

Legacy effects of grassland management on soil carbon to depth

Article

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1 **Legacy effects of grassland management on soil carbon to depth**

2 Running header: Management and deep soil carbon

3

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18

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20 legacy effect, carbon inventory

21 **Type of paper:** Primary Research Article

22 Abstract

23 The importance of managing land to optimise carbon sequestration for climate change
24 mitigation is widely recognised, with grasslands being identified as having the potential to
25 sequester additional carbon. However, most soil carbon inventories only consider surface
26 soils, and most large scale surveys group ecosystems into broad habitats without considering
27 management intensity. Consequently, little is known about the quantity of deep soil carbon
28 and its sensitivity to management. From a nationwide survey of grassland soils to 1 m depth,
29 we show that carbon in grasslands soils is vulnerable to management and that these
30 management effects can be detected to considerable depth down the soil profile, albeit at
31 decreasing significance with depth. Carbon concentrations in soil decreased as management
32 intensity increased, but greatest soil carbon stocks (accounting for bulk density differences),
33 were at intermediate levels of management. Our study also highlights the considerable
34 amounts of carbon in sub-surface soil below 30cm, which is missed by standard carbon
35 inventories. We estimate grassland soil carbon in Great Britain to be 2097 Tg C to a depth of
36 1 m, with ~60% of this carbon being below 30cm. Total stocks of soil carbon (t ha^{-1}) to 1 m
37 depth were 10.7% greater at intermediate relative to intensive management, which equates to
38 10.1 t ha^{-1} in surface soils (0-30 cm), and 13.7 t ha^{-1} in soils from 30-100 cm depth. Our
39 findings highlight the existence of substantial carbon stocks at depth in grassland soils that
40 are sensitive to management. This is of high relevance globally, given the extent of land
41 cover and large stocks of carbon held in temperate managed grasslands. Our findings have
42 implications for the future management of grasslands for carbon storage and climate
43 mitigation, and for global carbon models which do not currently account for changes in soil
44 carbon to depth with management.

45 Introduction

46 Permanent grasslands are found extensively across the temperate zone where they form the
47 backbone of agricultural systems. Global land cover estimates for grasslands range between
48 20-40% of the Earth (FAO 2015), and for the UK, constitute the largest category of land use
49 at 36% of land cover (Carey et al. 2008). The multiple values of grassland ecosystems to
50 mankind has long been recognised, ranging from direct benefits of agricultural production, to
51 indirect ecosystem services such as the regulation of climate and water quality, and
52 pollination services (Heidenreich 2009). As such, grasslands are arguably one of the most
53 valuable biomes for ecosystem service provision, but also are among the most threatened by
54 anthropogenic activities (Gibson 2008). Threats include increasing pressures to meet the
55 food demands of more affluent and larger global populations, and to deliver concomitant
56 multiple ecosystem services demanded by the sustainable intensification agenda (Garnett et
57 al. 2013). Of the multiple ecosystem services provided by grasslands, climate regulation via
58 soil carbon storage and sequestration, is highly valued (Heidenreich 2009).

59

60 In terms of terrestrial carbon storage, soils contain the largest global pool of terrestrial
61 carbon, storing more carbon than is present in plant biomass and the atmosphere combined
62 (Batjes 1996, Jobbagy and Jackson 2000). Temperate grasslands are the third largest global
63 store of carbon in soils and vegetation (after wetlands and boreal forests), storing an
64 estimated 304 Pg C, or 12.3% of global carbon (Royal Society 2001), most of which is in
65 soil. Such carbon stocks are known to be vulnerable to changes in land use and
66 intensification of agricultural management, with the conversion of croplands to permanent
67 grassland generally increasing soil carbon, and the reverse change from grassland to
68 croplands reducing soil carbon stocks (Guo and Gifford 2002, Smith et al. 2008). Moreover,
69 such changes in land use can have a long lasting legacy effect on soil carbon, on a scale of

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70 decades to several hundreds of years, which is often slow to reverse (Dupouey et al. 2002,
71 McLauchlan 2006, Smith 2014).

72

73 Grassland soil carbon has been shown to respond to changes in management intensity, with
74 agricultural practices such as fertiliser application, irrigation, and livestock grazing affecting
75 soil carbon stocks (Soussana et al. 2004, Smith et al. 2008, van Wesemael et al. 2010). In
76 many parts of Europe, the intensity of grassland management has substantially increased
77 since the 1950's. This has been driven largely by agri-environmental policy and farm
78 subsidies, combined with technological innovations, leading to widespread legacy effects of
79 long-term management on soils and vegetation. In addition to the documented effects of
80 management on soil carbon (Guo and Gifford 2002, Smith et al. 2008), intensification of
81 farming practices has led to widespread reductions in botanical diversity and loss of species-
82 rich, traditionally managed grasslands, which now cover less than 3% of the area they did in
83 the 1950's (Gamble et al. 2012). Furthermore, management intensification has caused major
84 changes in plant functional composition, with intensively managed grasslands typically being
85 dominated by fast-growing exploitative species, characterized by high specific leaf area
86 (SLA) and leaf nitrogen concentration (LNC). This compares with less fertile, extensively
87 managed grasslands that are dominated by slower-growing, conservative species of high leaf
88 dry matter content (LDMC) and low leaf N content (Lavorel and Garnier 2002, de Vries et al.
89 2012). Such shifts in plant functional composition are known to have important effects on
90 soil nutrient cycling and carbon dynamics (de Vries et al. 2012, Grigulis et al. 2013, Manning
91 et al. 2015), and LDMC has been correlated with soil fertility (Hodgson et al. 2011, Duru et
92 al. 2012). However, there is a lack of knowledge on the relationship between soil carbon and
93 management intensity with depth linked to the legacy of vegetation change.

