

1 **Carbon storage in hedge biomass - a case study of actively managed hedges in**
2 **England**

3 Matthew S. Axe^{a*}, Ian D. Grange^a, John S. Conway^a

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5 ^a School of Agriculture, Food and Environment, Royal Agricultural University, Cirencester,
6 Gloucestershire GL7 6JS, UK

7 * Corresponding author at: School of Agriculture, Food and Environment, Royal Agricultural
8 University, Cirencester, Gloucestershire GL7 6JS, UK

9

10 E-mail address: matthew.axe@pobroadband.co.uk (M S Axe).

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12 **Abstract**

13 Farmland hedges could be managed for carbon sequestration, but empirical data on their
14 carbon (C) stock in the UK is lacking. Lowland hedges managed by hedge laying and triennial
15 trimming using a mechanical flail formed a dense woody structure (mean 81 368 stems ha⁻¹).
16 Hedges untrimmed for 3 years (mean height 3.5 m, widths 2.6 - 4.2 m), contained an above
17 ground biomass (AGB) C stock of 42.0 ± 3.78 t C ha⁻¹ (14.0 ± 1.94 t C km⁻¹); when trimmed to
18 2.7 m high, and subsequently 1.9 m high, AGB C stocks were reduced to 40.6 ± 4.47 t C ha⁻¹
19 (11.4 t C km⁻¹) and 32.2 ± 2.76 t C ha⁻¹ (9.9 t C km⁻¹), respectively. A 4.2 m wide hedge
20 contained 9.7 t C km⁻¹ more AGB C stock than a 2.6 m wide hedge (mean height 3.5 m). Below
21 ground biomass (BGB) was 38.2 ± 3.66 t C ha⁻¹ (11.5 t C km⁻¹). Near horizontal stems,
22 arranged by hedge laying, 12 - 18 years prior to sampling, accounted for 5.2 t C ha⁻¹ (1.6 t C
23 km⁻¹) of AGB C. The empirical data demonstrated how changing management practices to
24 wider/taller hedges sequestered C in AGB. These estimates of hedgerow C stocks fill a
25 knowledge gap on C storage and identified the need for a more comprehensive biomass
26 inventory of hedgerows to strengthen the national carbon accounting of agro-ecosystems in
27 the UK.

28 **Key words**

29 Carbon Sequestration; Hedgerow Carbon Stocks; Hedge Management

30 **1 Introduction**

31 Hedges are woody linear features delineating field boundaries in many agro-ecosystems in
32 the UK. While the potential for woodlands, as well as agroforestry, to sequester carbon (C)
33 and mitigate for rising levels of Green-House Gasses (GHG) has received much attention
34 (Montagnini and Nair 2004; Luysaert *et al.* 2008; Ostle *et al.* 2009; Pan *et al.* 2011; Udawatta
35 and Jose 2012), little research has been carried out on whether hedgerows sequester C and
36 none on the effect of management practices. The lack of quantitative information on changes
37 to hedgerow C stocks, makes reporting their contribution to national GHG removals, or
38 emissions, challenging (MacCarthy *et al.* 2015). No empirical research on C stocks for hedges
39 in the UK has been published in scientific literature, neither for above ground biomass (AGB),
40 nor below ground biomass (BGB). Previous estimates of hedgerow AGB C stocks ($t\ C\ ha^{-1}$)
41 used averaged data from agricultural set-aside (Falloon *et al.* 2004) and woodland biomass
42 (Robertson *et al.* 2012), with an assumed proportional effect on C stock as hedge height
43 varied, and BGB C stocks omitted.

44 An estimated 456 000 km of hedge in England and Wales had been actively managed, such
45 that the woody plants no longer exhibited their natural shape (Carey *et al.* 2008). This
46 vegetation management is carried out to limit hedge outward growth, and to create an effective
47 barrier to livestock with a network of intertwined stems (Pollard *et al.* 1974; Baudry *et al.* 2000;
48 Jones *et al.* 2001). These actively managed hedgerows are cut in two distinct cycles. A short
49 period trimming cycle every 1 - 3 years, and a long period structural restoration cycle, after
50 approximately 40 years growth (Staley *et al.* 2015). Britt *et al.* (2011) reported 92% of farmers
51 in England and Wales used a tractor driven mechanical flail for trimming hedges; largely for
52 economic efficiency, since other trimming methods (circular saw, finger bar cutter, or hand
53 trimming) require additional labour to clear up cut debris (Semple *et al.* 1994a). The flail has

54 a relatively blunt cutting edge, striking the branch repeatedly and leaving a ragged cut (Semple
55 *et al.* 1994b); compared to uncut hawthorn hedges, the practice of flailing produced more thorn
56 tipped new shoots (Bannister and Watts 1995). Thorns are a plant defensive response to
57 herbivory, which can potentially elongate into shoots (Bannister and Watts 1995). This
58 mechanism may lead to an increased concentration of woody biomass in the hedge. For trees
59 in general, pruning practices can elicit an increased growth response, specifically branch
60 elongation (Rom and Ferree 1985; Goodfellow *et al.* 1987; Krueger *et al.* 2009); with growth
61 greatest in the first year following pruning, and declining with time (Follett *et al.* 2016). Beyond
62 a certain level of pruning however, growth can decline (Pinkard and Beadle 2000). Thus
63 growth form of hedges trimmed by flailing, and potentially their AGB C stocks, may differ from
64 woody vegetation formed by secondary succession and without trimming interventions; such
65 as unmanaged hedges (Küppers 1985), or woodland, (Poulton *et al.* 2003).

