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Planting hedgerows: Biomass carbon sequestration and contribution towards net-zero targets

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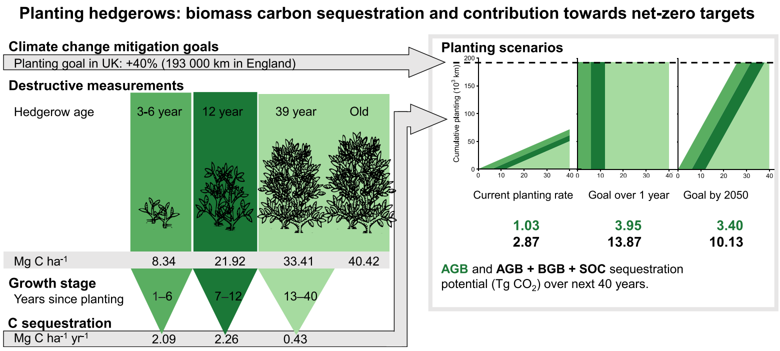
HIGHLIGHTS

- UK has set the goal of planting 193,000 km of hedges by 2050 to contribute to net-zero.
- Hedges of known age were destructively sampled for biomass C stock and sequestration rate.
- Planting 193,000 km would sequester 13.9–10.1 Tg CO_2 in biomass and soil over 40 years.
- Planting goal will offset annually 4.5–6.2 % of UK annual agricultural CO_2 emissions.
- Current planting rate needs to increase fourfold to reach hedgerow planting goal.

GRAPHICAL ABSTRACT

Graphical abstract showing the main stages of methodological workflow and the main results.



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ABSTRACT

Agroforestry practices, such as hedgerow planting, are widely encouraged for climate change mitigation and there is an urgent need to assess their contribution to national 'net-zero' targets. This study examined the impact that planting hedgerows at different rates could make to UK net-zero goals over the next 40 years, with a focus on 2050. We analysed the carbon (C) content of native hedgerow species and determined hedge aboveground biomass (AGB) C stock via destructive sampling of hedges of known ages. AGB C stocks ranged from 8.34 Mg C ha^{-1} in the youngest hedges, to 40.42 Mg C ha^{-1} in old ones. Knowing the age of the hedgerows, we calculated their annual average AGB C sequestration rate, which was highest in young hedges (2.09 Mg C ha^{-1} yr^{-1}), and lowest in 39 year old mature, regularly trimmed hedgerows (0.86 Mg C ha^{-1} yr^{-1}). We present a time series of the annual AGB C sequestration rate change between hedge age categories, which increases from 2.09 Mg C ha^{-1} yr^{-1} in the first 6 years after planting, to 2.26 Mg C ha^{-1} yr^{-1} in the next 6 years, and then decreases to 0.43 Mg C ha^{-1} yr^{-1} between years 13 and 40. Our results indicate that, if encouraged widely, hedgerow planting can be a valuable tool for atmospheric CO_2 capture and storage, contributing towards net-zero targets. However, current planting rates (1778.8 km yr^{-1}) are too low to reach the net-zero goal set by the UK Climate Change Committee of increasing hedgerow length by 40 % by 2050. An increased planting rate of 7148.1 km yr^{-1} will achieve this goal by 2050, and, over 40 years, store 3.41 Tg CO_2 in hedge AGB, or 10.13 Tg CO_2 in hedge total biomass and in the soil, annually offsetting 1.5 %–4.5 % of UK annual agricultural CO_2 emissions.

1. Introduction

Hedgerows, a common feature of farmed landscapes around the world, provide multiple ecosystem services (Baudry et al., 2000; Holden et al., 2019), including climate change mitigation, as they capture carbon dioxide

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(CO_2) and store it as carbon (C) in woody biomass and soil organic matter beneath the ground (Axe et al., 2017; Drexler et al., 2021; Biffi et al., 2022; Black et al., 2023). Hedgerows are linear features of shrubs and trees that were traditionally used to delineate fields, provide stock-proof boundaries and as a source of food, fuel and timber (Barnes and Williamson, 2008). Their characteristics vary depending on their geographical location, reflecting differences in pedo-climate, farming practices, woody species composition, and hedgerow management, which controls structural attributes such as hedge height and width. Thus, the term 'hedgerow' can encompass a wide range of features, from natural occurring treelines to frequently managed lines of planted shrubs (Burel, 1996). Despite their importance in agricultural landscapes, hedgerow length and condition have declined markedly since the mid-20th century across many European countries (e.g., Barr and Gillespie, 2000; Van Den Berge et al., 2019; Baudry et al., 2000; Carey et al., 2007) due to a combination of active removal to increase field size and lack of or over management (Baudry et al., 2000; Carey et al., 2007). Hedgerows are now protected by legislation in many countries (although not always successfully, e.g., Arnaiz-Schmitz et al., 2018; Black et al., 2023) and are designated as a Priority Habitat in the UK (Barr and Gillespie, 2000; Oreszczyn and Lane, 2000; Maddock, 2008).

