereas, with silicates there would be no CO₂ release, e.g. for the simple olivine Mg₂SiO₄:



293 According to Defra (2008), average annual lime rates are of the order of 250, 100 and 25 kg CaO ha⁻¹
294 on arable land, managed grassland and semi-natural grassland, respectively, and the respective
295 areas of these land uses in England and Wales are 64, 39 and 13 × 10³ km². If 2/56 kmol OH⁻ are
296 produced per kg CaO reacting, and 1 kmol CO₂ is saved per kmol H⁺ neutralised by silicate rather
297 than lime, then the total annual avoided emission is close to 1 million t CO₂-C.

298 Data compiled by Renforth et al. (2009, 2011) indicate there are many times the required amounts of
299 silicate wastes available from various sources across UK and globally. This includes wastes from
300 igneous rock quarry fines, concrete demolition, slags and fly ash, which amount to several tens of
301 million t CO₂-C equivalents.

302 Therefore, in principle this is a real possibility. The consequences for soil conditions would require
303 further investigation. In particular, the extent to which SiO₂ would accumulate in soils over the long
304 term, and the consequences of this for soil conditions; and also the extent of contaminant additions
305 with waste materials. Given that the acidity of the oceans is rising as atmospheric CO₂ concentrations
306 rise, the resulting increase in alkalinity might be beneficial. However the ecological consequences are
307 highly uncertain.

308 **Enhanced storage of carbon in urban soils**

309 Urban soils include any soil of natural or imported origin (e.g. made ground, including engineered fill)
310 or soil that has been modified, for example by the removal of topsoil or its mixture with the subsoil.
311 Urban land accounts for around 9.0% of land in England, whilst the equivalent percentage for Wales
312 is 4.3%% (Morton et al., 2011). It has been suggested that urban soils develop a distinct
313 biogeochemistry from their rural equivalents (Kaye *et al.* 2006). There is some evidence from
314 England that organic carbon storage may be enhanced in urban soil.

315 *Organic carbon*

316 Analyses of urban soil samples from three locations across the UK showed substantial variations in
317 organic carbon concentrations between centres and no consistent relationships with local, grassland
318 soils (Rawlins *et al.*, 2008). These data, in combination with unpublished data for other centres
319 suggest that the relative importance of the factors which influence soil organic carbon (SOC)
320 concentrations in urban soils may differ from those in rural soils. The wide variation in SOC
321 concentrations in urban topsoil across eight UK urban centres is shown in Table 1. It is notable that
322 median SOC concentrations are particularly large in Leicester (7%) and Stoke-on-Trent (6.8%).
323 These values are larger than for both permanent grassland (5.7%) and ley grassland (3.6%) in topsoil
324 across England and Wales (data from the Landis database (www.landis.org.uk)). The total quantity of
325 SOC in urban topsoil (0-15 cm depth) in England is around 8.5 MtC. This calculation was based on an
326 estimate of built up areas and garden land area (11 690 km²; Morton et al., 2011) assuming that
327 (Wood et al., 2006) 50% has zero carbon due to replacement by a sealed layer. We applied a
328 pedotransfer function to compute bulk density from SOC (Alexander, 1980) using the urban SOC
329 analyses for those data summarised in Table 1.

330 Further analyses of the SOC data for Coventry and Stoke showed that variations in soil texture cannot
331 account for the large differences in their median SOC concentrations. Application of the RothC model
332 to quantitative data for ten of the sites in Stoke-on-Trent suggested that annual carbon inputs required
333 to maintain SOC concentrations were between 1 and 5.4 tonnes C ha⁻¹ yr⁻¹; three sites had values >5
334 tonnes C ha⁻¹ yr⁻¹ which equates to substantial amounts of carbon addition. So either carbon inputs
335 are particularly large at these sites – which is not suggested by local land use – or the processes
336 controlling turnover of organic carbon are different to those found in soils under arable or pasture. If
337 the latter is the case, there are physical, chemical and biological mechanisms which could account for
338 maintenance of larger SOC concentrations. A possible physical mechanism is that urban soils have
339 been more severely compacted – due to construction-related activities – which contributes to the
340 enhanced preservation of SOC as soil microbes cannot mineralize a proportion of soil carbon.
341 Alternatively, the soil microbial population in urban soils may differ from that in equivalent rural soil
342 types leading to changes in carbon turnover and increased SOC concentrations. A potential chemical
343 mechanism is stabilisation of soil organic matter by Ca²⁺ (Oades, 1988). Soils of urban areas are

344 known to be enriched in exchangeable Ca^{2+} relative to rural soils due to the dispersal of construction
345 wastes (see next section). The other major factor which could account for the variations observed are
346 the frequency and timing of historical soil disturbance at these sampling sites which impact carbon
347 turnover. At present we do not have sufficient information on historic land use change to determine
348 whether this might account for the large observed differences.