66 Triennial trimming benefits increased flower and berry production for wildlife (Staley *et al.*
67 2012) and 47% of farmers in England cut their hedges every 2 or 3 years (DEFRA 2008).
68 Furthermore 30% of farmers that took up the first tier of Agri-Environmental Schemes (AES)
69 in England (the Entry Level Stewardship) opted to trim at least some of their hedges triennially
70 (Natural England, 2009). However trimming by flail alone does not prevent hedges losing their
71 dense woody form over time, so structural restoration is carried out on a long period cycle to
72 stimulate new growth from the hedge base (Croxtton *et al.* 2004; Staley *et al.* 2015). In England
73 and Wales 42% of farmers restored hedge structures by laying, compared to 15% using the
74 practice of coppicing (Britt *et al.* 2000). Hedge laying requires a large portion of the woody
75 hedge material to be removed, and then selected stems known as 'pleachers' to be partially
76 severed at their base or 'stool', laid over near horizontal, and retained in place with wooden
77 stakes; thus encouraging new vertical growth (Staley *et al.* 2015).

78 The hedgerow management activities of first laying shrubs, and then limiting their outward
79 growth by flailing, modifies their natural growth form. This warrants an investigation of the
80 biomass partitioning, to see if C stocks are comparable with those given for woodland settings.

81 Comparisons between hedges and other forms of silvaculture are also made difficult by a lack
82 of data on established hedge planting density; Staley *et al.* (2015) reported 1.8 stools m⁻¹ of
83 hawthorn hedge had 10 basal shoots per stool, however this was 3 years after traditional
84 hedge laying, with longer term shoot survival unknown.

85 In England and Wales combined the most frequently occurring woody hedge species were
86 hawthorn (*Crataegus monogyna* 90%) followed by blackthorn (*Prunus spinosa* 50%) (Barr *et*
87 *al.* 2000). Sampling hawthorn/blackthorn hedges that have been managed by triennial flailing
88 and periodic laying would allow for a useful comparison with previous hedgerow C stock
89 estimates of Falloon *et al.* (2004) and Robertson *et al.* (2012). Therefore a pilot study of in-
90 situ managed hedges was carried out to better understand AGB/BGB C stocks and the
91 shoot:root ratio. As in-situ sampling encompassed several factors (soil type/species mix/age
92 since last laid/width) that differed between hedges, and could potentially affect C stock, the
93 effects were combined and statistically tested to understand variability of hedgerows for future
94 studies. These findings will better inform management options for increasing C sequestration,
95 and place hedgerows within the context of national carbon accounting models.

96 **2 Method**

97 **2.1 Site description and sampling design**

98 The study hedges were located at Harnhill Manor Farm, Harnhill, Gloucestershire, (51°41'
99 N, 1°54' W) owned by the Royal Agricultural University. In November 2013, a stratified
100 random sampling approach was used to select three sample hedges, for the purpose of
101 quantifying AGB C stocks, and the effect of trimming hedge height, together with the BGB C
102 stocks. For the purpose of this pilot study, the multiple factors of soil type/species mix/age
103 since last laid/width (Table 1) were combined, and parameters (height, width, C stock) tested
104 for significant differences between hedges (Section 2.4). C stock partitioning was analysed
105 between the hedge stem/branches at 3 different heights, pleachers, litter layer, and roots, etc.

106 From each hedge, three 1 m long sections were randomly selected for destructive sampling
107 (Sections 2.2 and 2.3). Hedges 1 and 3 were comprised of hawthorn and Hedge 2 was a
108 hawthorn/blackthorn mix (Table 1). Hedge 1 was present from at least 1884 (Ordnance Survey
109 1884) with Hedges 2 and 3 being established in 1801 (Anon. 1801). Hedge 1 soils were of the
110 Evesham series, a pelocalcaric gley soil; and Hedges 2 and 3 were minor variants of the
111 Sherborne soil series, a lithomorphic brown rendzina (Avery 1990; Cranfield University 2015).

112 **2.2 Sampling hedge above ground biomass (AGB)**

113 Each 1 m replicate hedge section was characterised for structural woody components (stems
114 and branches, pleachers and regrowth). Three heights from ground level were recorded for
115 each replicate, that is: two previously trimmed heights that were clearly identified by severed
116 stems and new regrowth, and the most common existing stem height (the mode) (Figure 1).
117 Widths of each hedge section, both at 1.3 m high, and at the base of the canopy were also
118 recorded. Stems were demarcated as angled 'pleachers' from previous hedge laying activity,
119 or as vertical stems growing from either a pleacher, or a 'stool' - the partially cut main stem at
120 ground level. Woody plant species were recorded, including Bramble (*Rubus corylifolius*), if
121 present.

122 Two vertical cuts, 1 m apart, were made to separate the replicate sample from the source
123 hedge. Branches and stems extending outside the replicate were cut off where they crossed
124 the replicate boundary and excluded from the sample. Conversely, branches and stems
125 growing into the replicate from outside were cut off at the replicate boundary and included in
126 the sample. Stems and pleachers were cut off within 10 cm of the ground. Surface woody litter
127 was collected by hand raking.