In recent years, there has been a growing interest in the climate change mitigation potential of introducing woody species into agricultural landscapes via agroforestry and tree and hedgerow planting, and in the contribution that these practices can make to national 'net-zero' targets and meeting the Paris climate agreement (IPCC, 2006; Zomer et al., 2016; Cardinael et al., 2018; Mayer et al., 2022). Agroforestry is often included of Nationally Determined Contributions (Seddon et al., 2019) and several European countries have recently set hedgerow planting targets: for example, 4000 km will be planted in Belgium in 2020–2024 (SPW, 2022) and 7000 km in France in 2021–2022 (MAA, 2021). Germany, Denmark, and Ireland have also included hedgerows in their climate action programmes (Levin et al., 2020; Drexler et al., 2021; Black et al., 2023). In the UK, the Climate Change Committee has called for a 40 % increase in hedgerow length by 2050, with an interim goal of a 20 % increase by 2035 (Climate Change Committee, 2018, 2021). In England's arable and improved grassland landscapes this increment would equate to planting 193,000 km of hedgerows in less than three decades (Biffi et al., 2022). Reaching this goal would contribute significantly towards the 335,000 km hedgerow network expansion target set by Natural England for hedgerow habitats to support thriving biodiversity and achieve Favourable Conservation Status (Staley et al., 2020). However, little is known about how the UK is progressing towards reaching these planting goals. Moreover, there is a lack of information on the amount of C stored in hedgerows and on the rate at which C is sequestered in both their biomass and soil over time since planting. Filling these knowledge gaps will increase the accuracy of climate change mitigation modelling and facilitate the promotion of hedgerow planting as a tool for atmospheric CO_2 capture and storage.

In many European countries, semi-natural landscape corridors, such as hedgerows, have been promoted by public agri-environment schemes (AES) as a conservation tool (Batáry et al., 2015; José Javier Santiago-Freijanes et al., 2015; Rural Payments Agency, 2022), as hedgerows have been shown to support floral, insect, bird, and mammal farmland biodiversity (Marshall and Moonen, 2002; Graham et al., 2018; Froidevaux et al., 2019a; Finch et al., 2020; Litza and Diekmann, 2020; Prendergast-Miller et al., 2021), as well as nutrient interception and protection of surface water quality (Baah-Acheamfour et al., 2016; Holden et al., 2019; Rosier et al., 2023). In addition, NGOs, charities, and farmer associations are increasingly encouraging organizations, communities and individuals to plant hedgerows at both national and local level to benefit from their multiple ecosystem services (e.g., in England: Woodland Trust, 2019; The Tree Council, 2020; CPRE, 2022). There is also considerable economic interest within the private sector to increase C offsetting and insetting on farmland to help achieve corporate and supply-chain net-zero targets (Santos et al., 2021; Acampora et al., 2023). Together, these drivers promote and facilitate large-scale hedgerow planting for climate change mitigation. However, it is unclear to what extent the UK Climate Change Committee target of 40 % increase in hedgerow length by 2050 is achievable via current hedgerow planting rates in AES and in other initiatives and schemes receiving public and private funding.