349 In urban areas, architects are increasingly incorporating 'green roofs' into buildings Schrader and
350 Böning (2006) found between 1.8 and 4.6% carbon in the soils in such roofs in Hannover, depending
351 on age. It is not clear, however, if organic matter was incorporated with a mineral substrate at the
352 start of the experiment and to what extent the observed carbon storage reflects these starting values.

353 To summarise, it appears there may be a mechanism which is leading to the enhanced storage of
354 organic carbon in urban soil, but to date we do not have sufficient knowledge to explain it. With the
355 data available, we can make some estimates of its potential magnitude for enhancing carbon storage
356 in urban soil. Two urban centres (Stoke-on-Trent and Leicester) have median topsoil organic carbon
357 concentrations of around 7%, which is between 1 and 2.5 % greater than in the other urban areas. It
358 may be possible to increase SOC concentrations in some urban areas by this quantity, but further
359 research is needed to understand the mechanisms before a soil management strategy or other
360 interventions could be implemented.

361 *Inorganic carbon*

362 The contribution that mineral carbonation – the addition of certain minerals to soils to remove
363 CO_2 as carbonates – could make to enhanced carbon storage in soils is discussed above. The
364 essential requirements are the availability of calcium (Ca^{2+}) or magnesium (Mg^{2+}) cations and a
365 source of base to convert dissolved CO_2 to CO_3^{2-} . Certain silicate minerals may be suitable for
366 this, and urban soils may be particularly suited because of the local availability of such silicates
367 as wastes from the construction industry. The potential for this has been demonstrated by
368 Renforth *et al.* (2009) and Washbourne *et al.* (2012) who measured rates of *de novo* CaCO_3
369 formation of up to $25 \text{ kg C ha}^{-1} \text{ yr}^{-1}$ over 10 years in urban brownfield sites receiving demolition
370 waste from concrete buildings. Urban soils are known to be enriched in Ca due to the dispersal
371 of construction wastes, including hydrated cement minerals, the mineral portlandite ($\text{Ca}(\text{OH})_2$),
372 and, to a lesser extent, gypsum (CaSO_4) from plasterboard wastes. These minerals are prone to
373 weathering in the soil environment, yielding Ca^{2+} . Using data from the British Geological Survey's
374 geochemistry database for seven urban centres in south and eastern England, we found the
375 concentrations of total Ca were on average 4000 mg kg^{-1} greater in urban topsoil (0–15 cm
376 depth) compared with equivalent, adjacent rural topsoil, with typical enrichments of between 150
377 and 200% (Defra, 2010). We restricted our analysis to urban soils in south-east England
378 because we considered mean annual rainfall in these areas (<550 mm) would not be sufficient to

379 leach dissolved Ca^{2+} beyond depths of around 1 metre. Based on these data and some
380 simplifying assumptions, we computed the capacity of the soils in these urban areas to sequester
381 C (based on excess Ca) to be 0.5 MtC (megatonnes of carbon).

382

383

384 **Enhanced carbon storage in subsoils**

385 Kleber (2010) and Dungait et al. (2012) suggest that turnover of organic materials in soil is less about
386 what SOM is and more about where it is. Some geological parent materials contain small but
387 significant concentrations of fossil carbon which is incorporated into the soil during its formation. This
388 could be either inorganic, geogenic or organic carbon. An example of the former is the carbon
389 present as carbonate derived from the weathering of chalk parent materials. Organic carbon is also
390 often present in the clay-rich soil parent materials of southern England and also the recalcitrant
391 organic carbon derived from coal-bearing strata. It is not possible to increase the quantities of fossil
392 carbon in soil and so this fossil carbon is outside the scope of our study. However, stabilisation of
393 carbon on the surfaces of minerals derived from weathering of parent material can enhance C storage
394 in the subsoil.