94

95 Another factor contributing to uncertainty over legacy effects of management and land use
96 change is that most studies on soil carbon stocks are on more easily sampled surface soils.
97 Even the IPCC recommend soil carbon accounting for the surface 30 cm of soil only (IPCC
98 2006), and although they advocate sampling beyond 30cm, this is rarely done. As a result,
99 soil carbon stocks at depth are largely ignored (Fontaine et al. 2007, Chapman et al. 2013),
100 and little is known about the quantity of soil carbon at depth and how it responds to land
101 management and associated vegetation change in grasslands (Jobbagy and Jackson 2000,
102 Soussana et al. 2004, Fontaine et al. 2007). Given the substantial quantities of carbon in
103 grassland soils, and the fact that grasslands worldwide are subject to increasing
104 intensification of management, this represents a major gap in knowledge.

105

106 The overarching aim of our study was to quantify the distribution of soil carbon across
107 English grasslands to depth (1 metre), and the relationship of surface and deep soil carbon to
108 grassland management at a national scale. To do this, we carried out a nationwide survey of
109 English grasslands. This included all the main grassland habitats found in Great Britain,
110 namely acid, calcareous, mesotrophic and wet grassland, sampled across the broad range of
111 soil and climatic conditions (de Vries et al. 2012, Manning et al. 2015), thereby
112 encompassing a wide range of variation across a representative spatial domain (Smart et al.
113 2012). Cumulative soil carbon stocks and mean depths from the survey were then used in
114 conjunction with land cover data for matching grassland broad habitats from the Countryside
115 Survey (Carey et al. 2008) to estimate total grassland soil carbon stocks in Great Britain to a
116 depth of 1m, and to make comparisons with existing estimates of grassland soil carbon
117 storage. Using two abundance-weighted leaf traits known to be indicators of soil fertility and
118 management intensity (i.e., SLA and LDMC) (Hodgson et al. 2011; Grigulis et al. 2013), we

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119 also sought to test whether surface carbon stocks are more related to current plant functional
120 composition than deeper carbon.

121

122

123 **Methods**

124 *Field sampling.*

125 A survey of 180 permanent grasslands was conducted in summer 2010 from a range of acid,
126 calcareous, mesotrophic and wet grasslands, using a network of sites located throughout
127 England (Fig. 1) (de Vries et al. 2012, Manning et al. 2015). Sampling sites were in 60
128 different geographical locations, from 12 broad regions of England. At each of the 60
129 locations, three different fields were selected to give a gradient of management intensity of
130 extensive, intermediate and intensive management. These triplicate sets of fields were sited
131 on the same soil type, with similar topography and edaphic characteristics, and all three fields
132 at the same location were sampled on the same day. The three management intensity
133 classifications were based on expert judgement using information from consultations with
134 farmers and land owners, and from vegetation surveys (de Vries et al. 2012, Manning et al.
135 2015), and follow broad classifications that reflect dominant grassland systems in the UK and
136 Europe (Tallowin and Jefferson 1999, Tallowin et al. 2005, Manning et al. 2015) ([Table 1](#)).

137 There are clearly many different factors involved in the intensification of grassland
138 management, including increased use of fertilisers, increased disturbance through greater
139 cutting and grazing intensities, and changes in the amount and diversity of plant-derived
140 organic matter inputs to soil due to vegetation change. Given that it is not possible to
141 disentangle the individual effects of these factors on soil carbon stocks at the national scale of
142 sampling done here, we therefore compared grasslands subject to broadly defined levels of
143 agricultural intensification; this approach has been used widely to identify broad-scale trends

144 in, and relationships between, vegetation and soil properties along gradients of management
145 intensity (Bardgett and McAlister 1999, Grayston et al. 2004, Allan et al. 2015).

146

147 The extensively managed grasslands had relatively high plant diversity and high conservation
148 status, typically received less than 25 kg N ha⁻¹ yr⁻¹ and, have been managed in a traditional,
149 low intensity manner for many decades, with light grazing and annual cutting for hay. The
150 intensively managed agriculturally improved grasslands had low plant diversity of mainly
151 MG6 (*Lolium perenne* – *Cynosurus cristatus*) and MG7 (*Lolium perenne* leys and related
152 grasslands) communities (Rodwell 1992). These intensively managed grasslands typically
153 receive >100 kg N ha⁻¹ yr⁻¹, and have been subjected to standard intensive management
154 practices since the 1950's, with higher grazing pressures and more frequent cutting for silage
155 than the extensively managed grasslands (Tallowin and Jefferson 1999, Tallowin et al. 2005,
156 Critchley et al. 2007). The third category of grasslands is that of intermediate management
157 intensity, which falls between the two other categories, having typical inputs of ~ 25-50 kg N
158 ha⁻¹ yr⁻¹, and intermediate levels of plant diversity, grazing and cutting (Table 1).