Hedges sequester C, but there is a lack of studies that have quantified the C stocks in both soil and biomass of traditional managed hedgerows in the temperate zone. Studies have reported higher soil organic carbon (SOC) stocks under or near hedgerows compared to adjacent fields (Ford et al., 2019; Van Den Berge et al., 2021) and our recent study was the first to show how SOC sequestration rates change over time (Biffi et al., 2022). Where biomass C stocks have been quantified, it has been with a focus on how these change with hedgerow height and width (Axe et al., 2017; Black et al., 2023), rather than how they change over time since planting. In forestry and agroforestry research, under similar climatic conditions, the aboveground biomass (AGB) C sequestration potential of planting woody species is known to be affected by species composition, planting density, and planting configuration (Köhl et al., 2017; Preece et al., 2012; Paul et al., 2015). For UK hedges, these factors tend to have limited variation, as species composition is typical of Northwestern Europe, with a strong predominance of hawthorn (*Crataegus monogyna* Jacq.) and blackthorn (*Prunus spinosa* L., Barr and Gillespie, 2000) and planting usually occurs at prescribed density (6 plants per m) and width of the linear feature (Rural Payments Agency and Natural England, 2015) However, managed hedgerows undergo trimming every 1–3 years, to maintain their width and height. In addition, a large proportion of the woody biomass is removed on a 20–40 year timescale via hedge laying or coppicing, which rejuvenates the hedge by encourages new growth from the base (Staley et al., 2015). These management regimes mean that a proportion of the biomass is regularly removed, causing a loss of C from the habitat and making it difficult to estimate C sequestration rates. To date, studies that have estimated the C sequestration of hedgerow biomass have been based on forestry research data, woodland understory data, modelling approaches or very small sample size (e.g., Falloon et al., 2004; Robertson et al., 2012; Crossland, 2015; Burgess and Graves, 2022) and estimates range among these studies from 0 to 1.66 t C ha^{-1} yr^{-1}. As AGB C stock changes in managed hedges are unlikely to be linear, understanding the changes in AGB C sequestration rate over time since planting is crucial to understand the time frame in which most C is being sequester in hedge AGB (Nair, 2012).

To determine the AGB C sequestration of managed hedges we need to know their age, the amount of AGB, as well as the C fraction of native woody species within them. In forestry research, the AGB is often obtained with allometric equations, which estimates the AGB of individual trees from specific measurements, such as stem diameter, height, and/or wood density. These are known to introduce bias in tree AGB estimates (van Breugel et al., 2011; Calders et al., 2022), but are especially problematic to use in managed hedges, where the natural growth of individual shrubs is profoundly altered by human management. For this reason, destructive sampling of a known unit of volume is more appropriate to measure the AGB of managed hedges. Species-specific quantification of wood C content from a range of woody hedgerow species is also important to understand the capacity of hedges to capture and store C. In the UK, Milne and Brown (1997) has reported the C content of some forest species, while Axe et al. (2017) presented the C content for woody components of hawthorn and blackthorn, but estimates for many species commonly found in hedgerows are missing. Similarly, to the best of our knowledge, measurements of the C and nitrogen (N) content of woody biomass components of many UK hedge native species are lacking, as shown by searching the TRY global database of plant traits (Kattge et al., 2020).

Our main aim was to determine the AGB C stock and C sequestration rate of hedges by conducting destructive sampling of AGB biomass of hawthorn-dominated managed hedges of known ages. We assessed the C and N content of woody biomass components of typical hedgerow species of temperate climatic regions and used hawthorn stem C concentration to calculate the AGB C stock of hedgerows from saplings to mature, managed hedgerows. Knowing the age of the hedges, we were able to determine the average annual C sequestration rate of three hedge age categories. We used this chronosequence to provide a time series of how the net C sequestration potential of planting hedgerows changed over time since planting. We hypothesised that (*i*) hedge AGB C stock would be largest in mature hedgerows and that (*ii*) hedgerows' AGB C sequestration would be highest in young hedgerows and decline over time. A secondary aim was to (1) assess current hedgerow planting efforts within agri-environment schemes and other major national planting initiatives and (2) use the C sequestration rates found in this study, together with the SOC sequestration rate presented in Biffi et al. (2022), to estimate the AGB C and SOC sequestration potential of maintaining current planting rates and of increasing existing hedgerow length to reach the Climate Change Committee goal of 40 % increment in hedgerow length over one year and over 27 years (by 2050).

2. Materials and methods

2.1. Study area, hedge characteristics and sampling design

This study was conducted across five dairy farms in the county of Cumbria, Northwest England. The farms are located in the river Eden catchment, which is a rural area characterised by dairy and beef farming as the primary land use. The Koppen climate classification of the region is temperate oceanic (Beck et al., 2018), with an average annual temperature across the five farms of 8.8 °C, average annual rainfall of 1092 mm, and altitude of 135 m asl (see Biffi et al., 2022 for more information on the study area).

Across the five farms, 32 hedgerows were selected and grouped into four age categories (n = 8 for each category) based on interviews with the landowner: (1) '3-6 year old' if they were planted between 2017 and 2020, (2) '12 year old' if they were planted between 2016 and 2010, (3) '39 year old' if they were planted in 1983, and (4) 'Old' if they were planted before 2010. The latter category encompassed mature hedgerows for which the exact year of planting was not known, ranging from decades to potentially hundreds of years old. The '39 year old' category comprised of eight mature hedgerows located on the same farm for which the exact year of planting was known. The 3–6 and 12 year old hedgerows were all planted following AES guidelines on hedgerow planting (Rural Payments Agency and Natural England, 2015). These guidelines prescribe newly planted hedges to be double staggered rows of 2-year-old transplants (45–60 cm tall saplings) planted 40 cm apart, with a minimum of 6 plants per meter of hedgerow. Species must be native, with none making up more than 70 % of the total.