395 The question we pose here is whether it is possible to increase the quantities of organic carbon stored
396 in the subsoils (> 25 cm depth) of England and Wales either through different land management
397 practices (changes in land use or cultivation), or possibly the application of organic amendments to
398 the topsoil. Before we can address this question it is useful to review both the knowledge and
399 knowledge gaps concerning the carbon stored in subsoil of England and Wales and the mechanisms
400 which control it.

401 Bradley *et al.* (2005) have estimated that subsoils in England and Wales contain approx. 0.5% C by
402 weight (Table 2). On average, soil organic carbon becomes both more recalcitrant and older with
403 increasing depth as soil biota have utilised the simpler organic compounds, leaving behind the more
404 resistant, energy-poor fractions.

405 Studies have shown that, in topsoils, the dominant factors controlling SOC stabilization include
406 (reviewed by Davidson & Janssens, 2006) texture, mineralogy, base cation content, soil aggregation,
407 plant litter type and the chemical recalcitrance of soil organic matter, and microbial populations, plus
408 interactions between these factors. This constitutes an extremely complex system. Stewart *et al.*
409 (2007) demonstrated that certain topsoils may become carbon saturated. The inherent physical and
410 chemical characteristics of the soil may determine the maximum quantity of soil organic matter which
411 can be stabilised (Six *et al.*, 2002). There is strong evidence that iron-oxide content is the dominant
412 factor controlling stabilisation of organic matter in acid forest soils (Mikutta *et al.*, 2006), whilst the
413 quantity of clay and silt are most important in the surface horizons of arable and grassland systems
414 (Hassink & Whitmore, 1997).

415 Far less research has been undertaken on subsoil systems. One study showed that when fresh
416 carbon is added to subsoil it has a priming effect which leads to the degradation of previously stable
417 subsoil carbon (Fontaine *et al.*, 2007), though a subsequent study (Salome *et al.*, 2009) observed
418 greater spatial heterogeneity in factors which determine carbon turnover in subsoil compared to
419 topsoil and suggested that controls on carbon turnover may be different between topsoil and subsoil.
420 Observations that the microbial biomass or activity in subsurface soil is more variable than in topsoil
421 suggest that spatial relationships between organic matter and microbial communities may be more
422 significant in the former. This is consistent with observations of distinct flow paths along which
423 younger and less recalcitrant carbon is located, adjacent to the subsoil matrix containing smaller
424 quantities of more recalcitrant carbon (Chabbi *et al.*, 2009). This young carbon is likely to become
425 mineralised in the short or medium-term and may not contribute to long-term carbon storage.

426 There is evidence that the association between mineral surfaces and organic matter in subsoils differs
427 from that in topsoil. Organic matter coatings on subsoil mineral surfaces tend to be thin and patchy
428 whilst those in topsoil samples are thicker and often completely cover mineral particles. So the
429 potential for stabilising organic matter by adsorption to mineral surfaces in subsoil may be
430 substantially less than in topsoil (Wagai *et al.*, 2009). This may in part be explained by the nature of
431 the organic carbon; in subsoil it has undergone more microbial processing by comparison to that in
432 topsoil. The quantity of carbon stored in the subsoil may therefore depend more on its inherent
433 recalcitrance than the mechanisms of its stabilisation on mineral surfaces. Watts *et al.* (2005)
434 suggested that the action of the microbial biomass was crucial in the binding of organic matter and the
435 formation of soil aggregates and so it is possible that the reduced microbial activity in the subsoils has
436 an effect on carbon stabilisation.