159

160 Soil cores (3.5 cm diameter) were taken from three random areas in each field, to 1 m depth
161 (where possible) using an Eldeman auger, and divided into five depth increments: 0–7.5 cm,
162 7.5-20 cm, 20-40 cm, 40-60 cm and 60-100 cm. A soil pit was dug at one location in each
163 field and three bulk density cores (6 cm length x 6.3 cm diameter) were taken horizontally for
164 each depth increment, from three different faces of the pit. This methodology builds on
165 information from the previous sampling campaign at these locations, where soil was collected
166 from the surface 7.5 cm only (de Vries et al. 2012, Manning et al. 2015).

167

168 *Soil Analyses.*

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169 Soils were sieved (4 mm), oven dried at 60°C, ground using a ball mill, and analysed for total
170 carbon by combustion and gas chromatography (Elementar Vario EL CN analyser). Total
171 soil carbon (organic and inorganic) stocks per unit area (g C cm^{-3}) were calculated from
172 carbon concentrations (%C) and bulk density measures (g cm^{-3}) for all depth increments. A
173 further sample of the three surface soils (0 – 7.5 cm) collected from each field were pooled in
174 equal proportions for separation into soil organic matter (SOM) fractions (n=180). SOM
175 fractionation was by the flotation and sedimentation method using a sodium iodide (NaI)
176 solution (Sohi et al. 2001, Sohi et al. 2005). This fractionation method distinguishes
177 between: (a) a free SOM fraction (FR-SOM) at density $< 1.80 \text{ g cm}^{-3}$ which represents
178 discrete free organic particles located between stable soil aggregates; (b) an intra-aggregate
179 SOM fraction (IA-SOM) at density $< 1.80 \text{ g cm}^{-3}$ which represents discrete organic particles
180 located within stable soil aggregates; and (c) a residual heavy organo-mineral fraction at
181 densities $> 1.80 \text{ g cm}^{-3}$. Briefly, 7.5 g (dry wt) soil was added to 90 ml NaI at a density of
182 1.80 g cm^{-3} , centrifuged for 30 minutes and the first floating FR-SOM fraction removed by
183 suction. The remaining centrifuge pellet was then re-mixed with the NaI, sonicated for 195
184 seconds, re-centrifuged for 30 minutes, and the second floating IA-SOM fraction removed by
185 suction. The remaining pellet, thoroughly rinsed in water, forms the organo-mineral fraction.
186 All soil fractions were dried, then ground in a ball mill and analysed for total C and N as
187 above.

188

189 *Data analysis.*

190 Effects of depth and management on soil carbon concentration, bulk density and soil carbon
191 stocks were tested by ANOVA using generalised linear models (SAS Enterprise Guide 4.3),
192 with grassland type and region as factors. Cumulative soil carbon stocks to depth were
193 estimated by a Bayesian mixed modelling approach (supporting information S1), with

194 random effects of region and location included plus a fixed effect of soil depth. Estimates of
195 cumulative soil carbon stocks were summarised by the posterior distribution of values
196 estimated for each soil depth and each level of management intensity, with the clustering of
197 samples within locations accounted for in the mixed effects model. Abundance-weighted
198 means for plant traits SLA and LDMC were calculated for sample plots using plant species
199 data, derived from field surveys carried out in 2005 to help classify management intensity
200 classifications, and paired with soil carbon measurements at each soil depth. Plant trait
201 information was derived from the LEDA database based on UK values reported for each
202 species (Kleyer et al. 2008). We modelled the between-location variation in total soil carbon
203 at each depth increment in terms of the abundance weighted plant traits, testing linear and
204 quadratic models at each depth; region and location were introduced as random effects.

205

206 *Upscaling*

207 Cumulative soil carbon stocks and soil depths from our survey were combined with the UK
208 Countryside Survey land cover data (Carey et al. 2008) to estimate total grassland soil carbon
209 in Great Britain to a depth of 1m. Grassland types and management categories from our
210 survey were matched with the UK Countryside Survey (CS) broad habitat classifications of
211 improved, neutral, calcareous and acid grasslands (Emmett et al. 2010). Our 'intensively
212 managed' grassland category mapped to the CS category 'improved grasslands'; our
213 'intermediate' grasslands mapped to CS 'neutral' grasslands; and, our 'extensive' grassland
214 category mapped with the CS 'acid' and 'calcareous' grassland categories. These
215 assumptions were successfully validated by comparing the total grassland soil carbon storage
216 estimate from CS to a depth of 15cm with our modelled cumulative carbon stocks (see Fig.
217 3). Cumulative soil carbon stocks for each management category were multiplied by the land
218 cover area, and adjusted to account for the fact that not all grasslands surveyed had soil to the

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219 full 1m depth, to give an estimate of total grassland soil carbon stocks (supporting
220 information S2).

221

222

223 **Results**

224 *Field survey*

225 Across all sites, the greatest concentrations of total carbon (% total C) were in surface soils to
226 7.5 cm depth ($F_{4,2096} = 288$, $P < 0.0001$) (Table 2). Soil carbon concentration decreased with
227 increasing management intensity ($F_{2,2096} = 10.9$, $P < 0.0001$), with significantly lower carbon
228 in the most intensive relative to intermediate and extensively managed grasslands, based on
229 all soils at all depths sampled (Table 2). Management effects were strongest in the surface
230 7.5 cm soil (supporting information S3), where total carbon concentration decreased with
231 intensification, being 19% and 25% lower in intensively managed than intermediate and
232 extensively managed grasslands respectively (Table 2). The effects of management intensity
233 on total % carbon decreased with depth, but were still significant to 40cm depth ($P < 0.05$)
234 and weakly significant ($P < 0.10$) at 60 cm depth. 70% of fields contained soils to 60cm
235 depth, and 55% of all fields had soils to the full 1 m depth; therefore, the number of samples
236 analysed decreased down the profile (Table 2). Those with deeper soils tended to be from
237 more carbon rich mesotrophic and wet grasslands, hence the observed trend for increased
238 mean carbon concentration at the 60-100 cm depth (Table 2).

