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Research Paper

Carbon storage in hedge biomass—A case study of actively managed hedges in England

Matthew S. Axe*, Ian D. Grange, John S. Conway

Centre for the Environment, Royal Agricultural University, Cirencester, Gloucestershire GL7 6JS, UK

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A B S T R A C T

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.

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 Watt, 1995). Thorns are a plant defensive response to herbivory, which can potentially elongate into shoots (Bannister and Watt, 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

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

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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).

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	55.0	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

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) (Fig. 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; Fig. 1) and weighed fresh before sub-sampling to determine the dry matter using a forced air oven, drying at 65 °C 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.

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