437 Increasing the storage of organic carbon in subsoil (> 30 cm depth) requires: i) a mechanism for its
438 emplacement at depth, and ii) confidence that this carbon will stay in the soil (i.e. be stabilised), and
439 will not be degraded by soil biota or lead to enhanced losses of existing soil carbon. We consider that
440 methods involving direct emplacement of fresh organic carbon into subsoil will not lead to enhanced
441 storage of carbon, and could be counter-productive through disturbance and mineralisation losses of
442 topsoil carbon. An alternative to direct emplacement is to enhance the natural process of migration of
443 carbon from surface to depth; this is dominated by leaching of dissolved organic carbon (DOC).
444 Leaching of DOC is known to be greater under forests than grassland and arable land. Minerals
445 deeper in the soil profile, such as iron oxides, have a large capacity to stabilise this carbon (Mikutta *et al.*
446 *et al.*, 2006). Plant breeding might also enhance access to these stabilising sites (Kell, 2012)

447 A recent study from California (Sanderman & Amundson, 2009) demonstrated that DOC movement
448 and retention in a fine-textured (clay-rich) mineral soil contributes 22% of the annual C inputs below
449 40 cm in a coniferous forest, whereas only 2% of the C inputs below 20 cm in equivalent grassland
450 (prairie) soils were accounted for by this process. The authors suggest that in more coarsely textured
451 soil, the carbon transported to depth may be less effectively stabilised by comparison to clay-rich

452 lithologies. Another study (Arevalo *et al.*, 2009) which compared the storage of carbon in deeper soil
453 horizons under different land use types also demonstrated that long-term forested sites store more
454 carbon at 20-50 cm depth than recent forest plantation (2-9 years), grassland or crops. The majority
455 of the organic carbon in the subsoil was associated with the finer fractions. Hence, there is evidence
456 that conversion of grassland or arable land use to forest could enhance carbon storage in subsoil
457 where it has a fine texture or large quantities of Fe-oxide phases (Mikutta *et al.*, 2006).

458 **Conclusions**

459 Most means to store carbon in soil suffer from slow build up or restrictions in general use based on
460 climate, soil type or the need to grow food on the land. Those technologies show that promise for
461 widespread, rapid manipulation of the carbon cycle such as (i) the use of polyphenols to complex
462 SOM or inhibit enzymes that decompose it, (ii) enhancing storage in topsoil based on mechanisms of
463 physical protection that currently operate in the subsoil, or (iii) mineral carbonation, all require
464 research before they could be used or their potential deployment in practice be assessed. Increased
465 use of improved grasses where possible could increase carbon storage now; breeding might provide
466 additional perennial crops or varieties in the future that divert carbon to the subsoil. Interventions on
467 urban soils are necessarily restricted to a small percentage of the land area.

468

References

- Abberton, M.T., MacDuff, J.H., Marshall, A.H. & Humphreys, M.W. 2007. The genetic improvement of forage grasses and legumes to reduce greenhouse gas emissions. <http://ftp.fao.org/docrep/fao/010/ai779e/ai779e00.pdf>. pp 17.
- Aerts, R.J., Barry, T.N. & McNabb, W.C. 1999. Polyphenols and agriculture: beneficial effects of proanthocyanidins in forages. *Agriculture Ecosystems and Environment*, **75**, 1–12.
- Andrews, J.E., Burgess, D., Cave, R.R., Coombes, E.G., Jickells, T.D., Parkes, D.J. & Turner, R.K. 2006. Biogeochemical value of managed realignment, Humber estuary, UK. *Science of the Total Environment*, **371**, 19–30.
- Andrews, J.A. & Schlesinger, W.H. 2001. Soil CO₂ dynamics, acidification, and chemical weathering in a temperate forest with experimental CO₂ enrichment. *Global Biogeochemical Cycles*, **15**, 149–162.
- Anon (2011) The natural choice: securing the value of nature. TSO pp 75.
- Anon (2011) UK National Ecosystem, Assessment, Technical report, UNEP-WCMC pp 1466
- Arevalo, C.B.M., Bhatti, J.S., Chang, S.X. & Sidders, D. 2009. Ecosystem carbon stocks and distribution under different land-uses in north central Alberta, Canada. *Forest Ecology and Management*, **257**, 1776–1785.
- Billett, M.F., Charman, D.J., Clark, J.M., Evans, C.D., Evans, M.G., Ostle, N.J., Worrall, F., Burden, A., Dinsmore, K.J., Jones, T., McNamara, N.P., Parry, L., Rowson, J.G. & Rose, R. 2010. Carbon balance of UK peatlands: current state of knowledge and future research challenges. *Climate Research*, **45**, 13–29.
- Blagodatsky, S., Blagodatskaya, E., Yuyukina, T. & Kuzyakov, Y. 2010. Model of apparent and real priming effects: Linking microbial activity with soil organic matter decomposition. *Soil Biology & Biochemistry*, **42**, 1275–1283.
- Bolin, B., Sukmar, R., Cias, P., Cramer, W., Jarvis, P., Kehshgi, H., Nobre, C., Semenov, S. & Steffen, W. 2000. Global perspective. Pages 23–51 in *Land use, land-use change, and forestry, a special report of the IPCC*. Eds R.T. Watson, I.R. Noble, B. Bolin, N.H. Ravindrannath, D.J. Verardo & D.J. Dokken. Cambridge University Press, Cambridge .
- Benoit, R.E. & Starkey, R.L. 1968a. Effect of purified plant tannin on decomposition of some organic compounds and plant materials *Soil Science*, **105**, 153–158.
- Benoit, R.E. & Starkey, R.L. 1968b. Enzyme inactivation as a factor in the inhibition of decomposition of organic matter by tannins. *Soil Science*, **105**, 203–208.
- de Boer W., Folman, L.B., Summerbell, R.C. & Boddy, L. 2005. Living in a fungal world: impact of fungi on soil bacterial niche development. *Fems Microbiology Reviews*, **29**, 795–811.
- Bradley, R.I., Milne, R., Bell, J., Lilly, A., Jordan, C. & Higgins, A. 2005. A soil carbon and land use database for the United Kingdom. *Soil Use and Management*, **21**, 363–369.
- Carney, K.M., Hungate, B.A., Drake, B.G. & Megonigal, J.P. 2007. Altered soil microbial community at elevated CO₂ leads to loss of soil carbon. *Proceedings of the National Academy of Sciences*, **104**, 490–495.