239

240 Soil bulk density increased with depth down the soil profile ($F_{4,2011} = 57.5$, $P < 0.0001$), and
241 was also influenced by grassland management ($F_{4,2011} = 25.9$, $P < 0.0001$) (Table 3, Table
242 S3.1). The strongest effects of management were in the top 20 cm of the profile, where bulk
243 density was lowest in extensively managed and greatest in intensively managed grasslands,

244 and a trend for greater bulk density in intensively managed grasslands continued to 1 m
245 depth. Total soil carbon stocks per unit area (g C cm^{-3}), calculated from both the soil carbon
246 concentration and bulk density, were also strongly influenced by depth, with greatest mean
247 carbon stocks per unit area in the top 7.5 cm of the profile ($F_{4,1965} = 228$, $P < 0.0001$), and by
248 management intensity ($F_{2,2096} = 3.1$, $P = 0.05$) (Fig. 2). Specifically, for all soils analysed,
249 total soil C stocks (g C cm^{-3}), were significantly greater in grasslands of intermediate
250 management intensity relative to both the extensive and intensive managed grasslands (Fig.
251 2.). When analysed by depth increments, soils from grasslands at intermediate levels of
252 management had greater soil carbon stocks relative to extensive grasslands at 7.5 cm, and
253 relative to intensive grasslands at 7.5 to 20cm depth ($P < 0.05$), with a trend for greatest C
254 stocks at intermediate levels of management detected to 60 cm depth ($P = 0.1$) (supporting
255 information S3). We estimated cumulative soil carbon storage per m^2 , at 5 depth increments
256 to 1 m depth (Table 4) using a Bayesian mixed effects model (supporting information S1).
257 Uncertainties in carbon stock estimates increased with depth (Table 4), reflecting greater
258 incremental size categories and smaller sample numbers because fewer profiles reached the
259 full 1 m depth. This is a pattern commonly encountered with soil carbon measurements at
260 depth (Syswerda et al. 2011), and in our sites, soils with samples present at 1m depth also
261 tended to be those with greater carbon concentrations. Cumulative stocks of carbon to 1 m
262 depth in grasslands with intermediate levels of management were 10.7 and 7.8% greater than
263 for grasslands with intensive and extensive management respectively (Table 4). This
264 unimodal relationship between soil carbon stocks and management is less apparent in other
265 studies where bulk density has not been taken into account.

266

267 Although we measured total carbon in bulk soils, fractionation of surface soils (7.5 cm depth)
268 showed that it was only the relatively labile soil organic matter (SOM) fractions that

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269 responded to management (Table 2). More specifically, the amount of carbon (g C kg^{-1} soil)
270 in the free SOM, which represents $\sim 15\%$ of soil mass (mean of all samples), reduced with
271 increasing management intensity. The amount of carbon in the intra-aggregate SOM
272 fractions ($\sim 2\%$ of soil mass) was also lower in the intensive compared with the other two
273 levels of management intensity. In contrast, the amount of carbon present in the recalcitrant
274 organo-mineral fraction, which accounted for the largest remaining proportion of soil mass,
275 did not respond to management intensity.

276

277 Plant traits and soil carbon at varying depth

278 Of 20 model tests (linear and quadratic fits attempted for two traits at five depths) only two
279 significant relationships were found. These were for a unimodal and linear model between
280 abundance-weighted SLA and soil carbon at 40 and 60cm depth, respectively. Consequently
281 there was little evidence for consistent relationships with the plant traits SLA and LDMC and
282 their systematic change down the soil profile.

283

284 Discussion

285 The aim of this study was to investigate the amount of soil carbon in grasslands to 1 m depth,
286 and the sensitivity of soil carbon to management intensity at depth increments to 1 m. Our
287 study was carried out at a national scale across a broad range of grasslands and soil
288 conditions, thus extending knowledge from past studies into land management and deep
289 carbon at the field scale. We reveal two key findings. First, we show that long-term changes
290 in grassland management intensity have strongly influenced soil carbon, and that this effect is
291 seen to considerable depths down the soil profile, albeit at decreasing significance with depth.
292 Second, we show that considerable stocks of carbon are contained in sub-surface grassland
293 soils, below the standard carbon inventory default depth of 30cm under tier 1 of the IPCC

294 (2006), suggesting that large stocks of unaccounted for carbon are sensitive to management
295 change.

296

297 *Management intensity*

298 Our data show that intensive management has reduced the concentration of carbon in soil (%
299 total C), and that soil carbon stocks per m² are greatest at intermediate levels of grassland
300 management intensity. This sensitivity of soil carbon to management has been found in other
301 grassland studies for surface soils in Europe (Soussana et al. 2004, Allard et al. 2007).

302 However, by sampling to 1 m depth from a large number of sites across a broad range of
303 grassland and soil types, our study extends the knowledge of grassland management effects
304 on soil carbon by demonstrating that, although management effects on soil carbon were
305 strongest in surface soils, they are still observed to considerable depth down the soil profile,
306 indicating that extensive stocks of soil carbon at depth are sensitive to management change.