128 The component parts of each 1 m section were separated (stem and branches of growth stage
129 increments 1- 3, 'pleachers', surface woody litter, hung up deadwood; Figure 1) and weighed
130 fresh before sub-sampling to determine the dry matter using a forced air oven, drying at 65°C
131 until a constant mass was achieved. The selected temperature was comparable with other

132 methodology (Jackson *et al.* 2013; Ruiz-Peinado *et al.* 2013; Ferez *et al.* 2015) and avoided
133 loss of volatile organic compounds associated with higher drying temperatures (Reuter *et al.*
134 1986). The oven dried woody components were sub-sampled in replicate and milled to <0.5
135 mm, and analysed for C using an Elementar vario EL Cube CNS automated elemental
136 analyser, using high temperature decomposition with purge and trap gas chromatography
137 (Table 2).

138 **2.3 Sampling hedge below ground biomass (BGB)**

139 The lateral extent of BGB was hidden and not readily determined, particularly as several lateral
140 roots within 0-100 cm soil depth were observed growing perpendicular outwards from the
141 middle of the hedge, beyond the root sampling zone. Therefore, after AGB removal, a BGB
142 sample area of each hedge section replicate length (1 m), by the canopy base width, was
143 demarcated on the ground with spray paint, stumps were labelled, and marked with their north-
144 south orientation and the ground level. A 3.5 tonne mini-digger excavated the soil from the
145 demarcated sample area depositing it on plastic sheets. As each labelled stump and root
146 crown was levered out, the lateral roots generally broke at the excavation boundary; this being
147 the weak point where the unexcavated consolidated soil still gripped the root.

148 Root crowns were separated and stored for processing. The excavated soil containing finer
149 roots was split into 'upper' and 'lower' root zones, broadly corresponding with the Evesham
150 soil series B/BC horizon boundary (Hedge 1, 0.65 m depth) and the B/Cr horizon boundary for
151 the Sherborne soil series variants (Hedges 2 and 3, 0.43 m depth). The excavation stopped
152 when the depth of the pit reached either 1 m or the bedrock. Any 'detached roots' ≥ 0.2 cm in
153 diameter were then separated by hand from these soils in the field.

154 Each root crown was washed with a mains pressure water-pipe, with a secondary container
155 retaining any further washed off 'detached root' material; after air drying over a period of
156 weeks, the 'attached roots' were cut from the root crown and separated into diameter classes
157 of (< 0.2 cm, ≥ 0.2 cm). The woody material from the root crowns, and from the excavated

158 soils was weighed, and sub-sampled for dry weight and C analysis using the same method as
159 for the AGB (Section 2.2.)

160 **2.4 Statistical analysis**

161 Statistical analysis was carried out with Genstat 15th Edition with significance at 5% levels
162 unless otherwise stated. Data normality was determined by an Anderson-Darling test
163 (normality accepted at $p > 0.1$ where $n < 30$) and homoscedasticity by Bartlett's test. The affect
164 of species/soil type/age since last laid/width on C stock were combined in the treatment factor
165 Hedge number, and the parameters hedge width, height, AGB and BGB C stock were tested
166 using ANOVA. Effect of hedge component (species/branch, root etc.) on C content and C
167 stock were also analysed by ANOVA.

168 ANOVA assumptions were accepted where the data was normally distributed, and residual
169 variance was, a) unaffected by treatment (Levene's test), b) from a Normal distribution
170 (Shapiro-Wilk test), and c) additive where $n \geq 12$ (Levene's tests on residual variance between
171 small to large data values, and between intermediate to small and large data values
172 combined). Multivariate analysis was by Tukey's test. Where data was homoscedastic, but
173 ANOVA assumptions breached, effects of species on AGB C content, diameter class on
174 hawthorn root C content and root zone (upper/lower) on BGB C stock were analysed by a
175 Kruskal-Wallis test, or a two sample Mann-Whitney test. Relationships were analysed with
176 Spearman's rank correlations and simple linear regression.

177 **3 Results**

178 **3.1 Carbon content in hedgerow woody species and component parts**

179 To improve accuracy of carbon stocks, C content values of biomass components were
180 analysed at the species level (Table 2). AGB C content data, transformed to the fourth power,
181 were homoscedastic and demonstrated a highly significant difference between hawthorn,
182 blackthorn and deadwood ($H = 11.68$, $p < 0.01$, $n = 81$). Hawthorn and deadwood C content

183 did not differ significantly between each of the components, but was very highly significantly
184 different between blackthorn components ($F = 19.87$, $p < 0.001$; Table 2).

185 AGB C content values were reported separately for bramble (*Rubus corylifolius*) (only in
186 Hedge 1), and spindle (*Euonymus europaeus*) (from only a single occurrence in Hedge 2).
187 There was a very highly significant difference in BGB C content between roots of diameter $<$
188 0.2 and ≥ 0.2 cm, both for hawthorn ($U = 18.0$, $p < 0.001$), and blackthorn ($F = 55.35$, $p < 0.001$;
189 Table 2). BGB C content data for hawthorn roots ≥ 0.2 cm diameter were not normally
190 distributed so the median value ($479.4 \text{ mg C g}^{-1} \text{ DM}$) was used to calculate carbon stocks.