Woody species composition of the hedges was typical of England and Cumbria (Barr and Gillespie, 2000; Carey et al., 2007; Cumbria Biodiversity Data Centre, 2010), with a strong predominance of hawthorn (70 %) and blackthorn (15 %), and occasional presence of other native species (all listed in Table 2). All mature hedges (>12 year old) were managed by mechanical trimming every 1–2 years and laying every 20–30 years. The 39 year old hedges had been laid once, 20 years after planting. Most hedges were fenced for protection from livestock grazing. Although the terms hedgerow and hedge are commonly used interchangeably in the context of field boundaries, here we use "hedgerow" to collectively define all the components of the field boundary (ground flora, woody vegetation, and adjacent field margins) and "hedge" to refer to the upright woody shrub vegetation within a hedgerow (Barr and Gillespie, 2000).

The farms were visited in July 2021 to survey the 32 hedgerows and sample woody biomass components (stem, shoot and root) of different hedge species for C and N analysis. Table 1 shows the average height, width and volume per 1 m hedge length of each age group, as well as the average diameter of three randomly selected hawthorn main stems per hedge, measured at 10 cm height (diameter at ground height, DGH) and at the top of the main stem (top stem diameter, TSD). The farms were visited again in November 2022, when we destructively sampled five replicates of 1 m length of hedge for each hedge age category to obtain AGB measures. The AGB C stock was calculated by determining the dry weight of AGB in a 1 m length of hedge and multiplying by the C content of hawthorn stems.

Table 1

Average (and 95 % confidence intervals) height, width, volume, and hawthorn main stem diameter at ground height (DGH) and at the top (TSD) for each of the hedge age categories sampled in this study.

Age	n	Height (cm)	Width (cm)	Volume ($m^3 m^{-1}$)	DGH (cm)	TSD (cm)
3–6 years	8	135 (95–175)	85 (50–120)	1.8 (−0.4–3.9)	3.1 (2.5–3.7)	1.24 (1.07–1.41)
12 years	8	215 (185–245)	165 (140–180)	2.3 (1.4–3.1)	4.8 (4.4–5.3)	2.06 (1.91–2.21)
39 years	8	210 (160–260)	195 (150–235)	3.2 (1.8–4.7)	7.9 (7.3–8.5)	3.51 (3.23–3.79)
Old	8	210 (180–240)	185 (155–210)	3.6 (2.2–5.0)	10.7 (9.5–11.8)	3.55 (3.21–3.89)

2.2. Carbon and nitrogen content of different biomass components

Shoot and stems samples from all shrub species present in a 30 m hedge segment were harvested for elemental analysis of C and N content (see Appendix A). Shoot samples were taken by harvesting all new hedge growth from a known surface area (size of an A4 sheet of paper, 0.062 m^2), while stem samples were obtained by cutting a length (minimum 15 cm) of woody stem from within the permanent hedge biomass. Due to the prevalence of hawthorn and blackthorn in English hedges (Cumbria Biodiversity Data Centre, 2010) only these two species were sampled across all age categories. The remaining 13 species were sampled based on their occurrence (Appendix B).

A root sample of hawthorn and blackthorn was taken from one individual of each species from each of the hedge age categories. Only roots with at least 3 cm diameter at approximately 15 cm depth were selected. Moreover, a sample of grass was taken from a point 15 m in the field perpendicularly to the hedgerow. Only one sample was taken from fields adjacent to multiple hedges (n = 24). Aboveground and belowground biomass in a 15 × 15 cm square was sampled for comparison of grassland C and N content with woody hedgerow species.

On return to the laboratory, all harvested biomass components were oven dried at 65 °C until constant mass was reached. Root samples were thoroughly washed with deionised water to remove soil debris prior to oven drying. Each sample was passed through a 500 μm screen using a floor standing cutting mill (Cutting Mill SM 100, Retsch, Germany). Total C and N concentrations were determined using an elemental analysis (Vario EL cube, Elementar, Germany).