307

308 We suggest that both biological and physical mechanisms contributed to the greater
309 cumulative carbon stocks observed at intermediate levels of grassland management. Soil
310 carbon sequestration is dictated by processes controlling the balance of carbon inputs and
311 carbon outputs. Carbon inputs are derived from primary productivity through photosynthetic
312 uptake of carbon, input to soil in the form of root exudates and litter; plus additional inputs
313 from animal manure. Carbon losses are through a range of biological and physical processes
314 including respiration, decomposition, erosion, leaching and removal of biomass by harvesting
315 or grazing animals. Because we measured total rather than organic soil carbon, it is possible
316 that differences in total soil carbon are due, in part, to variations in inorganic carbon, from
317 liming or the influence of parent bedrock, particularly in calcareous soils. It is also possible
318 that black carbon (charcoal) made up a small proportion of the total carbon observed

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319 (Manning et al. 2015). However, by sampling triplicate groups of fields from the same
320 bedrock across a management intensity gradient, we suggest that these effects would be
321 minimal.

322

323 There are clearly many factors involved in the intensification of grassland management, such
324 as fertiliser addition, the intensity of grazing and biomass removal, and compaction
325 associated with livestock and machinery, and it is difficult to separate out the effects of each
326 of these in terms of their influence on soil carbon. Such management factors also impact on
327 plant community composition, which is known to influence soil carbon dynamics (De Deyn
328 et al. 2008, Manning et al. 2015). We did not directly measure plant productivity,
329 decomposition, or other processes involved in carbon cycling. However, it has been shown
330 in other studies that extensive grassland management can reduce soil carbon accumulation
331 over time as plant productivity declines in response to nutrient limitation (Allard et al. 2007),
332 and that intensive management involving the application of large amounts of fertiliser can be
333 detrimental to soil carbon (Mack et al. 2004, Soussana et al. 2004, Schipper et al. 2007).
334 Conversely, the application of fertiliser in modest amounts in intermediate grasslands has
335 been shown to enhance soil carbon (Conant et al. 2011, Leifeld et al. 2011, Smith 2014),
336 which is likely related to an increase in primary productivity without over-stimulating
337 decomposition, although, as pointed out, the effect of other concomitant management factors
338 cannot be ruled out.

339

340 In addition to changes in bulk soil carbon, we also found that different fractions of carbon in
341 surface soils to 7.5 cm depth varied in their sensitivity to management. In particular, both the
342 labile free SOM and intra-aggregate SOM fractions were reduced by management
343 intensification. While these two SOM fractions make up less than a quarter of total soil mass,

344 they are of vital importance to soil carbon storage as they contain a greater concentration of
345 carbon than the recalcitrant organo-mineral fraction and account for 31% of soil carbon in
346 intensively managed soils, rising to 37% and 44% of soil carbon in intermediate and
347 extensively managed grassland soils respectively. We found no evidence of a systematic
348 relationship between total soil carbon at varying depth and community weighted values of
349 two key leaf traits (i.e. SLA and LDMC) that are known to be responsive to grassland
350 intensification and to mediate effects on carbon storage via differences in the
351 decomposability of plant material (De Deyn et al. 2008). We expected that the relationship
352 between leaf traits and soil carbon would be strongest at the soil surface and decline in
353 strength with soil depth, reflecting historic plant traits prior to intensification in the last 60
354 years. Using the same network of grassland sites, Manning et al (2015) investigated
355 relationships between plant traits and soil carbon fractions in surface soil (7.5 cm soil depth)
356 and found that only the labile carbon fraction was partially explained by community weighted
357 SLA, with soil carbon stocks being greatest under vegetation with thick and/or dense leaves.
358 In contrast, the less active fractions, which make up the bulk of the carbon pool, were better
359 explained by abiotic factors, including pH and climate (Manning et al. 2015). Our results
360 indicate that the lack of correlation between leaf traits and soil carbon propagates down the
361 soil profile, suggesting that the mediating effect of current plant trait variation on soil carbon
362 is weaker than the long-term effect of other environmental controls on the production and
363 storage of carbon at depth.

364

365 Differences in carbon stocks between management levels were also strongly influenced by
366 variations in soil bulk density, which increased as management intensified and with depth.
367 This increase in bulk density with more intensive management is likely largely explained by
368 soil compaction from a greater use of machinery and trampling from grazing animals

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369 (Gifford and Roderick 2003, Batey 2009), but also the greater proportion of higher density
370 soil fractions in fertilised soils (Fornara et al. 2011). The combination of low carbon
371 concentration with high bulk density in intensive grasslands, and high carbon concentration
372 with low bulk density in extensive grasslands, contributed to the equivalence of carbon stocks
373 observed at high and low levels of management intensity, and their lower levels relative to
374 intermediate intensity. This highlights a dilemma in comparing soil carbon stocks both
375 spatially and temporally, in that soil carbon stocks calculated per unit area could be increased
376 by simple physical compaction without a change in soil carbon concentration, particularly if
377 measured at shallow sampling depths. Gifford and Roderick (2003) propose an alternative
378 way of calculating soil carbon based on soil mass rather than volume to avoid this problem of
379 bulk density change associated with land use. For comparison, we estimated cumulative
380 carbon stocks on a soil mass rather than volume basis, using approximated soil mass values
381 (supporting information). On this approximated soil mass basis, differences in cumulative
382 carbon stocks between intermediate and extensive grasslands were reduced, whereas the
383 difference in cumulative carbon stocks for intensive relative to both intermediate and
384 extensive grasslands increased, to an estimated 15% less carbon in intensively managed
385 grasslands (supporting information). This differs from our findings on a bulk density basis,
386 where soil carbon stocks were greatest under intermediate compared with both intensive and
387 extensive intensity of management, but highlights the strong detrimental effect of intensive
388 management on grassland soil carbon stocks. However, these results need to be treated with
389 caution as calculations were made retrospectively on approximated soil mass values without
390 following the recommended protocol (Gifford and Roderick 2003), and did not meet the
391 requirement for samples to be taken from adjacent positions (Chapman et al. 2013).