191 **3.2 Carbon stocks of flailed hedges**

192 **3.2.1 Above ground biomass**

193 The hedge section widths (m) differed between Hedges 1 (2.6 ± 0.13)^a, 2 (4.2 ± 0.13)^b and 3
194 (2.9 ± 0.07)^a, ($F = 49.53$, $p < 0.001$) and were not correlated with years elapsed since hedge
195 laying (Table 1), or hedge section height. The AGB linear C stock (t C km^{-1}) for the hedge
196 sections (including surface litter) ranged from 7.6 to 24.2 t C km^{-1} , with a mean of 14.0 ± 1.94
197 t C km^{-1} (median 13.1 t C km^{-1} ; $n = 9$). These data were very highly significantly correlated with
198 hedge section width ($\rho_{adj} = 0.886$, $p < 0.001$); but were heteroscedastic, and the significance
199 of a regression of AGB linear C stock on hedge section width could not be established. The
200 significant variation in widths between Hedges, affected the mean AGB linear C stocks (t C
201 km^{-1}); Hedge 1 (9.5 ± 1.59), Hedge 2 (19.2 ± 3.25), and Hedge 3 (13.2 ± 2.89), (Table 3),
202 making comparisons of C stock difficult on an equivalent basis, both between hedges, or with
203 other vegetation classes. Focus was therefore placed on presenting AGB C stock data on a
204 unit area basis (t C ha^{-1}), allowing for comparison with similar hedgerow studies (e.g. Falloon
205 *et al.* 2004; Robertson *et al.* 2012).

206 Hedges 1, 2 and 3 were measured in 2013 to include widths, and also a first trimmed height
207 (growth stage 1), a second trimmed height (growth stage 2) and the untrimmed height prior to
208 triennial trimming (growth stage 3) (Section 2.2; Figure 1). All interim and final hedge heights

209 were comparable between hedges, except for Hedge 1 at growth stage 2 which was
210 significantly shorter than the other two hedges (Table 3).

211 When hedges were kept trimmed to a mean height of 1.9 m, as in the initial stages of
212 management, there were no significant differences in AGB C stock between each of the
213 hedges, with a mean C stock of 32.2 ± 2.76 t C ha⁻¹ (equivalent to 9.9 t C km⁻¹; Table 3). There
214 was no significant correlation between C stock and hedge section height at growth stage 1
215 (Figure 2). At the second trimmed height (growth stage 2) the incremental increase in height
216 (m) for Hedge 1 was significantly shorter, that is, Hedges 1 (0.27)^a, 2 (0.67)^b, and 3 (0.80)^b; (F
217 = 41.6, p <0.001). Therefore, the additional C stock contained in Hedge 1 at this trimmed
218 growth stage 2 was only 3.7 ± 0.45 t C ha⁻¹ from a height increment of 0.27 m, compared to
219 Hedges 2 and 3, with 6.2 ± 1.11 t C ha⁻¹ from a mean height increment of 0.7 m; representing
220 7 years hedge regrowth which had twice been trimmed back to the height increment. This
221 gave an AGB of 40.6 ± 4.47 t C ha⁻¹ for these two hedges at a mean trimmed total height of
222 2.7 m (equivalent to 11.4 t C km⁻¹; Table 3). There was no significant correlation between C
223 stock and hedge section height at growth stage 2.

224 The final growth increment measured was that of three years regrowth following the second
225 trimming and prior to any further triennial trimming (growth stage 3). The corresponding AGB
226 C stock of this regrowth did not differ significantly between hedges, accumulating 4.4 ± 0.44 t
227 C ha⁻¹ over 3 years, equivalent to a mean height increase of 1 m. The total hedge AGB C stock
228 data, at growth stage 3, ranged from 27.0 to 57.4 t C ha⁻¹ with a mean of 42.0 ± 3.78 t C ha⁻¹
229 (median 43.8 t C ha⁻¹; n = 9). No significant differences were found in these total AGB C stocks
230 between Hedges 1, 2 and 3 (Table 3 and Figure 2); so that total AGB C stocks were not
231 significantly affected by differences in soil type, species mix, or age since last being laid (12,
232 18 and 14 years, respectively). There was a significant correlation between C stock and hedge
233 height, $\rho_{adj} = 0.496$, p = 0.04 but a regression could not be established due to height data
234 being heteroscedastic, with variability of AGB C stock preventing establishment of the
235 significance of the relationship with height. While this was the only growth stage with a

236 significant correlation between AGB C stock and hedge section height, the AGB C stock
237 always increased for each individual hedge section as sampled height was raised.

238 An assessment was also made of the relative proportions of AGB C within the hedgerow
239 components, that is: stems and branches of the three growth increments, pleachers, hung up
240 deadwood and surface litter. AGB component C stock data, transformed to the fourth root,
241 were homoscedastic and normally distributed, with a very highly significant differences in
242 between hedge components ($F = 67.78$, $p < 0.001$; Figure 3). As expected, the stems and
243 branches in the core of the hedge (growth stage 1, Figure 3) made the largest contribution to
244 AGB C, with a mean of 22.6 t C ha^{-1} when back transformed. The additional growth increments
245 to the hedge in subsequent years to growth stage 2 and 3 contributed similar amounts of AGB
246 C to that of the pleachers, each being close to 5 t C ha^{-1} (Figure 3).

