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

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Abstract

Farmland hedges could be managed for carbon sequestration, but empirical data on their carbon (C) stock in the UK is lacking. Lowland hedges managed by hedge laying and triennial trimming using a mechanical flail formed a dense woody structure (mean 81 368 stems ha^{-1}). Hedges untrimmed for 3 years (mean height 3.5 m, widths 2.6 - 4.2 m), contained an above 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 2.7 m high, and subsequently 1.9 m high, AGB C stocks were reduced to 40.6 ± 4.47 t C ha^{-1} (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 contained 9.7 t C km^{-1} more AGB C stock than a 2.6 m wide hedge (mean height 3.5 m). Below ground biomass (BGB) was 38.2 ± 3.66 t C ha^{-1} (11.5 t C km^{-1}). Near horizontal stems, arranged by hedge laying, 12 - 18 years prior to sampling, accounted for 5.2 t C ha^{-1} (1.6 t C km^{-1}) of AGB C. The empirical data demonstrated how changing management practices to wider/taller hedges sequestered C in AGB. These estimates of hedgerow C stocks fill a knowledge gap on C storage and identified the need for a more comprehensive biomass inventory of hedgerows to strengthen the national carbon accounting of agro-ecosystems in the UK.

Key words

Carbon Sequestration; Hedgerow Carbon Stocks; Hedge Management

1 Introduction

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

An estimated 456 000 km of hedge in England and Wales had been actively managed, such that the woody plants no longer exhibited their natural shape (Carey *et al.* 2008). This vegetation management is carried out to limit hedge outward growth, and to create an effective barrier to livestock with a network of intertwined stems (Pollard *et al.* 1974; Baudry *et al.* 2000; Jones *et al.* 2001). These actively managed hedgerows are cut in two distinct cycles. A short period trimming cycle every 1 - 3 years, and a long period structural restoration cycle, after approximately 40 years growth (Staley *et al.* 2015). Britt *et al.* (2011) reported 92% of farmers in England and Wales used a tractor driven mechanical flail for trimming hedges; largely for economic efficiency, since other trimming methods (circular saw, finger bar cutter, or hand trimming) require additional labour to clear up cut debris (Semple *et al.* 1994a). The flail has a relatively blunt cutting edge, striking the branch repeatedly and leaving a ragged cut (Semple *et al.* 1994b); compared to uncut hawthorn hedges, the practice of flailing produced more thorn tipped new shoots (Bannister and Watts 1995). Thorns are a plant defensive response to herbivory, which can potentially elongate into shoots (Bannister and Watts 1995). This mechanism may lead to an increased concentration of woody biomass in the hedge. For trees in general, pruning practices can elicit an increased growth response, specifically branch elongation (Rom and Ferree 1985; Goodfellow *et al.* 1987; Krueger *et al.* 2009); with growth greatest in the first year following pruning, and declining with time (Follett *et al.* 2016). Beyond a certain level of pruning however, growth can decline (Pinkard and Beadle 2000). Thus growth form of hedges trimmed by flailing, and potentially their AGB C stocks, may differ from woody vegetation formed by secondary succession and without trimming interventions; such as unmanaged hedges (Küppers 1985), or woodland, (Poulton *et al.* 2003).

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

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

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

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

2 Method

2.1 Site description and sampling design

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

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

2.2 Sampling hedge above ground biomass (AGB)

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

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

The component parts of each 1 m section were separated (stem and branches of growth stage increments 1- 3, ‘pleachers’, surface woody litter, hung up deadwood; Figure 1) and weighed fresh before sub-sampling to determine the dry matter using a forced air oven, drying at 65^0C until a constant mass was achieved. The selected temperature was comparable with other methodology (Jackson *et al.* 2013; Ruiz-Peinado *et al.* 2013; Ferez *et al.* 2015) and avoided loss of volatile organic compounds associated with higher drying temperatures (Reuter *et al*. 1986). The oven dried woody components were sub-sampled in replicate and milled to <0.5 mm, and analysed for C using an Elementar vario EL Cube CNS automated elemental analyser, using high temperature decomposition with purge and trap gas chromatography (Table 2).