392

393 *Carbon stocks at depth*

394 Our study revealed that considerable stocks of soil carbon are contained in sub-surface
395 grassland soils below the standard carbon inventory default depth of 30cm (IPCC 2006).
396 Using Great Britain as a case study, we combined our model of cumulative soil carbon stocks
397 across a range of grasslands and management intensities with land cover data (Carey et al.
398 2008) for comparable grassland categories, to estimate total grassland soil carbon storage to 1
399 m depth. Cumulative soil carbon stocks were adjusted for depth, based on our survey results
400 of a decreasing proportion of grasslands having soil to the full sampling depth, with 55% of
401 all fields having soil to the full 1 m depth (Table 4). From this, we estimate a total carbon
402 stock in British grassland soils of 2097 Tg C to a depth of 1 m (Fig. 3). This is over three
403 times the amount for soil organic carbon estimated by the latest Countryside Survey to 15 cm
404 depth (660 Tg), and more than double the amount when extrapolated to the standard IPCC
405 recommended carbon accounting depth of 30 cm (estimated at 880 Pg, Fig. 3). Of this figure
406 of 2097 Tg C for grassland carbon storage to 1 m depth, the greatest proportion of grassland
407 soil carbon stocks (1130 Tg C) were in improved grasslands, which account for the largest
408 land cover of all grasslands in Great Britain (Carey et al. 2008) and are most likely to contain
409 soil to 1 m depth. Total stocks of soil carbon to 1 m depth (Table S2.2) were 10.7% greater
410 at intermediate relative to intensive management, which equates to 10.1 t ha^{-1} in surface soils
411 to 30 cm depth, and an additional 13.7 t ha^{-1} in soils from 30-100 cm depth.

412

413 At shallower soil depths, our soil carbon values of 76 and 97 t ha^{-1} at 15 and 30 cm depths
414 respectively, are in line with those reported elsewhere for the UK, of $48\text{-}90 \text{ t ha}^{-1}$ at 15 cm
415 and 100 t ha^{-1} at 30 cm depth (Bradley et al. 2005, Emmett et al. 2010, Chapman et al. 2013).
416 However, our estimation of grassland soil carbon stocks of 2097 Tg C to 1 m depth is
417 considerably greater than that of Bradley et al. (2005), estimated at 1345 Tg C for UK
418 pasture, and of Chapman (2013), who reported 138 t ha^{-1} for improved and 185 t ha^{-1} for

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419 semi-natural grasslands, compared with our value of at 229 t ha^{-1} at 1 m depth. This suggests
420 that grassland carbon stocks at depth may be greater than previously thought. However,
421 extrapolation of data needs to be treated with caution, due to the high variability of carbon
422 stocks at depth and regional differences between management and grassland types (Maskell
423 et al. 2013), and our modelling results explicitly quantify the uncertainty associated with our
424 estimates and how the uncertainty increases with depth (Table 4). Differences in soil carbon
425 accounting at depth between studies are likely due to increased uncertainties caused by lower
426 sample numbers and greater incremental size categories (Syswerda et al. 2011), and
427 differences between land use classifications; for example, Bradley et al (2005) estimate a
428 further 2015 Tg C to 1m depth in their semi natural category. Our data also show that around
429 60% of the total grassland soil carbon stocks to 1 m depth are found in sub-surface soils
430 below 30 cm depth. Previous estimates, albeit for organic not total carbon, commonly quote
431 a 50/50 split between surface and sub-surface (30-100 cm) soil carbon (Batjes 1996, Jobbagy
432 and Jackson 2000, Schils et al. 2008), although 60% sub-surface organic carbon has been
433 previously estimated for some grassland soils (Hiederer 2009).

434

435 Our data clearly reveal an important stock of carbon in grassland soil at depth, which is
436 unrecognised in current surface soil carbon accounting (IPCC 2006, Emmett et al. 2010).
437 Despite the tier 1 default soil sampling depth being 30 cm, the IPCC advocate sampling
438 beyond 30 cm depth, although in likelihood this is rarely done. Our findings provide clear
439 support for the IPCC recommendation of the need for deeper C sampling, not only to improve
440 soil C inventories, but also to take into account changes in soil carbon at depth due to
441 management intensification.