247 While bramble only occurred in Hedge 1, it was notable that it contributed an additional $3.8 \pm$
248 1.46 t C ha^{-1} to the AGB C. Hung up deadwood within the hedge, and stakes that still remained
249 since the hedges were last laid, contributed a further 0.4 and 0.5 t C ha^{-1} , respectively. Surface
250 litter amounted to 0.8 t C ha^{-1}

251 **3.2.2 Below ground biomass**

252 The hedge section canopy base widths (m) were highly significantly different between Hedges
253 1 (1.6 ± 0.13)^a, 2 (3.0 ± 0.09)^b and 3 (2.3 ± 0.08)^c, ($F = 45.17$, $p < 0.001$) and were very highly
254 significantly correlated with age since hedge laying (Table 1) ($\rho_{adj} = 0.949$, $p < 0.001$) but not
255 with hedge section untrimmed height. BGB (including sub-surface woody debris) linear C stock
256 (t C km^{-1}) for Hedge 1 (9.0 ± 1.01), Hedge 2 (20.9 ± 4.84), and Hedge 3 (11.6 ± 2.15) were
257 highly significantly correlated with the hedge section base width ($\rho = 0.783$, $p < 0.01$); but were
258 heteroscedastic, and the significance of a regression of BGB C stock (t C km^{-1}) on hedge
259 section width could not be established. Reciprocal transformed BGB linear C stock did not
260 differ between Hedges (back transformed mean 11.5 t C km^{-1}), but the width effect on linear
261 C stocks (t C km^{-1}), as described for the AGB, prevented equivalent comparisons between

262 hedges or other vegetation; thus BGB C was also analysed on a unit area basis (t C ha^{-1}). The
263 C stock data for the total woody BGB (including sub-surface woody debris) in each hedge
264 section replicate ranged from 24.9 to 56.1 t C ha^{-1} with a mean of $38.2 \pm 3.66 \text{ t C ha}^{-1}$; median
265 37.2 t C ha^{-1} ; $n = 9$. The data were normally distributed, demonstrating an inherent variability
266 similar to the AGB. There was no significant difference in hedge section BGB C stock between
267 Hedges (Table 3; Figure 4), so that differences in soil type, or species mix, between Hedges
268 (Section 2.1; Table 1) had no detectable effect on BGB C stocks. The BGB C stock data were
269 also not significantly correlated with hedge section untrimmed height.

270 The C stock of the BGB woody components of the hedge sections was analysed. These
271 components were first categorised by the root zone in which they were found (upper/lower;
272 Section 2.3); the upper zone being anticipated as having the majority of root activity. There
273 was a very highly significant difference in fourth root transformed C stock between BGB in the
274 upper and the lower root zone ($U = 0.0$, $p < 0.001$, back transformed medians 34.6 t C ha^{-1} and
275 2.0 t C ha^{-1} respectively). The depth of the hedge section upper/lower root zone boundary
276 varied between the differing soils of Hedge 1 (pelocalcaric gley soil 63 - 69 cm) and Hedges
277 2 and 3 (lithomorphic brown rendzina 32 - 53 cm), but this depth had no significant effect on
278 lower root zone BGB C stocks; giving confidence that the lower root zone had been identified
279 as a zones of low root activity.

280 BGB C stocks (\log_e transformed) also differed significantly between components within each
281 root zone (upper or lower) ($H = 23.28$, $p < 0.001$; $U = 8.0$, $p < 0.01$ respectively; Figure 5). The
282 upper root zone detached roots were an important proportion of the overall BGB C stock (21%;
283 back transformed mean 8.2 t C ha^{-1}), but those in the lower root zone contributed much less
284 (3%; back transformed mean 1.3 t C ha^{-1}).

285 The sub-surface woody litter recovered from the soil was distinguishable by having straight
286 lengthwise profiles, compared to the undulating profiles of roots. Much of the woody litter had
287 heavily damaged ends and/or angular cuts, indicating it had been mechanically fractured,

288 rather than naturally broken. Evidence of fracturing, location, and hedge management history
289 were strongly indicative of this material being debris originating from flailing the hedge. Within
290 the two root zones this material amounted to $2.4 \pm 0.31 \text{ t C ha}^{-1}$.

291 **3.2.3 Hedgerow root to shoot ratios**

292 Root:shoot ratios as decimal fractions were calculated for each hedge section from the ratio
293 BGB:AGB C stock, reflecting hedgerow vegetation rather than individual plants, with the
294 woody litter separated between sub-surface/surface divisions, and the root crowns included
295 as root biomass (Mokany *et al.* 2006). The hedge section replicate BGB:AGB carbon stock
296 data were normally distributed, and ranged from 0.55 to 1.26, with a mean of 0.94 ± 0.084 and
297 median 0.95. The BGB C stock was significantly correlated with AGB C stock at 10% level (ρ
298 = 0.333, $p = 0.09$). Root:shoot ratios were significantly different between Hedges 1 (1.21)^a, 2
299 (0.92)^{ab} and 3 (0.69)^b ($F = 11.11$, $p = 0.01$; Table 3), and were significantly correlated with
300 depth of the upper/lower root zone boundary ($\rho = 0.617$, $p = 0.019$).

301 **4 Discussion**

302 **4.1 Hedgerow AGB carbon stocks**

303 There were no significant differences in AGB C stock (t C ha^{-1}) between the sampled Hedges
304 at the same growth stage despite differences in species mix, age since hedge laid, or soil type
305 (Table 3). However hedge height did differ significantly between Hedge 1, and Hedges 2 and
306 3 at the second trimmed height, so mean AGB C stock values of 42.0 ± 3.78 , 40.6 ± 4.47 , and
307 $32.2 \pm 2.76 \text{ t C ha}^{-1}$ are given for sampled Hawthorn and Hawthorn/Blackthorn hedges, laid 12
308 - 18 years previously, and trimmed by mechanical flail triennially at heights of 3.5 m, 2.6 m
309 and 1.9 m, respectively (Table 3), 3 years having elapsed since hedges at 3.5 m height were
310 last trimmed, but all other heights representing AGB C stocks immediately post-trimming.