2.3. Aboveground biomass carbon stock

The amount of AGB in a 1 m length of hedgerow was determined via destructive sampling. The harvesting was performed by a professional hedge layer after annual trimming had occurred and during the winter dormant period. For each hedgerow, we selected a section composed of predominantly hawthorn and measured hedge height and width. As the younger hedgerows (3–6 and 12 year old) had been planted in accordance with government guidelines (i.e. six plants per meter), six individual plants were randomly selected from the hedge for harvesting to represent a 1 m section replicate. The individual plants were harvested by cutting the main stem at ground level. For the mature hedges (39 year old and Old), instead, we harvested all biomass between two vertical cuts 1 m apart. For each replicate, all harvested biomass was shredded on site using a commercial woodchipper (TW 150 DHB Timberwolf disc chipper, Chambers et al., 2010). The total woodchip produced per 1 m section of hedge was weighed using a bucket and spring balance to obtain the total weight of fresh biomass (AGB_{fresh}). A subsample of approximately 1.5 kg of woodchips was placed in a sealed plastic bag for the determination of moisture content. Upon return to the laboratory, the subsamples were weighed (fresh weight, W_{fresh}) and oven dried at 65 °C until constant mass was reached (dry weight, W_{dry}). The moisture content relative to fresh weight (MC) was calculated as:

$$MC = W_{fresh} - W_{dry}/W_{fresh}. \tag{1}$$

The total dry biomass (AGB_{dry}, kg) of woodchip produced per meter of hedge was then calculated as:

$$AGB_{dry}(kg) = AGB_{fresh} - \left(AGB_{fresh} \times MC\right). \tag{2}$$

The C content of the AGB was then calculated as:

$$AGB_{Ccon}(kg) = AGB_{dry} \times C_{con}. \tag{3}$$

where C_{con} is the average C content (g kg^{-1}) of hawthorn stem samples, as the sampled hedge sections were dominated by hawthorn. The AGB C stock in 1 m^3 of hedgerows was calculated from $AGBC_{con}$ and the hedge volume as:

$$AGB\ \ C\ stock\ \left(kg\ C\ m^{-3}\right) = AGB_{Ccon}/HV. \tag{4}$$

where HV is the volume of 1 m length of hedge, obtained by multiplying hedge height by hedge width. Finally, the AGB C stock per surface area was obtained as:

$$AGB\ C\ stock\ \left(Mg\ C\ ha^{-1}\right) = AGB\ C\ stock\ \left(kg\ C\ m^{-3}\right) \times height_{hedge}(m) \times 10. \tag{5}$$

The AGB C stock was also reported as Mg C km^{-1} assuming a hedge width of 1.5 m, the 'favourable condition' threshold for hedges (DEFRA, 2007), by dividing Mg C ha^{-1} by 6.67, and as Mg CO_2 by multiplying Mg C by the ratio of molecular weight of CO_2 to that of C (ratio = 3.67).

The average AGB C stock of hawthorn saplings was determined from 24 individual ~2 year old transplants obtained from a nursery. The saplings had an average height of 53.7 cm (stem = 39.0 cm and roots = 14.7 cm) and stem diameter of 0.31 cm. The AGB and root system of the saplings were separated and weighed for each individual to obtain W_{fresh} and then dried at 65 °C to measure W_{dry}. For each sapling, the AGB C stock relative to fresh weight was calculated using Eq. (4). We calculated the C stock in the AGB of 1 m of 1.5 m wide hedge at the time of planting as the average AGB C stock of one hawthorn sapling multiplied by six, based on sapling density guidelines for hedge planting (Rural Payments Agency and Natural England, 2015).

2.4. Average carbon sequestration rate of hedges of different ages

An average annual AGB C sequestration rate (AGB C_{seq}) was calculated per hedge age category as:

$$AGB\ C_{seq}\left(Mg\ C\ ha^{-1}\ yr^{-1}\right) = \frac{AGB\ C\ stock}{years\ since\ planting}. \tag{6}$$

where years since planting was 4, 12, and 39 years, respectively. Old hedges were not included, as their exact age was not known and ranged from a few decades to potentially centuries. The average sequestration rate for each age category was also reported as kg C m^{-3}, as Mg C km^{-1} assuming a hedge width of 1.5 m, (the 'favourable condition' threshold for hedges, DEFRA, 2007) and as annual CO_2 sequestration rate (Mg CO_2 ha^{-1} yr^{-1} and Mg CO_2 km^{-1} yr^{-1}) by multiplying Mg C by the ratio of molecular weight of CO_2 to that of C (ratio = 3.67). No sequestration rate was calculated for the hawthorn sapling as they represent "time zero" since planting. We did not compare the hedge AGB C stock to an alternative land use, such as grassland, as this is standards practice in agroforestry research (IPCC, 2019). Moreover, ground flora co-exists in the hedge understorey, especially in younger hedges.