442

443 *Conclusion*

444 In conclusion, the findings of our national-scale study, which encompassed a broad range of
445 grasslands and environmental conditions, show that carbon in grasslands soils is vulnerable to
446 management, and that the legacy of long-term grassland management impacts on soil carbon
447 to considerable depth down the profile. Moreover, we highlight the presence of substantial
448 stocks of carbon in sub-surface soil in grasslands, which are not accounted for by the majority
449 of standard carbon inventories (IPCC 2006, Emmett et al. 2010, Sanderman et al. 2011),
450 indicating that large stocks of unaccounted for soil carbon are sensitive to changes in land
451 management intensity. Our finding suggest potential future benefits for soil carbon
452 sequestration alongside biodiversity through extensification of the most highly managed and
453 fertilised grasslands, given that soil carbon concentrations decrease with management
454 intensity, and that cumulative stocks of soil carbon to depth when bulk density was accounted
455 for were greatest in grasslands managed at intermediate levels of intensity and plant diversity.
456 Given the global extent of managed grasslands, these findings not only have implications for
457 their future management for soil carbon storage and climate mitigation, that would benefit
458 future global carbon targets (United Nations FCCC 2015), but also for global carbon models
459 which need to take account of deep soil carbon stocks, and changes in this soil carbon at
460 depth due to management.

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642

643 Supporting Information

644 S1. Methods for modelling cumulative soil carbon.

645 S2. Upscaling cumulative soil carbon to the whole of Great Britain.

646 S3. Statistical effects for soil carbon and bulk density.

647 S4. Estimating soil C stocks on soil mass basis.

648 S5. BUGS code for modelling cumulative soil carbon stocks.

649

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650 **Tables**

651 **Table 1.** Typical values for grassland management practices, including fertiliser use, grazing
 652 management (LU = livestock units), cutting regimes, and plant species diversity for the three
 653 levels of management intensity.

	Extensive	Intermediate	Intensive
Fertiliser application rate	< 25 kg N ha ⁻¹ yr ⁻¹	25 – 50 kg N ha ⁻¹ yr ⁻¹	> 100 kg N ha ⁻¹ yr ⁻¹
Grazing	Set stocking or continuous grazing at stocking rates generally below 1.0 LU ha ⁻¹	Set stocking or continuous grazing at stocking rates up to 1.5 LU ha ⁻¹	Rotational/paddock grazing commonly used with stocking rates of 2.0 – 3.5+ LU ha ⁻¹
Cutting	Generally one cut in mid – late summer for hay or haylage. Regrowth generally grazed in late summer/autumn	Generally one cut in mid-summer for silage or haylage. Regrowth generally grazed in late summer/autumn	Two – three silage cuts per year (May, July, September/October)
¹ Plant diversity	High diversity (Mean 21 sp. m ⁻²)	Intermediate Diversity (Mean 15 sp. m ⁻²)	Low Diversity (Mean 10 sp. m ⁻²)

654

655 ¹Data on plant species diversity are derived from De Vries et al. (2012).

656 **Table 2.** Effects of management intensity on soil carbon, measured as (a) % C of bulk soil
 657 and (b) C content of soil fractions in surface soils.

	Soil depth (cm)	(n)	Extensively managed	Intermediate management	Intensively managed	
(a) Bulk soil carbon concentration (%C)						
Depth (cm)	0 – 7.5	(515)	11.53 (\pm 0.54) ^a	10.60 (\pm 0.54) ^b	8.59 (\pm 0.44) ^c	**
	7.5 – 20	(499)	8.18 (\pm 0.59) ^a	7.77 (\pm 0.53) ^a	6.13 (\pm 0.47) ^b	**
	20 – 40	(446)	6.48 (\pm 0.84) ^{ab}	6.34 (\pm 0.74) ^a	5.59 (\pm 0.72) ^b	**
	40 – 60	(359)	6.85 (\pm 1.28)	6.51 (\pm 1.12)	5.35 (\pm 0.96)	*
	60 – 100	(277)	9.76 (\pm 1.66)	7.25 (\pm 1.43)	7.55 (\pm 1.37)	
(b) Carbon content of soil fractions in surface soils (0-7.5 cm) (g C kg⁻¹ soil)						
	Free SOM		43.9 (\pm 9.1) ^a	34.3 (\pm 8.9) ^b	23.6 (\pm 7.9) ^c	**
	Intra-aggregate SOM		3.0 (\pm 0.5) ^a	2.6 (\pm 0.3) ^a	1.8 (\pm 0.2) ^b	**
	Organo-mineral		59.9 (\pm 4.0)	62.3 (\pm 3.9)	56.7 (\pm 3.8)	

658 Values are means \pm s.e. Significant management effects shown by ** ($P < 0.05$) and *

659 ($P < 0.10$), with letters denoting differences between the 3 levels of management.

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660 **Table 3.** Soil bulk density (g cm^{-3}), for grassland soils at each of five depth increments
 661 sampled, by management intensity and depth.

Soil depth (cm)	(n)	Extensively managed	Intermediate management	Intensively managed	
0 – 7.5	(486)	0.64 (\pm 0.02)	0.73 (\pm 0.02)	0.83 (\pm 0.02)	**
7.5 – 20	(464)	0.85 (\pm 0.02)	0.91 (\pm 0.02)	0.98 (\pm 0.02)	**
20 - 40	(399)	1.06 (\pm 0.03)	1.00 (\pm 0.03)	1.06 (\pm 0.03)	**
40 - 60	(362)	1.05 (\pm 0.04)	1.06 (\pm 0.04)	1.13 (\pm 0.03)	**
60 - 100	(300)	1.02 (\pm 0.05)	1.05 (\pm 0.04)	1.09 (\pm 0.04)	**

662 Values are means \pm s.e. Significant management effects shown by ** ($P < 0.05$).

663

664 **Table 4.** Mean cumulative soil carbon (kg C m⁻²).