311 **4.2 Height effect on hedge AGB C stocks**

312 The height of the hedge sections, 3 years after trimming, and the AGB C stocks, were
313 significantly correlated, but once hedges were trimmed the significance ceased (Section

314 3.2.1), so in this pilot study, using hedge height alone to estimate AGB C stock (t C ha^{-1}) was
315 a poor model for recently trimmed hedges. However there was always a positive addition to
316 each hedge section hedge AGB C stock, as height increased (Section 3.2.1; Table 3) which
317 supports the broad mechanistic use of hedge height to estimate hedgerow C stocks (t C ha^{-1}),
318 such as used by Robertson *et al.* (2012). The variability in AGB C stock within each hedge
319 prevented the establishment of a relationship with height (Figure 2), most likely trimming
320 shrubs disrupted the height from reflecting plant vigour and C stocks.

321 **4.3 Comparisons with published AGB C stock estimates**

322 Sampled hedge AGB C stocks (t C ha^{-1}) were higher than predicted by linear extrapolations
323 from Falloon *et al.* (2004); for each hedge, and at all three heights (Table 3). Most likely the
324 data from arable set-aside, utilised by Falloon *et al.* (2004) in the absence of hedge data,
325 underestimated C stocks. Robertson *et al.* (2012) used broad height classes ($\leq 2 \text{ m}$, $> 2 \text{ to } \leq$
326 3 m , $> 3 \text{ to } \leq 6 \text{ m}$) to estimate AGB C stocks; which also underestimated all sampled hedges
327 except in the $> 3 \text{ to } \leq 6 \text{ m}$ height range class, where estimates were similar to the sample
328 results (Table 3). Robertson *et al.* (2012) utilised hawthorn and hazel secondary woodland
329 understorey data from Poulton *et al.* (2003); where a stem density of 2082 stems ha^{-1} for stems
330 $> 2.5 \text{ cm}$ diameters at 1.3 m high (DBH) gave AGB C stocks of 45 t C ha^{-1} . The hedgerow
331 samples, in contrast, included all stems at 1.3 m high (mean 81368 stems ha^{-1}). The mean
332 Basal Area (BA) for the hedgerows ($60 \text{ m}^2 \text{ ha}^{-1}$) was greater than the hawthorn and hazel
333 understorey ($23.9 \text{ m}^2 \text{ ha}^{-1}$; Poulton *et al.* 2003), so that the hedgerow structure had a larger
334 area of woody growth comprised of more stems; but of smaller average diameter (1.5 cm
335 DBH). Despite the common presence of hawthorn, the hedgerows differed from the woodland
336 understorey in biomass characteristics, with hedgerow stems being more closely spaced. The
337 compact spacing of stems in hedgerows, leads to an efficient use of space for AGB C storage;
338 comparing favourably with 37.2 t C ha^{-1} for 30 year old Beech (*Fagus sylvatica*) forest (stem
339 and branchwood $490 \text{ mg C g}^{-1} \text{ DM}$, 3480 stems ha^{-1} , BA $20.7 \text{ m}^2 \text{ ha}^{-1}$; Granier *et al.* 2000),
340 and with 7.6 - 20 t C ha^{-1} for second rotation Willow (*Salix spp.*) Short Rotation Coppice,

341 although the latter was accumulated in the 2 - 3 years before harvest, (circa 10 000 - 12 000
342 trees ha⁻¹; Aylott *et al.* 2008; Guénon, *et al.* 2016).

343 **4.4 Biomass partitioning in actively managed hedges**

344 This in-situ study of actively managed hedges, identified biomass partitions that resulted from
345 both the short period trimming, and the longer period structural restoration cycles. If the
346 hedges were trimmed back to the same height every 3 years, the untrimmed regrowth prior to
347 triennial flailing (4.4 t C ha⁻¹), would be expected to be lost to the soil surface, and decay over
348 time. The existing surface litter amounted to 0.8 t C ha⁻¹, with additional hung-up deadwood
349 (0.4 t C ha⁻¹), which was mostly identified as associated with flailing. This was further
350 supplemented by 2.4 t C ha⁻¹ sub-surface woody debris resulting from flailing. So 3 years after
351 trimming, the sampled hedges had 3.6 t C ha⁻¹ in decaying woody products from flailing.

352 The long period hedge laying, 12 - 18 years prior to sampling, produced pleachers which
353 contributed 5.2 t C ha⁻¹ to the AGB, along with a few surviving requisite wooden stakes (0.5 t
354 C ha⁻¹). This gave a total of 5.7 t C ha⁻¹ woody products from hedge laying activity. These
355 biomass partitions aid C cycling understanding of actively managed hedges.

356 **4.5 Hedgerow BGB carbon stocks**

357 Unlike determining the visible AGB hedge width, the lateral extent of BGB was more difficult
358 to assess without spatially extensive soil excavation. BGB measurements were therefore
359 restricted to the width of the hedgerow canopy base. Field observations of hedge root
360 structures indicated the presence of root laterals growing perpendicular beyond the sampled
361 areas. However, despite this probable underestimate of BGB C stock, at the width measured,
362 nearly half of the overall total mean hedgerow C stock was below ground (35.8 t C ha⁻¹ for
363 roots, 2.4 t C ha⁻¹ for sub-surface woody debris; root:shoot 0.94:1). The addition of a mean
364 38.2 ± 3.66 C t ha⁻¹ BGB added considerably to the overall sampled C stock. Published
365 hedgerow C estimates (e.g. Falloon *et al.* 2004; Robertson *et al.* 2012) had not accounted for

