HEDGEROW AGROFORESTRY IN ENGLAND AND WALES: INCREASING WIDTH TO SEQUESTER ADDITIONAL CARBON

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Introduction

Hedgerow systems are one of the more prominent agroforestry systems in temperate European agriculture, and the UK has the second largest extent of these in the European Union (Herzog 2000; den Herder et al. 2016). An estimated 456 000 km of hedge in England and Wales has been actively managed (Carey et al. 2008); which limits hedge outward growth, and maintains an effective barrier to livestock (Pollard et al. 1974). This management consists of 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). A mechanical flail is used for the short period trimming cycle by 92% of farmers in England and Wales (Britt et al. 2011). Typical 'Enclosure' hedges in England and Wales were planted with only hawthorn (*Crataegus monogyna*), in single, or double rows, from the 16th Century onwards (Maclean 2006). Hawthorn is still the dominant woody species, found within 90% of hedges in England and Wales, but a mix of woody species is common, and blackthorn (*Prunus spinosa*) is the second most frequent species, found within 50% of these hedges (Barr et al. 2000).

The potential for temperate agroforestry to sequester carbon (C), and mitigate rising levels of Green-House Gasses (GHG), is beginning to receive more attention (Udawatta and Jose 2012). Axe et al. (2017) showed the potential to sequester C where wider managed hedges had greater C stocks (t C km^{-1}). Allowing such hedges to grow wider from lateral branch growth only, without increasing planting density, may not be the most effective way to accumulate Above Ground Biomass (AGB) C. It also introduces uncertainty in using area C stock values (t C ha^{-1}) to estimate AGB C (t C), as this parameter assumes a linear relationship with hedge width.

Here new data on the contribution made by blackthorn to AGB C stock, and the correlation between hedge width and t C km^{-1}, from the pilot study of triennially flailed hedge biomass (Axe et al. 2017), along with supporting evidence on shrub growth in unmanaged hedges (Küppers 1985), is examined to advance how atmospheric C could be sequestered by increasing hedge width.

Materials

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, three replicates each from three sample hedges were selected for biomass C stock quantification by stratified random sampling. Hedges 1 and 3 were comprised of hawthorn and Hedge 2 was a hawthorn/blackthorn mix. Hedges had been present from at least 1884 (Ordnance Survey 1884). Hedge 1 grew in a pelocalcaric gley soil; and Hedges 2 and 3 grew in a lithomorphic brown rendzina (**Table 1**). Each AGB replicate was a 1 m length of hedge. The height from ground level for each replicate was recorded of, a) height of the lowest previously trimming; identified by severed stems with new regrowth, and b) most common existing stem height (the mode). These two heights were differentiated as growth stages 1 and 2. Widths of each hedge section at 1.3 m high were recorded along with stem basal area (BA) at 10 cm above ground. The replicate biomass samples were isolated from the hedge with two vertical cuts through branches, and by horizontal cuts through all stems at ≤ 10 cm above ground level. Only the sections of branches and stems found within the replicate boundary were included in the sample. Surface woody litter was collected by hand. Component parts of each replicate were separated, weighed fresh, and sub-sampled to determine dry matter and C content. (See Axe et al. 2017 for further details of methodology).

Statistical analysis was carried out with Genstat 15th Edition. Data normality was determined by an Anderson-Darling test (normality accepted at $p > 0.1$ where $n < 30$) and homoscedasticity by Bartlett's test. Effects of species/soil type/age since hedge laid, were combined in the single treatment factor Hedge number, and tested against the parameters hedge width, height, and AGB

C stock using ANOVA. Multivariate analysis was by Tukey's test. Where data was parametric, associations were analysed with Pearson's correlation coefficient, otherwise Spearman's rank correlation coefficient was used. Linear regressions were not reported due to data heteroscedasticity.

Table 1: Descriptive data for sampled hedges.