	Extensively managed	Intermediate management	Intensively managed
Surface to 7.5cm depth	6.61 (± 5.26-8.32)	7.14 (± 5.68-8.96)	6.45 (± 5.12-8.11)
Surface to 20 cm depth (97% of samples)	8.47 (± 6.75-10.65)	9.15 (± 7.29-11.47)	8.26 (± 6.56-10.37)
Surface to 40 cm depth (87% of samples)	12.59 (± 10.04-15.82)	13.60 (± 10.83-17.02)	12.28 (± 9.76-15.40)
Surface to 60 cm depth (70% of samples)	18.71 (± 14.90-23.54)	20.21 (± 16.07-25.36)	18.24 (± 14.53-22.92)
Surface to 100 cm depth (55% of samples)	41.38 (± 32.65-52.33)	44.62 (± 35.20-56.47)	40.30 (± 31.84-50.98)

665 Values are best estimates of the mean carbon stock where soil samples were present, with
666 lower and upper credible intervals (2.5 and 97.5%tiles of the posterior distribution from a
667 Bayesian mixed effects model).

668 **Figure captions**

669

670 **Figure 1.** Sampling locations in England (DeVries et al. 2012). Five farms were selected in
671 each of the 12 regions, and three fields in each farm were sampled: one extensively managed,
672 one of intermediate management and one intensively managed. Regions are: (a) Worcester,
673 (b) Upper Thames, (c) Somerset, (d) Devon, (e) Cotswolds, (f) High Weald, (g) South
674 Downs, (h) Breckland, (i) Dales meadows, (j) Yorkshire Ings, (k) Yorkshire Dales/South
675 Lake District, (l) Lake District.

676

677 **Figure 2.** Total carbon per unit area in grassland soils (g C cm^{-3} soil). Shown for each of five
678 depth increments sampled, with management intensity indicated by coloured bars: white for
679 extensively managed, grey for intermediate management and black for intensively managed
680 soils. Values are means \pm s.e.

681

682 **Figure 3.** Estimated cumulative total soil carbon stocks for grasslands in Great Britain (Tg
683 C), adjusted for the availability of soil at depth. Shown in depth increments to 1 m, with
684 management intensity indicated by colour: white for extensively managed, grey for
685 intermediate management and black for intensively managed soils. The solid black circle
686 shows the current GB estimate of soil carbon at 15 cm depth. Dashed lines indicate
687 recommended soil sampling depths (GB Countryside Survey 15cm, IPCC at 30cm).

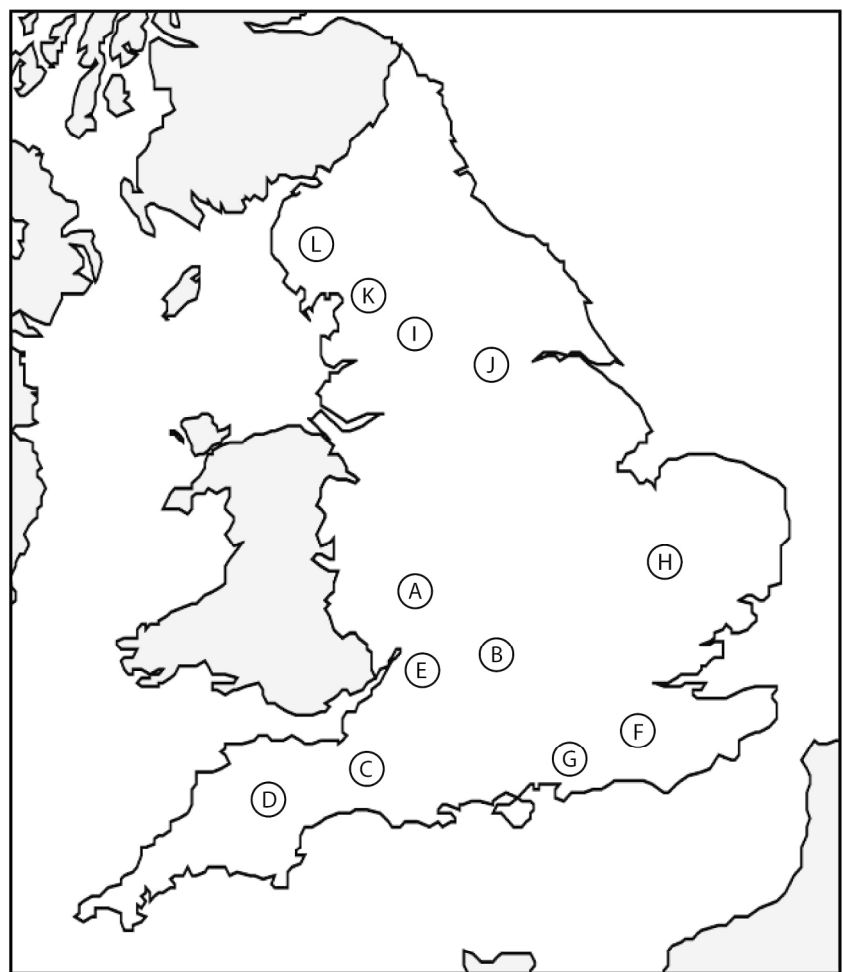


Figure 1
209x234mm (300 x 300 DPI)