We also estimated the C sequestration rate for the new biomass growth that occurs between periods of trimmings of mature hedges by calculating the C stock (C $stock_{NG}$) in the new growth of mature 39 year old and Old hedges. This was obtained from the dry weight of shoot biomass (SB_{dry}) of hawthorn plants as:

$$C\ stock_{NG}(kg\ m\text{-}2) = \frac{C\ stock_{NG}}{0.062}, \tag{7}$$

where 0.062 is the surface of an A4 sheet of paper in m^2. The C stock in new growth (C $stock_{NG}$) over the surface of linear length of hedgerow was calculated as:

$$C\ stock_{NG}\left(Mg\ km^{-1}\right) = C\ stock_{NG} \times surface_{hedge}, \tag{8}$$

where $surface_{hedge}$ is the surface available for new growth to occur on, which includes both sides and the top 1 m of a 2 m tall and 1.5 m wide hedge (5.5 m^2). The resulting C $stock_{NG}$, which is in kg m^{-1}, can be also expressed as Mg km^{-1}. This height is representative of managed hedgerows in England (Carey et al., 2007), while the width is the prescribed planting width within AES (Rural Payments Agency and Natural England, 2015). As hedges in the study were trimmed every 1 or 2 years, the C sequestration of new growth (C_{seqNG}) was calculated as:

$$C_{seqNG}\left(Mg\ km^{-1}\right) = \frac{C\ stock_{NG}}{1.5}. \tag{9}$$

2.5. Data analysis

Differences in the C and N content, and C to N ratio of different woody components (shoot, stem and root) of hedgerow species, and the AGB C stock of hedges of different ages were investigated using ANOVAs or non-parametric Kruskal-Wallis rank test when the data distribution did not meet the assumption of normality. In case of significant differences (at an *alpha* level of 0.05), these were followed by post-hoc pairwise *t*-tests or Wilcoxon rank sum tests with Benjamini-Hochberg false discovery rate-corrected p-values for multiple comparisons. All analyses were conducted in R (R Core Team, 2022).

2.6. Upscaling of results to estimate the climate change mitigation potential of planting hedgerows

We assessed hedgerow planting rates and hedge gapping up rates within national hedgerow planting schemes, to establish how these have changed over time and the increase in rate of planting that will be required to reach the Climate Change Committee goal of 40 % increase in hedgerow length by 2050. The schemes considered included public agri-environmental schemes (AES) between 2004 and 2022. The options considered were 'PH - Hedgerow planting new hedges' and 'HR - Hedgerow restoration' in the Environmental Stewardship and old Countryside Stewardship schemes (Natural England, 2023b, 2023c, 2023a), and 'BN11 - Planting new hedges' and 'BN7 - Hedgerow Gapping' in the 2016 Countryside Stewardship scheme (Natural England, 2023a). "Gapping up" is a hedgerow restoration method that consists in filling gaps of >20 m in hedgerows to create a continuous length of hedge. Finally, we assessed hedgerow planting rates within other publicly and privately funded national schemes, namely "Close the Gap" Hedgerows Project run by the Tree Council in 2021–2022 (The Tree Council, 2020, personal correspondence in 2022), and the "MOREhedges" scheme run by the Woodland Trust in 2014–2022 (Woodland Trust, 2019, personal correspondence in 2022).

The AGB C sequestration rates determined for each hedge age category in this study were used to estimate the amount of C sequestered by the Climate Change Committee goal of a 40 % increment in existing hedgerow length in three hedgerow planting scenarios. In England, this goal requires the planting of an additional 193,000 km of hedges, as calculated in Biffi et al. (2022) from the estimated length of well-maintained hedgerows and tree lines in 2007 and hedges planted by AES around improved grassland and arable fields in 2004–2019. The planting scenarios we evaluated were:

- *Business-as-usual (BaU)*: Hedgerow planting continues at current hedgerow planting rate, calculated as the sum of hedgerow planting and gapping up in 2022 by AES (1778.8 km yr^{-1}),
- *Scenario A*: All additional 193,000 km of hedgerows are planted within one year (by the end of 2024),
- *Scenario B*: 193,000 km of hedgerows are planted within 27 years at 7148.1 km yr^{-1} (by the end of 2050).