366 below ground C storage. The direct hedgerow measurements presented here are therefore
367 likely to be the only ones available to date, thus comparisons are restricted to the closest
368 related ecosystem type of temperate woodlands. Patenaude *et al.* (2003) estimated only 28 t
369 C ha⁻¹ for root biomass in an English semi-natural woodland, representing a root:shoot ratio
370 of 0.284:1 Mokany *et al.* (2006) also found a relatively lower mean root:shoot ratio of 0.46:1
371 from a sample of 14 temperate broadleaf woodlands. The high root:shoot ratios, were largely
372 explained by hedgerow maintenance activities, such as repeated flailing and laying of the
373 AGB. The process of laying the sampled hedges resulted in multiple, small diameter, stems
374 growing from stools of much larger diameter. These stools and root crowns contained 43 % of
375 the BGB C (16.3 t C ha⁻¹). Hedge AGB is periodically removed by trimming, and disturbance
376 of AGB has reportedly caused high root:shoot ratios in shrublands (1.84:1), while root:shoot
377 ratios generally decreased with AGB accumulation in developing woodlands (Mokany *et al.*
378 2006).

379 **4.6 AGB C sequestration from increasing hedge dimensions on landscape** 380 **scales**

381 When hedges are actively managed, both the height and width can be controlled. The sampled
382 hedge widths varied significantly, affecting AGB linear C stock (t C km⁻¹); Hedge 2 was 1.6 m
383 wider than Hedge 1, with 9.7 t C km⁻¹ greater AGB C stock. Wider hedges had greater linear
384 AGB C stocks (t C km⁻¹); the correlation was very highly significant, but an exact relationship
385 could not be determined from this dataset. However, on the landscape scale allowing hedges
386 to grow wider could sequester considerable quantities of atmospheric C into the AGB
387 structure, for example if Hedge 1, represented the 456 000 km of managed hedge in England
388 and Wales (Carey *et al.* 2008), then the 1.6 m increase in width to that of Hedge 2 would
389 sequester 4.4 Mt C in AGB.

390 An optional agri-environmental scheme in England, the Entry Level Stewardship encouraged
391 farmers to increase hedges to either 1.5 m or 2.0 m tall (Natural England 2005; 2008; 2010;
392 2013). Britt *et al.* (2011) reported 30% of farmers visited had allowed their hedges to grow

393 taller, mainly because of an agri-environmental scheme; the remaining 70% of farmers must
394 have managed their hedges to a constant or lower height, therefore a substantial capacity
395 must exist in the industry to sequester C by raising the height of trimmed hedges.

396 A height increase of 1.0 m in hedge regrowth, three years after trimming, accumulated $4.4 \pm$
397 0.44 t C ha , but this AGB C is typically removed, with hedges periodically trimmed back to a
398 previous height on a 1 to 3 year rotation. A more permanent accumulation of AGB C was
399 demonstrated with the increase between first and second trimmed height. Raising this from
400 2.0 m to 2.7 m accumulated a mean of 6.2 t C km^{-1} after 7 years in hedges ranging from 2.8
401 to 4.3 m wide (Hedges 2 and 3). If, for example, this 0.7 m height increase in sampled hedges,
402 represented a height increase to 70% of the 456 000 km of managed hedge in England and
403 Wales (Carey *et al.* 2008), then 2.0 Mt C could be sequestered in the AGB.

404 These two example extrapolations demonstrate how altering hedge management practices
405 could achieve a useful contribution to GHG removal over landscape scales, provided a level
406 of permanency was achieved. Such practices could be incentivised by incorporating into future
407 agri-environmental schemes.

408 **5. Conclusion**

409 This investigation reported the first empirically derived values for AGB and BGB C stocks for
410 representative English hawthorn/blackthorn flailed laid hedges. These actively managed
411 hedges exhibited increased C storage with increased width and height. Relatively large
412 amounts of BGB were encountered in the hedgerow (mean $38.2 \pm 3.66 \text{ t C ha}^{-1}$; 0.94:1 root
413 to shoot ratio), a C stock not considered in previous estimates. High concentrations of stems
414 per unit area were found in the hedgerows, leading to an efficient use of space for AGB C
415 storage, when compared to other woody vegetation.

416 Example extrapolations demonstrated how such increases in hedge dimensions over
417 landscape scales could achieve a useful contribution to GHG removal. These management
418 practices could be incentivised by incorporating into future agri-environmental schemes. The

419 reported C stock values ($t\ C\ ha^{-1}$), should aid with quantifying changes to hedgerow stocks in
420 the UK, and fill a knowledge gap for national land use C accounting. A more comprehensive
421 biomass inventory study of hedgerows would further strengthen C accounting of national agro-
422 ecosystems.