Hedge No.	**1**	**2**	**3**
Species	Hawthorn	Hawthorn/ Blackthorn	Hawthorn
Soil description	Pelocalcaric gley soil	Lithomorphic brown rendzina	Lithomorphic brown rendzina
Aspect	NW:SE	NW:SE	NW:SE
Management method: Long cycle	Hedge laying (2001)	Hedge laying (1995)	Hedge laying (1999)
Short cycle	Triennial flailing (since 2007)	Triennial flailing (since 2007)	Triennial flailing (since 2007)
Width (m)	$2.6^a \pm 0.13$	$4.2^b \pm 0.13$	$2.9^a \pm 0.07$
BA (cm^2)	73.5 ± 14.26	143.3 ± 32.85	115.4 ± 25.90
Stems (mean integer)	18	39	25
Height at growth stage 1 (trimmed) (m)	1.9 ± 0.06	2.0 ± 0.03	1.9 ± 0.03
Height at growth stage 2 (untrimmed) (m)	3.4 ± 0.03	3.5 ± 0.15	3.5 ± 0.13
Area C stock at growth stage 1 (trimmed) (t C ha^{-1})	27.9 ± 3.95	35.8 ± 3.95	32.9 ± 6.66
Area C stock at growth stage 2 (untrimmed) (t C ha^{-1})	35.8 ± 4.06	45.7 ± 6.60	44.5 ± 9.06
Linear C stock at growth stage 1 (trimmed) (t C km^{-1})	7.5 ± 1.46	15.0 ± 2.03	9.7 ± 2.13
Linear C stock at growth stage 2 (untrimmed) (t C km^{-1})	9.5 ± 1.59	19.2 ± 3.25	13.2 ± 2.89

Superscript letters denote significant difference at $p < 0.05$ (Tukey's test)

Results

Hedge 2 was 1.6 m and 1.3 m wider than Hedges 1 and 3 respectively, ($F = 49.53$, $p < 0.001$; **Table 1**). While hedge heights were comparable between the hedges at each growth stage, there was a 1.6 m difference between growth stages 2 and 1, with the mean hedge area AGB C stock data falling from 42.0 ± 3.78 t C ha^{-1} to 32.2 ± 2.76 t C ha^{-1} when hedges were trimmed back to 1.9 m tall. Since there were no significant differences in area AGB C stock (t C ha^{-1}) between the hedges, at the same growth stage, no effects from differences in species mix, soil type, or age since hedge laid, were detected. A significant correlation existed between C stock and hedge replicate height at growth stage 2 ($\rho_{adj} = 0.496$, $p < 0.05$), and with both stages combined ($\rho_{adj} = 0.399$, $p < 0.05$).

The linear AGB C stocks (t C km^{-1}) for the hedges at both growth stages were analysed to examine the width effect on C stocks. These data varied between growth stage 1 with a mean of 10.7 ± 1.47 t C km^{-1} (median 10.5 t C km^{-1}; $n = 9$) and growth stage 2, with a mean of 14.0 ± 1.94 t C km^{-1} (median 13.1 t C km^{-1}; $n = 9$). There were significant correlations between these data and hedge section width, BA at 10 cm, and stem frequency (**Table 2**).

Table 2: Correlation matrix for sampled hedges at two growth stages.

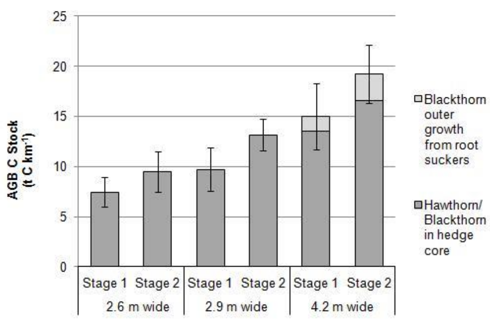
Growth stage 1	**Linear AGB C Stock (t C km^{-1})**	**Width (m)**	**BA at 10 cm height (cm^2)**
Width (m)	0.8684, $p<0.01$		
BA at 10 cm height (cm^2)	0.9038, $p<0.001$	0.7108, $p<0.05$	
Stem Frequency at 10 cm height (*n*)	0.318, $p< 0.05$	0.8287, $p<0.01$	0.4709, *n.s.*
Growth stage 2			
Width (m)	0.8334, $p<0.01$		
BA at 10 cm height (cm^2)	0.9497, $p<0.001$	0.7108, $p<0.05$	
Stem Frequency at 10 cm height (*n*)	0.6453, *n.s.*	0.8287, $p<0.01$	0.4709, *n.s.*