For each scenario (Fig. 1), we calculated the change in C stock stored in the AGB of the hedge increment by 2050. In addition, we calculate the change in C stock stored in AGB, in belowground biomass (BGB, using BGB:AGB C stock estimates from Axe et al., 2017), and in the soil (using SOC data presented in Biffi et al., 2022) of the increment by the end of 2063, 40 years after each planting scenario started. Based on the hedge age categories sampled in our study, we designated three hedge life stages defining the first 40 years after planting: (1) *new*, for the first 6 years after planting, (2) *intermediate*, from year 7 to 12 after planting, and (3) *mature*, from year 13 to 40 after planting. We attributed to each life stage a net sequestration rate (ΔAGB C_{seq}) based on the change in average AGB C stock as a hedge grows. New hedges were given the AGB C_{seq} rate of the 3–6 year old hedges sampled in our study. The ΔAGB C_{seq} rate of intermediate and mature hedges was calculated from the change in AGB C stock between the current and previous life stage as:

$$\Delta\text{AGB } C_{seq} = \frac{\text{average AGB C stock}_{current} - \text{average AGB C stock}_{previous}}{yr_{LS}}. \quad (10)$$

where yr_{LS} are the number of years of that life stage, namely 6 for intermediate hedges and 28 for mature hedges.

Before we can define the cumulative length of hedges within each life stage, we need to introduce auxiliary definitions. Namely, let pr_S be the planting rate of scenario S (BaU, A, or B), i.e. $pr_{BaU} = 1778.8$, $pr_A = 193{,}000$, and $pr_B = 7148.1$ km yr^{-1}. From the planting rate of each scenario we define the cut-off time $t_{\max,\ S}$ for each scenario as the time after which the planting goal has been achieved, i.e. $t_{\max,\ S} = 193{,}000 km/pr_S$. Concretely, the cut-off times are $t_{textmax,\ BaU} = 108$, $t_{textmax,\ A} = 1$, and $t_{textmax,\ B} = 27$. To describe the hedge length in a given life stage (new, intermediate, or mature) after time t, we first define the delayed planting rate for the age category c:

$$pr_{S,c}(t) = \begin{cases} pr_S & \text{if } 1 \le t - t_c \le t_{\max,S}, \text{or} \\ 0 & \text{otherwise,} \end{cases} \quad (11)$$

where t_c is the "delay", i.e. the number of years it takes for a newly planted hedge to belong to life stage c: $t_{\text{new}} = 0$, $t_{\text{intermediate}} = 6$, $t_{\text{new}} = 12$. For instance, in scenario B, at $t = 3$ years, the delayed planting rate will be $pr_{B,\ \text{new}} = pr_B$ for new hedges, and $pr_{B,\ \text{intermediate}} = 0$ for intermediate ones, since none of the hedges planted during the first 3 years have reached the intermediate life stage ($t_{\text{intermediate}} = 6$). At $t = 10$ years, both rates equal pr_B. In the year 2050, once $t_{\max,\ B} = 27$ has been reached, $pr_{B,\ \text{new}}$ drops to 0, but for the following 6 years, the intermediate delayed planting rate remains at pr_B (Fig. 1).

For each scenario, the cumulative length of 1.5 m wide hedges of different ages can now be calculated as:

$$\text{Length}_{S,\text{mature}}(t) = \sum_{i=1}^{t} pr_{S,\text{mature}}(i) \quad (12)$$

$$\text{Length}_{S,\text{intermediate}}(t) = \left(\sum_{i=1}^{t} pr_{S,\text{intermediate}}(i)\right) - \text{Length}_{\text{mature}}(t) \quad (13)$$

$$\text{Length}_{S,\text{new}}(t) = \left(\sum_{i=1}^{t} pr_{S,\text{new}}(i)\right) - \text{Length}_{\text{intermediate}}(t) - \text{Length}_{\text{mature}}(t) \quad (14)$$

The annual sequestration rate $SR_S(t)$ for a scenario (S) depends on how many km of hedges in each life stage are present in that moment in time (t), and thus on how many years have passed since planting started:

$$\begin{aligned} SR_S(t) = {} & \text{Length}_{\text{new}}(t) \times \Delta\text{AGB } C_{seqnew} \\ & + \text{Length}_{\text{intermediate}}(t) \times \Delta\text{AGB } C_{seqintermediate} \\ & + \text{Length}_{\text{mature}}(t) \times \Delta\text{AGB } C_{seqmature} \end{aligned} \quad (15)$$