2.3 Sampling hedge below ground biomass (BGB)

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

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

Each root crown was washed with a mains pressure water-pipe, with a secondary container retaining any further washed off 'detached root' material; after air drying over a period of weeks, the 'attached roots' were cut from the root crown and separated into diameter classes of (< 0.2 cm, ≥ 0.2 cm). The woody material from the root crowns, and from the excavated soils was weighed, and sub-sampled for dry weight and C analysis using the same method as for the AGB (Section 2.2.)

2.4 Statistical analysis

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

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

3 Results

3.1 Carbon content in hedgerow woody species and component parts

To improve accuracy of carbon stocks, C content values of biomass components were analysed at the species level (Table 2). AGB C content data, transformed to the fourth power, were homoscedastic and demonstrated a highly significant difference between hawthorn, blackthorn and deadwood ($H = 11.68$, $p < 0.01$, $n = 81$). Hawthorn and deadwood C content did not differ significantly between each of the components, but was very highly significantly different between blackthorn components (F = 19.87, p <0.001; Table 2).

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

3.2 Carbon stocks of flailed hedges

3.2.1 Above ground biomass

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

Hedges 1, 2 and 3 were measured in 2013 to include widths, and also a first trimmed height (growth stage 1), a second trimmed height (growth stage 2) and the untrimmed height prior to triennial trimming (growth stage 3) (Section 2.2; Figure 1). All interim and final hedge heights were comparable between hedges, except for Hedge 1 at growth stage 2 which was significantly shorter than the other two hedges (Table 3).

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

The final growth increment measured was that of three years regrowth following the second trimming and prior to any further triennial trimming (growth stage 3). The corresponding AGB C stock of this regrowth did not differ significantly between hedges, accumulating 4.4 ± 0.44 t C ha^{-1} over 3 years, equivalent to a mean height increase of 1 m. The total hedge AGB C stock 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} (median 43.8 t C ha^{-1}; n = 9). No significant differences were found in these total AGB C stocks between Hedges 1, 2 and 3 (Table 3 and Figure 2); so that total AGB C stocks were not significantly affected by differences in soil type, species mix, or age since last being laid (12, 18 and 14 years, respectively). There was a significant correlation between C stock and hedge height, ρ_{adj} = 0.496, p = 0.04 but a regression could not be established due to height data being heteroscedastic, with variability of AGB C stock preventing establishment of the significance of the relationship with height. While this was the only growth stage with a significant correlation between AGB C stock and hedge section height, the AGB C stock always increased for each individual hedge section as sampled height was raised.

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

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

3.2.2 Below ground biomass

The hedge section canopy base widths (m) were highly significantly different between Hedges 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 significantly correlated with age since hedge laying (Table 1) (ρ_{adj} = 0.949, p <0.001) but not with hedge section untrimmed height. BGB (including sub-surface woody debris) linear C stock (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 highly significantly correlated with the hedge section base width (ρ = 0.783, p <0.01); but were heteroscedastic, and the significance of a regression of BGB C stock (t C km^{-1}) on hedge section width could not be established. Reciprocal transformed BGB linear C stock did not differ between Hedges (back transformed mean 11.5 t C km^{-1}), but the width effect on linear C stocks (t C km^{-1}), as described for the AGB, prevented equivalent comparisons between hedges or other vegetation; thus BGB C was also analysed on a unit area basis (t C ha^{-1}). The C stock data for the total woody BGB (including sub-surface woody debris) in each hedge section replicate ranged from 24.9 to 56.1 t C ha^{-1} with a mean of 38.2 ± 3.66 t C ha^{-1}; median 37.2 t C ha^{-1}; $n = 9$. The data were normally distributed, demonstrating an inherent variability similar to the AGB. There was no significant difference in hedge section BGB C stock between Hedges (Table 3; Figure 4), so that differences in soil type, or species mix, between Hedges (Section 2.1; Table 1) had no detectable effect on BGB C stocks. The BGB C stock data were also not significantly correlated with hedge section untrimmed height.

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

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

The sub-surface woody litter recovered from the soil was distinguishable by having straight lengthwise profiles, compared to the undulating profiles of roots. Much of the woody litter had heavily damaged ends and/or angular cuts, indicating it had been mechanically fractured, rather than naturally broken. Evidence of fracturing, location, and hedge management history were strongly indicative of this material being debris originating from flailing the hedge. Within the two root zones this material amounted to 2.4 ± 0.31 t C ha^{-1}.