- Chabbi, A., Kögel-Knabner, I. & Rumpel, C. 2009. Stabilised carbon in subsoil horizons is located in spatially distinct parts of the soil profile. *Soil Biology and Biochemistry*, **41**, 256-261.
- Conant, R.T., Easter, M., Paustian, K., Swan, A. & Williams, S. 2007. Impacts of periodic tillage on soil C stocks: A synthesis. *Soil & Tillage Research*, **95**, 1–10
- Davidson, E.A. & Janssens, I.A. 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. *Nature* **440**, 376–386.
- Defra. 2006. Land by agricultural and other uses: 2005. *e-Digest of Environmental Statistics, Environment in your pocket, Sustainable Development Indicators in your Pocket*. Defra, London.
- Defra. 2008. *British Survey of Fertiliser Practice. Fertiliser Use on Farm Crops for Crop Year 2007*. Defra, London.
- Defra 2009. Safeguarding our soils – A strategy for England pp48
- Defra, 2010. To evaluate the potential of technologies for increasing carbon storage in soil to mitigate climate change. SP1605 A – sub-project A. Defra, London.
- Defra. 2012. *Grip blocking and methane emissions*. Final report of project SP1202. Defra, London.
- Dungait, J.A.J., Hopkins, D.W., Gregory, A.S. and Whitmore, A.P. (2012) Soil organic matter turnover is governed by accessibility not recalcitrance. *Global Change Biology*. **18**, 1781-1796. doi: 10.1111/j.1365-2486.2012.02665.x
- Fontaine, S., Barot, S., Barre, P., Bdioui, N., Mary, B. & Rumpel C. 2007. Stability of organic carbon in deep soil layers controlled by fresh carbon supply. *Nature*, **450**, 277–210.
- Freeman, C., Ostle, N. & Kang, H. 2001. An enzymic 'latch' on a global carbon store *Nature*, **409**, 149.
- Glasstone, S., Laidler, K.J. & Eyring, H. 1941. *The Theory of rate processes*, McGraw-Hill, New York.
- Glover, J.D., Reganold, J.P., Bell, L.W., Borevitz, J., Brummer, E.C., Buckler, E.S., Cox, C.M., Cox, T.S., Crews, T.E., Culman, S.W., DeHaan, L.R., Eriksson, D., Gil, I.B.S., Holland, J., Hu, F., Hulke, B.S., Ibrahim, A.M.H., Jackson, W., Jones, S.S., Murray, S.C., Paterson, A.H., Ploschuk, E., Sacks, E.J., Snapp, S., Tao, D.D. van Tassel, L. Wade, L.J., Wyse, D.L. & Xu Y. 2010. Increased food and ecosystem security via perennial grains. *Science*, **328**, 1638–1639
- Guo, L.B. & Gifford, R.M. 2002. Soil carbon stocks and land use change: a meta analysis. *Global Change Biology*, **8**, 345–360.
- Guo, Z.L., Cai, C.F., Li, Z.X., Wang, T.W. & Zheng, M.J.. 2009. Crop residue effect on crop performance, soil N₂O and CO₂ emissions in alley cropping systems in subtropical China. *Agroforestry Systems*, **76**, 67–80.
- Hartmann, J. & Kempe, S. 2008. What is the maximum potential for CO₂ sequestration by "stimulated" weathering on the global scale? *Naturwissenschaften*, **95**, 1159–1164.
- Hassink, J. & Whitmore, A.P. 1997. A model of the physical protection of organic matter in soils. *Soil Science Society of America, Journal*, **61**, 131–139.
- Jones, D.L., Nguyen, C. & Finlay, R.D. 2009. Carbon flow in the rhizosphere: carbon trading at the soil-root interface. *Plant and Soil*, **321**, 5–33.
- Jose, S. 2009. Agroforestry for ecosystem services and environmental benefits: an overview. *Agroforestry Systems*, **76**, 1–10.

