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

2 Running header: Management and deep soil carbon

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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.

Introduction

Permanent grasslands are found extensively across the temperate zone where they form the

backbone of agricultural systems. Global land cover estimates for grasslands range between

20-40% of the Earth (FAO 2015), and for the UK, constitute the largest category of land use

at 36% of land cover (Carey et al. 2008). The multiple values of grassland ecosystems to

mankind has long been recognised, ranging from direct benefits of agricultural production, to

indirect ecosystem services such as the regulation of climate and water quality, and

pollination services (Heidenreich 2009). As such, grasslands are arguably one of the most

valuable biomes for ecosystem service provision, but also are among the most threatened by

anthropogenic activities (Gibson 2008). Threats include increasing pressures to meet the

food demands of more affluent and larger global populations, and to deliver concomitant

multiple ecosystem services demanded by the sustainable intensification agenda (Garnett et

al. 2013). Of the multiple ecosystem services provided by grasslands, climate regulation via

soil carbon storage and sequestration, is highly valued (Heidenreich 2009).

In terms of terrestrial carbon storage, soils contain the largest global pool of terrestrial

carbon, storing more carbon than is present in plant biomass and the atmosphere combined

(Batjes 1996, Jobbagy and Jackson 2000). Temperate grasslands are the third largest global

store of carbon in soils and vegetation (after wetlands and boreal forests), storing an

estimated 304 Pg C, or 12.3% of global carbon (Royal Society 2001), most of which is in

soil. Such carbon stocks are known to be vulnerable to changes in land use and

intensification of agricultural management, with the conversion of croplands to permanent

grassland generally increasing soil carbon, and the reverse change from grassland to

croplands reducing soil carbon stocks (Guo and Gifford 2002, Smith et al. 2008). Moreover,

such changes in land use can have a long lasting legacy effect on soil carbon, on a scale of

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

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.*

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 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 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 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

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

269   responded to management (Table 2). More specifically, the amount of carbon (g C kg^{-1} soil)

270   in the free SOM, which represents ~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 (~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 m^2 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

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

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 48-90 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

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   In conclusion, the findings of our national-scale study, which encompassed a broad range of

444   grasslands and environmental conditions, show that carbon in grasslands soils is vulnerable to

445   management, and that the legacy of long-term grassland management impacts on soil carbon

446   to considerable depth down the profile. Moreover, we highlight the presence of substantial

447   stocks of carbon in sub-surface soil in grasslands, which are not accounted for by the majority

448   of standard carbon inventories (IPCC 2006, Emmett et al. 2010, Sanderman et al. 2011),

449   indicating that large stocks of unaccounted for soil carbon are sensitive to changes in land

450   management intensity. Our finding suggest potential future benefits for soil carbon

451   sequestration alongside biodiversity through extensification of the most highly managed and

452   fertilised grasslands, given that soil carbon concentrations decrease with management

453   intensity, and that cumulative stocks of soil carbon to depth when bulk density was accounted

454   for were greatest in grasslands managed at intermediate levels of intensity and plant diversity.

455   Given the global extent of managed grasslands, these findings not only have implications for

456   their future management for soil carbon storage and climate mitigation, that would benefit

457   future global carbon targets (United Nations FCCC 2015), but also for global carbon models

458   which need to take account of deep soil carbon stocks, and changes in this soil carbon at

459   depth due to management.

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641

642   **Supporting Information**

643   S1. Methods for modelling cumulative soil carbon.

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

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

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

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

648

649 **Tables**

650 **Table 1.** Typical values for grassland management practices, including fertiliser use, grazing

651 management (LU -= livestock units), cutting regimes, and plant species diversity for the three

652 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 to1.5 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})

653

654 [1]Data on plant species diversity are derived from De Vries et al. (2012).

655   **Table 2.** Effects of management intensity on soil carbon, measured as (a) % C of bulk soil

656   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 (± 0.54) [a]	10.60 (± 0.54) [b]	8.59 (± 0.44) [c]	**
	7.5 – 20	(499)	8.18 (± 0.59) [a]	7.77 (± 0.53) [a]	6.13 (± 0.47) [b]	**
	20 – 40	(446)	6.48 (± 0.84) [ab]	6.34 (± 0.74) [a]	5.59 (± 0.72) [b]	**
	40 – 60	(359)	6.85 (± 1.28)	6.51 (± 1.12)	5.35 (± 0.96)	*
	60 – 100	(277)	9.76 (± 1.66)	7.25 (± 1.43)	7.55 (± 1.37)	
(b) Carbon content of soil fractions in surface soils (0-7.5 cm) (g C kg^{-1} soil)						
Free SOM			43.9 (± 9.1) [a]	34.3 (± 8.9) [b]	23.6 (± 7.9) [c]	**
Intra-aggregate SOM			3.0 (± 0.5) [a]	2.6 (± 0.3) [a]	1.8 (± 0.2) [b]	**
Organo-mineral			59.9 (± 4.0)	62.3 (± 3.9)	56.7 (± 3.8)	

657   Values are means ± s.e. Significant management effects shown by ** ($P<0.05$) and *

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

659   **Table 3**. Soil bulk density (g cm^{-3}), for grassland soils at each of five depth increments

660   sampled, by management intensity and depth.

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

661   Values are means ± s.e. Significant management effects shown by ** ($P < 0.05$).

662

663   **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)

664   Values are best estimates of the mean carbon stock where soil samples were present, with

665   lower and upper credible intervals (2.5 and 97.5%tiles of the posterior distribution from a

666   Bayesian mixed effects model).

667   **Figure captions**

668

669   **Figure 1.** Sampling locations in England (DeVries et al. 2012). Five farms were selected in

670   each of the 12 regions, and three fields in each farm were sampled: one extensively managed,

671   one of intermediate management and one intensively managed. Regions are: (a) Worcester,

672   (b) Upper Thames, (c) Somerset, (d) Devon, (e) Cotswolds, (f) High Weald, (g) South

673   Downs, (h) Breckland, (i) Dales meadows, (j) Yorkshire Ings, (k) Yorkshire Dales/South

674   Lake District, (l) Lake District.

675

676   **Figure 2.** Total carbon per unit area in grassland soils (g C cm^{-3} soil). Shown for each of five

677   depth increments sampled, with management intensity indicated by coloured bars: white for

678   extensively managed, grey for intermediate management and black for intensively managed

679   soils. Values are means +/- s.e.

680

681   **Figure 3.** Estimated cumulative total soil carbon stocks for grasslands in Great Britain (Tg

682   C), adjusted for the availability of soil at depth. Shown in depth increments to 1 m, with

683   management intensity indicated by colour: white for extensively managed, grey for

684   intermediate management and black for intensively managed soils. The solid black circle

685   shows the current GB estimate of soil carbon at 15 cm depth. Dashed lines indicate

686   recommended soil sampling depths (GB Countryside Survey 15cm, IPCC at 30cm).