3.2.3 Hedgerow root to shoot ratios

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

4 Discussion

4.1 Hedgerow AGB carbon stocks

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

4.2 Height effect on hedge AGB C stocks

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

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

4.3 Comparisons with published AGB C stock estimates

Sampled hedge AGB C stocks (t C ha^{-1}) were higher than predicted by linear extrapolations from Falloon *et al.* (2004); for each hedge, and at all three heights (Table 3). Most likely the data from arable set-aside, utilised by Falloon *et al.* (2004) in the absence of hedge data, underestimated C stocks. Robertson *et al.* (2012) used broad height classes (≤ 2 m, > 2 to ≤ 3 m, > 3 to ≤ 6 m) to estimate AGB C stocks; which also underestimated all sampled hedges except in the > 3 to ≤ 6 m height range class, where estimates were similar to the sample results (Table 3). Robertson *et al.* (2012) utilised hawthorn and hazel secondary woodland understorey data from Poulton *et al.* (2003); where a stem density of 2082 stems ha^{-1} for stems > 2.5 cm diameters at 1.3 m high (DBH) gave AGB C stocks of 45 t C ha^{-1}. The hedgerow samples, in contrast, included all stems at 1.3 m high (mean 81368 stems ha^{-1}). The mean Basal Area (BA) for the hedgerows (60 m^2 ha^{-1}) was greater than the hawthorn and hazel understorey (23.9 m^2 ha^{-1}; Poulton *et al.* 2003), so that the hedgerow structure had a larger area of woody growth comprised of more stems; but of smaller average diameter (1.5 cm DBH). Despite the common presence of hawthorn, the hedgerows differed from the woodland understorey in biomass characteristics, with hedgerow stems being more closely spaced. The compact spacing of stems in hedgerows, leads to an efficient use of space for AGB C storage; comparing favourably with 37.2 t C ha^{-1} for 30 year old Beech (*Fagus sylvatica*) forest (stem and branchwood 490 mg C g^{-1} DM, 3480 stems ha^{-1}, BA 20.7 m^2 ha^{-1}; Granier *et al.* 2000), and with 7.6 - 20 t C ha^{-1} for second rotation Willow (*Salix spp.*) Short Rotation Coppice, although the latter was accumulated in the 2 - 3 years before harvest, (circa 10 000 - 12 000 trees ha^{-1}; Aylott *et al.* 2008; Guénon, *et al.* 2016).

4.4 Biomass partitioning in actively managed hedges

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

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

4.5 Hedgerow BGB carbon stocks

Unlike determining the visible AGB hedge width, the lateral extent of BGB was more difficult to assess without spatially extensive soil excavation. BGB measurements were therefore restricted to the width of the hedgerow canopy base. Field observations of hedge root structures indicated the presence of root laterals growing perpendicular beyond the sampled areas. However, despite this probable underestimate of BGB C stock, at the width measured, nearly half of the overall total mean hedgerow C stock was below ground (35.8 t C ha^{-1} for roots, 2.4 t C ha^{-1} for sub-surface woody debris; root:shoot 0.94:1). The addition of a mean 38.2 ± 3.66 C t ha^{-1} BGB added considerably to the overall sampled C stock. Published hedgerow C estimates (e.g. Falloon *et al.* 2004; Robertson *et al.* 2012) had not accounted for below ground C storage. The direct hedgerow measurements presented here are therefore likely to be the only ones available to date, thus comparisons are restricted to the closest related ecosystem type of temperate woodlands. Patenaude *et al.* (2003) estimated only 28 t C ha^{-1} for root biomass in an English semi-natural woodland, representing a root:shoot ratio of 0.284:1 Mokany *et al.* (2006) also found a relatively lower mean root:shoot ratio of 0.46:1 from a sample of 14 temperate broadleaf woodlands. The high root:shoot ratios, were largely explained by hedgerow maintenance activities, such as repeated flailing and laying of the AGB. The process of laying the sampled hedges resulted in multiple, small diameter, stems growing from stools of much larger diameter. These stools and root crowns contained 43 % of the BGB C (16.3 t C ha^{-1}). Hedge AGB is periodically removed by trimming, and disturbance of AGB has reportedly caused high root:shoot ratios in shrublands (1.84:1), while root:shoot ratios generally decreased with AGB accumulation in developing woodlands (Mokany *et al.* 2006).