The replicates from the widest hedge, Hedge 2, comprised of a core with one blackthorn shrub, and many hawthorn shrubs, and also an outer layer of blackthorn stems from root suckers along both sides of the hedge. The C stock quantities from the blackthorn sucker growth, at growth stages 1 and 2, were 1.5 ± 0.62 t C km^{-1}, and 2.6 ± 1.21 t C km^{-1}, respectively (**Figure 1**).

Discussion

The mechanism that AGB C increases with taller hedges was supported by the results, with a positive addition to each hedge replicate AGB C stock as height increased. The height of the hedge replicates, and the AGB C stocks (t C ha^{-1}), were significantly correlated when both growth stages were included in the dataset. A height increase of 1.6 m (growth stage 1 to 2), over 6

Figure 1: Linear AGB C stock for sampled hedges at three widths and two stages of growth.



years, including an intermediate episode of trimming, yielded an average increase of 3.3 t C km^{-1} across all hedges. Increasing height of managed hedges on a national scale could thus be a useful means to sequester C, however such hedges would still be regularly flailed, and as with the examples here, some of this reported AGB C gain would be lost when the hedges are next trimmed.

Estimating individual hedge C quantities from area C stocks (t C ha^{-1}) assumes a linear scaling with the hedge width, but utilising the linear C stocks (t C km^{-1}) removed this assumption and gave a better representation of C quantity for an individual hedge. The positive correlation between these linear C stocks and width supported the principle that C quantities increase with hedge width, but a stronger correlation was found with the BA. Thus the mechanism that increased hedge C was more dependent on increasing numbers and/or diameter of vertical stems, rather than hedge width; which would increase from lateral branch elongation alone. The make up of Hedge 2 showed it was wider than the other hedges in part due to the presence of blackthorn from sucker growth, along the outer edge of both sides of the hedge. This species is clonal, spreading mainly by root suckers, and is intolerant of shade. Küppers (1985) also observed blackthorn growing along the outer hedge canopy in mature untrimmed spontaneous hedgerows; concluding that, in response to competition for light, it used root suckering to migrate into open space, rather than the woody community. This was in contrast with *Crataegus spp.,* which responded to competition for light with epitonic shoots and vertical growth into the hedge canopy, not lateral migration (Küppers 1985). The increase in width in the example of Hedge 2, sampled 18 years after restorative management, of a managed hedge with a hawthorn core, and developing blackthorn outgrowths, represented a viable plant association from natural succession. Wider managed hedges could be realised by deliberately planting additional rows of shrubs, but the blackthorn regeneration observed here increased basal area, hedge width, and AGB C, at a minimal cost.

Allowing managed hedges to grow wider is very likely a more efficient practice to sequester C in AGB, compared to allowing them to grow taller. At growth stage 1, Hedge 2, was 1.6 m wider than Hedge 1, and had 7.5 t C km^{-1} more AGB C, but when Hedge 2 grew 1.6 m taller (growth stage 2), it only gained a further 4.2 t C km^{-1} AGB C. Hedges in England and Wales are generally narrow, (77% < 2 m wide; Barr et al. 2000) so there is potential capacity in the landscape to increase AGB C stocks through this practice.

Conclusion

Compared to increasing the hedge height, widening hedges was more efficacious at sequestering C into hedge AGB. This can be achieved using a propensity for blackthorn to naturally colonise outwards from hedges. Hedges are narrow in England and Wales, giving an extensive capacity to sequester C through this mechanism.

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