- Kaye, J.P., Groffman, P.M., Grimm, N.B., Baker, L. M. & Pouyat, R.V. 2006. A distinct urban biogeochemistry? *Trends in Ecology and Evolution*, **21**, 192–199.
- Kell, D.B. (2012) Large-scale sequestration of atmospheric carbon via plant roots in natural and agricultural ecosystems: why and how. *Philos Trans R Soc Lond B Biol Sci.* **367**,1589-97. doi: 10.1098/rstb.2011.0244.
- Kirk, G.J.D., Bellamy, P.B. & Lark, R.M. 2010. Changes in soil pH across England and Wales in response to decreased acid deposition. *Global Change Biology*, **16**, 3111–3119.
- Kuzyakov, Y. 2010. Priming effects: Interactions between living and dead organic matter. *Soil Biology & Biochemistry*, **42**, 1363–1371.
- Manning, D.A.C. & Renforth, P. 2013. Passive sequestration of atmospheric CO₂ through coupled plant-mineral reactions in urban soils. *Environmental Science & Technology*, **47**, 135–141.
- Mikutta, R., Kleber, M., Torn, M. S. & Jahn, R. 2006. Stabilization of soil organic matter: Association with minerals or chemical recalcitrance? *Biogeochemistry*, **77**, 25–56.
- Montagnini, F. & Nair, P.K.R. 2004. Carbon sequestration: An underexploited environmental benefit of agroforestry systems. *Agroforestry Systems*, **61**, 281–295.
- Morton, D., Rowland, C., Wood, C. Meek, L., Marston, C., Smith, G., Wadsworth, R., Simpson, I.C. 2011. Final Report for LCM2007 - the new UK land cover map. Countryside Survey Technical Report No 11/07 NERC/Centre for Ecology & Hydrology 112pp.
- Moulton, K.L., West, J. & Berner, R.A. 2000. Solute flux and mineral mass balance approaches to the quantification of plant effects on silicate weathering. *American Journal of Science*, **300**, 539–570.
- Nair, P.K.R., Kumar, B.M. & Nair, V.D. 2009a. Agroforestry as a strategy for carbon sequestration. *Journal of Plant Nutrition and Soil Science*, **172**, 10–23.
- Nair, P.K.R., Nair, V.D., Kumar, B.M. & Haile, S.G. 2009b. Soil carbon sequestration in tropical agroforestry systems: a feasibility appraisal. *Environmental Science & Policy*, **12**, 1099–1111.
- Nye, P.H. & Ameloko, A.Y, 1987. Predicting the rate of dissolution of lime in soil. *Journal of Soil Science*,**38**, 641–644.
- Oades, J.M. 1988. The retention of organic matter in soils. *Biogeochemistry*, **5**, 35–70.
- Paterson, E., Midwood, A.J. & Millard, P. (2009) Tansley Review. Through the eye of the needle: a review of isotope approaches to quantify microbial processes mediating soil carbon balance. *New Phytologist*, **184**, 19–33.
- Powlson, D.S., Bhogal, A., Chambers, B.J., Macdonald, A.J., Coleman, K., Goulding, K.W.T. & Whitmore, A.P. 2012. The potential to increase soil carbon stocks through reduced tillage or organic additions – an England and Wales case study. *Agriculture, Ecosystems and Environment* **146**, 23–33.
- Powlson, D.S., Whitmore, A.P. & Goulding, K.W.T. 2011. Soil carbon sequestration to mitigate climate change – a critical re-examination to identify the true and the false. *European Journal of Soil Science*, **62**, 42–55.
- Quinkenstein, A., Wollecke, J., Bohm, C., Grunewald, H., Freese, D., Schneider, B.U. & Huttli, R.F. 2009. Ecological benefits of the alley cropping agroforestry system in sensitive regions of Europe. *Environmental Science & Policy*, **12**, 1112–1121.