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545 **TABLES**546 **Table 1. Summary descriptions of the hedges sampled in the field investigation**

| Hedge No. | 1 | 2 | 3 |
|---------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|
| Species | Hawthorn | Hawthorn/ Blackthorn | Hawthorn |
| Soil series (Avery 1990) | Evesham | Sherborne | Sherborne |
| Aspect | NW:SE | NW:SE | NW:SE |
| Management | Hedge laying/ Triennial flailing | Hedge laying/ Triennial flailing | Hedge laying/ Triennial flailing |
| Date Laid (yrs) | 2001 | 1995 | 1999 |
| Width (m) | 2.6 ± 0.13 | 4.2 ± 0.13 | 2.9 ± 0.07 |
| Shrubs ha ⁻¹ | 13931 | 8070 | 13571 |
| Stems stool ⁻¹ | 5 | 13 | 6 |
| Stems ha ⁻¹ | 65701 | 94275 | 84127 |
| BA (m ² ha ⁻¹) | 45.1 | 55 | 80.2 |
| DW:FW | 0.64:1 | 0.64:1 | 0.55:1 |
| 1st height (trimmed) (m) | 1.9 ± 0.06 | 2.0 ± 0.03 | 1.9 ± 0.03 |
| 2nd height (trimmed) (m) | 2.2 ± 0.09 | 2.6 ± 0.03 | 2.7 ± 0.03 |
| 3rd height (untrimmed) (m) | 3.4 ± 0.03 | 3.5 ± 0.15 | 3.5 ± 0.13 |

547

548 **Table 2 Summary of C content from hedgerow woody components from three different Hedges**

| Species | Component | mg C g ⁻¹ DM <i>mean ± SE</i> |
|---------------------------------------|--|--|
| <u>AGB</u> | | |
| Hawthorn <i>Crataegus monogyna</i> | { Growth stages 1, 2 (trimmed), and 3 (untrimmed), pleachers | 483.6 ± 0.85 |
| Unknown | { Surface woody litter, hung-up deadwood | 482.6 ± 1.93 |
| Blackthorn <i>Prunus spinosa</i> | { Growth stage 1 (trimmed) Growth stage 2 (trimmed) Growth stage 3 (untrimmed) | 482.1 ± 1.08 489.9 ± 1.84 495.9 ± 1.24 |
| Bramble <i>Rubus corylifolius</i> | { Liane | 481.2 ± 1.83 |
| Spindle <i>Euonymus europaeus</i> | { Growth stage 1 (trimmed) Growth stage 2 (trimmed) Growth stage 3 (untrimmed) | 474.4 (a) 465.7 (a) 459.3 (a) |
| <u>BGB</u> | | |
| Hawthorn <i>Crataegus monogyna</i> | { Roots <0.2 cm diameter Roots ≥0.2 cm diameter | 509.1 ± 3.19 480.7 ± 1.12 |
| Blackthorn <i>Prunus spinosa</i> | { Roots <0.2 cm diameter Roots ≥0.2 cm diameter | 496.2 ± 2.08 476.5 ± 1.56 |
| (a) denotes singular occurrence only | | |

549

550 **Table 3 Mean C stocks for each sampled hedge at different hedge heights and phases of trimming**

| Parameter | Mean hedge | | Parameter Mean ($t\ C\ ha^{-1}$) | | | | Significance level |
|-----------------------|------------|----------------|------------------------------------|----------------------|---------------------|------------------|--------------------|
| | height (m) | Trimming state | Hedge 1 | Hedge 2 | Hedge 3 | Combined | |
| AGB C stock | 3.5 ± 0.06 | Untrimmed | 35.8 ± 4.06 | 45.7 ± 6.60 | 44.5 ± 9.06 | 42.0 ± 3.78 | <i>n.s.</i> |
| | 2.7 ± 0.03 | 2nd trimming | – | 41.5 ± 5.40 | 39.7 ± 8.35 | 40.6 ± 4.47 | <i>n.s.</i> |
| | 2.2 ± 0.09 | 2nd trimming | 31.6 ± 4.39 | – | – | – | |
| | 1.9 ± 0.02 | 1st trimming | 27.9 ± 3.95 | 35.8 ± 3.95 | 32.9 ± 6.66 | 32.2 ± 2.76 | <i>n.s.</i> |
| BGB C stock | 3.5 ± 0.06 | Untrimmed | 43.0 ± 3.82 | 42.6 ± 8.53 | 28.9 ± 3.12 | 38.2 ± 3.66 | <i>n.s.</i> |
| BGB:AGB | 3.5 ± 0.06 | Untrimmed | 1.21:1 ^a | 0.92:1 ^{ab} | 0.69:1 ^b | 0.94:1 ± 0.084:1 | p = 0.01 |
| Total C stock | 3.5 ± 0.06 | Untrimmed | 78.7 ± 7.85 | 88.3 ± 15.13 | 73.4 ± 11.79 | – | – |
| | 2.5 ± 0.09 | 2nd trimming | 74.6 ± 8.18 | 84.1 ± 13.92 | 68.6 ± 11.90 | – | – |
| | 1.9 ± 0.02 | 1st trimming | 70.9 ± 7.73 | 78.4 ± 12.40 | 61.8 ± 9.52 | – | – |
| Estimated C stock (a) | 3.5 ± 0.06 | Untrimmed | 34 | 35 | 38 | – | – |
| | 2.5 ± 0.09 | 2nd trimming | 22 | 26 | 27 | – | – |

| | | | | | | | |
|---------------------------------|----------------|--------------|-------|-------|-------|---|---|
| <i>Falloon et al.</i> (2004) | 1.9 ± 0.02 | 1st trimming | 19 | 20 | 19 | – | – |
| Estimated C | 3.5 ± 0.06 | Untrimmed | 45 | 45 | 45 | – | – |
| stock | 2.5 ± 0.09 | 2nd trimming | 22.5 | 22.5 | 22.5 | – | – |
| <i>(Robertson et al. 2012)</i> | 1.9 ± 0.02 | 1st trimming | 11.25 | 11.25 | 11.25 | – | – |

551 (a) denotes simple linear extrapolation of Falloon et al. (2004) for mean hedge height.