4.6 AGB C sequestration from increasing hedge dimensions on landscape scales

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

An optional agri-environmental scheme in England, the Entry Level Stewardship encouraged farmers to increase hedges to either 1.5 m or 2.0 m tall (Natural England 2005; 2008; 2010; 2013). Britt *et al.* (2011) reported 30% of farmers visited had allowed their hedges to grow taller, mainly because of an agri-environmental scheme; the remaining 70% of farmers must have managed their hedges to a constant or lower height, therefore a substantial capacity must exist in the industry to sequester C by raising the height of trimmed hedges.

A height increase of 1.0 m in hedge regrowth, three years after trimming, accumulated 4.4 ± 0.44 t C ha, but this AGB C is typically removed, with hedges periodically trimmed back to a previous height on a 1 to 3 year rotation. A more permanent accumulation of AGB C was demonstrated with the increase between first and second trimmed height. Raising this from 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 to 4.3 m wide (Hedges 2 and 3). If, for example, this 0.7 m height increase in sampled hedges, represented a height increase to 70% of the 456 000 km of managed hedge in England and Wales (Carey *et al.* 2008), then 2.0 Mt C could be sequestered in the AGB.

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

5. Conclusion

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

Example extrapolations demonstrated how such increases in hedge dimensions over landscape scales could achieve a useful contribution to GHG removal. These management practices could be incentivised by incorporating into future agri-environmental schemes. The reported C stock values (t C ha^{-1}), should aid with quantifying changes to hedgerow stocks in the UK, and fill a knowledge gap for national land use C accounting. A more comprehensive biomass inventory study of hedgerows would further strengthen C accounting of national agro-ecosystems.

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TABLES

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

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

Species	Component	mg C g^{-1} DM *mean ± SE*
	AGB	
Hawthorn *Crataegus monogyna*	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 *Prunus spinosa*	Growth stage 1 (trimmed)	482.1 ± 1.08
	Growth stage 2 (trimmed)	489.9 ± 1.84
	Growth stage 3 (untrimmed)	495.9 ± 1.24
Bramble *Rubus corylifolius*	Liane	481.2 ± 1.83
Spindle *Euonymus europaeus*	Growth stage 1 (trimmed)	474.4 (a)
	Growth stage 2 (trimmed)	465.7 (a)
	Growth stage 3 (untrimmed)	459.3 (a)
	BGB	
Hawthorn *Crataegus monogyna*	Roots <0.2 cm diameter	509.1 ± 3.19
	Roots ≥0.2 cm diameter	480.7 ± 1.12
Blackthorn *Prunus spinosa*	Roots <0.2 cm diameter	496.2 ± 2.08
	Roots ≥0.2 cm diameter	476.5 ± 1.56

(a) denotes singular occurrence only

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

			Parameter Mean *(t C ha^{-1})*				
Parameter	**Mean hedge height (m)**	**Trimming state**	**Hedge 1**	**Hedge 2**	**Hedge 3**	**Combined**	**Significance level**
AGB C stock	3.5 ± 0.06	Untrimmed	35.8 ± 4.06	45.7 ± 6.60	44.5 ± 9.06	42.0 ± 3.78	*n.s.*
	2.7 ± 0.03	2nd trimming	_	41.5 ± 5.40	39.7 ± 8.35	40.6 ± 4.47	*n.s.*
	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	*n.s.*
BGB C stock	3.5 ± 0.06	Untrimmed	43.0 ± 3.82	42.6 ± 8.53	28.9 ± 3.12	38.2 ± 3.66	*n.s.*
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	_	_

Falloon et al. (2004)	1.9 ± 0.02	1st trimming	19	20	19	_	_
Estimated C stock *(Robertson et al. 2012)*	3.5 ± 0.06	Untrimmed	45	45	45	_	_
	2.5 ± 0.09	2nd trimming	22.5	22.5	22.5	_	_
	1.9 ± 0.02	1st trimming	11.25	11.25	11.25	_	_

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