- Rawlins, B.G., Vane, C.H., Kim, A.W., Tye, A.M., Kemp, S. & Bellamy, P.H. 2008. Methods for estimating types of soil organic carbon and their application to surveys of UK urban areas. *Soil Use & Management*, **24**, 47–59.
- Renforth, P., Manning, D.A.C. & Lopez-Capel, E. 2009. Carbonate precipitation in artificial soils as a sink for atmospheric carbon dioxide. *Applied Geochemistry*, **24**, 1757–1764.
- Renforth, P., Washbourne, C.-L., Taylder, J. & Manning, D.A.C. 2011. Silicate production and availability for mineral carbonation. *Environmental Science & Technology*, **45**, 2035–2041.
- Rimmer, D.L. 2006. Free radicals, antioxidants, and soil organic matter recalcitrance. *European Journal of Soil Science*, **57**, 91–94.
- Rimmer, D. L., McKenna, B. A., Vaughan, S. M. Menzies, N. W. (2013) Antioxidant capacity and rate of decomposition of organic amendments in a Vertisol *European Journal of Soil Science* **64**, 104-109 DOI 10.1111/ejss.12001
- Rimmer, D.L. & Smith, A.M. 2009. Antioxidants in soil organic matter and in associated plant materials. *European Journal of Soil Science*, **60**, 170–175.
- Royal Society. 2009a. *Reaping the benefits: Science and the sustainable intensification of global agriculture*. RS Policy document 11/09. The Royal Society, London.
- Royal Society. 2009b. *Geoengineering the climate. Science, governance and uncertainty*. RS Policy document 10/09. The Royal Society, London.
- Russell, E.W. 1973. *Soil conditions and plant growth*. Longman, London.
- Salome, C., Naoise, N., Valerie, P., Thomas, Z.L. & Claire C. 2009. Carbon dynamics in topsoil and in subsoil may be controlled by different regulatory mechanisms. *Global Change Biology*, **16**, 416–426.
- Sanderman, J. & Amundson, R. 2009. A comparative study of dissolved organic carbon transport and stabilization in California forest and grassland soils. *Biogeochemistry*, **92**, 41–59.
- Schuling, R.D. & Krijgsman, P. 2006. Enhanced weathering: An effective and cheap tool to sequester CO₂. *Climate Change*, **74**, 349–354.
- Shackley S & Sohi S (2009) Final Report to Defra project SP0576: An assessment of the benefits and issues associated with the application of biochar to soil pp 132
- Sinasbaugh RL 2010 Phenol oxidase, peroxidase and organic matter dynamics of soil. *Soil Biology and Biochemistry* **42**, 391-404.
- Six, J., Conant, R.T., Paul, E.A. & Paustian K. 2002. Stabilization mechanisms of soil organic matter: Implications for C-saturation of soils. *Plant and Soil*, **241**, 155–176.
- Skinner, R.H., Sanderson, M.A., Tracy, B.F. & Dell, C.J. 2006. Above and belowground productivity and soil carbon dynamics of pasture mixtures. *Agronomy Journal*, **98**, 320–326.
- Smith, P., Powlson, D.S., Smith, J.U., Falloon, P. & Coleman, K. 2000. Meeting Europe's climate change commitments: quantitative estimates of the potential for carbon mitigation by agriculture. *Global Change Biology*, **6**, 525–539.
- Stewart, C.E., Paustian, K., Conant, R.T., Plante, A.F., & Six, J. 2007. Soil carbon saturation: concept, evidence and evaluation. *Biogeochemistry*, **86**, 19–31.

- Stockmann, U., Adams, M.A., Crawford, J.W., Field, D.J., Henakaarchchi, N., Jenkins, M., Minasny, B., McBratney, A.B., de Remy de Courcelles, V., Singh, K., Wheeler, I., Abbott, L., Angers, D.A., Baldock, J., Bird, M., Brookes, P.C., Chenu, C., Jastrow, J.D. Lal, R., Lehmann, J., Donnell, A.G., Parton, W.J., Whitehead, D., Zimmermann, M. (2013) The knowns, known unknowns and unknowns of sequestration of soil organic carbon, *Agriculture, Ecosystems & Environment*. **164**, 80-99, 10.1016/j.agee.2012.10.001.
- Tisdall, J.M. & Oades, J.M. 1982. Organic matter and water-stable aggregates in soil. *Journal of Soil Science*, **33**,141–163.
- Toberman, H., Freeman, C., Evans, C., Fenner, N. & Artz, R.R.E. 2008. Summer drought decreases soil fungal diversity and associated phenol oxidase activity in upland Calluna heathland soil. *FEMS Microbiology Ecology* **66**, 426–436.
- Verchot, L.V., Brienza, S., de Oliveira, V.C., Mutegi, J.K., Cattanio, J.H. & Davidson, E.A. 2008. Fluxes of CH₄, CO₂, NO, and N₂O in an improved fallow agroforestry system in eastern Amazonia. *Agriculture Ecosystems & Environment*, **126**,113–121.
- Wagai, R., Mayer, L.M. & Kitayama, K. 2009. Extent and nature of organic coverage of soil mineral surfaces assessed by a gas sorption approach. *Geoderma*, **149**, 152–160.
- Washbourne, C.-L., Renforth, P. & Manning, D.A.C. 2012. Investigating carbonate formation in urban soils as a method for capture and storage of atmospheric carbon. *Science of the Total Environment*, **431**, 166–175.
- Watts, C.W., Whalley, W.R., Brookes, P.C., Devonshire, B.J. & Whitmore, A.P. 2005. Biological and physical processes that mediate micro-aggregation of clays. *Soil Science*, **170**, 573–583.
- Webb, J., Loveland, P.J., Chambers, B.J., Mitchell, R. and Garwood, T. 2001. The impact of modern farming practices on soil fertility and quality in England and Wales. *Journal of Agricultural Science, Cambridge*, **137**, 127–138.
- Wood, G., Braganza, S., Brewer, T., Kamporaki, M., Harris, J. et al. 2006. Monitoring urban sealing from space. Technical report of GIFTSS project BNSC/ITT/54, Defra code SP0541.
<http://randd.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=12897>
- Wutzler, T. & Reichstein, M. 2008. Colimitation of decomposition by substrate and decomposers – a comparison of model formulations. *Biogeosciences*, **5**, 749–759.
- Zibilske, L.M. & Bradford, J.M. 2006. Oxygen effects on carbon, polyphenols and nitrogen mineralisation potential in soil. *Soil Science Society of America Journal*, **71** 133–139.

Table 1 Median soil organic C contents of urban top soils (0–15 cm depth) from eight urban centres in the UK

Urban centre	Sample counts (n)	Median OC* (g kg ⁻¹)	Median OC* (%)
Glasgow	1382	52	5.2
Stoke-on-Trent	747	68	6.8
Coventry	396	34	3.4
Derby	276	43	4.3
Manchester	301	49	4.9
Leicester	309	70	7.0
Belfast	1198	41	4.1
London**	6468	43	4.2

* estimated from loss on ignition analysis – may include a component of recalcitrant (black) carbon

**?

Source of data?

Q why both g/kg and %, Also shouldn't 43 g/kg be 4.3%?

Table 2 Average organic C contents of subsoils at two depth ranges in different land uses across England and Wales

Soil depth range (cm)	Organic C content (g kg ⁻¹)			
	Arable	Ley grass	Permanent grass	Other
25–50	13.0	13.6	15.7	18.5
50–100	3.6	4.0	4.4	4.3