We can now calculate the cumulative sequestered C in scenario S after t years as:

$$\text{Seq}_S(t) = \sum_{i=1}^{t} SR_S(i) \quad (16)$$

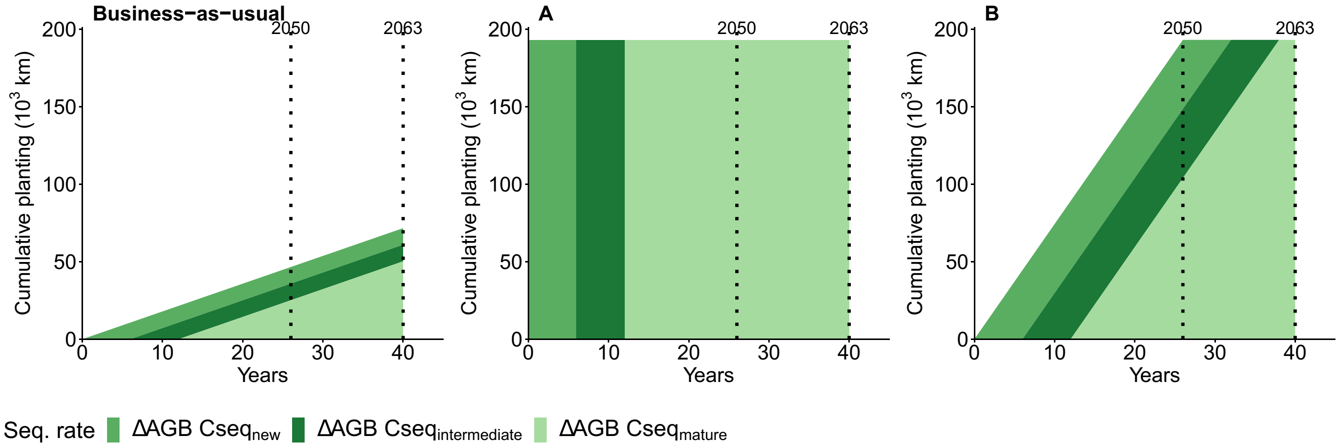

Fig. 1. Schematic representation of the three upscaling scenario considered in the study, showing cumulative hedgerow planting over the next 40 years. Sequestration potential if current planting rates remain unchanged (business-as-usual). The 40 % increment in existing hedgerow length (193,000 km) set by the Climate Change Committee to aid net-zero (Climate Change Committee, 2018) is reached (A) in one year, maximising sequestration potential, or (B) by 2050 with an interim target of 20 % increment by 2035 based on (Climate Change Committee, 2021). Darker shades indicate higher sequestration rates (ΔAGB C_{seq}). All scenarios relate to a hedge of 1.5 m width, the 'favourable condition' threshold for hedges (DEFRA, 2007).

Table 2
Sample size, and average C and N content and C:N (and 95 % confidence intervals) of biomass components (stem, shoot and root) of hawthorn, blackthorn and other commonly found woody hedgerow species in the UK, and intensive grassland dominated by perennial ryegrass (*Lolium perenne*).

Component	Species	n	C (g kg^{-1})	N (g kg^{-1})	C:N
Shoot	*Lolium perenne*	24	449.5 (443.8–455.3)	26.3 (23.3–29.3)	19.0 (15.6–22.4)
Root		22	370.5 (349.5–391.5)	14.6 (13.7–15.4)	25.6 (24.0–27.3)
Stem	*Crataegus monogyna*	31	495.4 (492.0–498.9)	10.5 (8.4–12.6)	57.0 (49.0–65.1)
	Prunus spinosa	14	501.4 (497.4–505.5)	7.7 (6.2–9.0)	70.1 (59.0–81.2)
	Acer pseudoplatanus	1	483.0	7.4	64.9
	Alnus glutinosa	2	514.3	8.5	69.1
	Corylus avellana	1	501.6	7.7	65.4
	Fraxinus excelsior	1	490.1	8.1	60.7
	Ilex aquifolium	1	506.6	6.1	82.8
	Malus sylvestris	2	507.5	9.2	61.9
	Quercus robur	1	499.8	9.0	55.4
	Rosa canina	4	502.4 (497.0–507.9)	8.2 (4.2–12.3)	65.0 (36.2–93.7)
	Salix aurita	1	499.6	7.6	65.9
	Sambucus nigra	4	497.9 (493.1–502.7)	10.6 (6.0–15.2)	50.6 (21.0–80.3)
	Sorbus aucuparia	1	502.1	5.2	96.8
	Ulmus sp.	1	481.3	22.8	21.1
	Viburnum opulus	1	506.3	5.8	86.9
Shoot	*Crataegus monogyna*	30	500.3 (496.3–504.2)	18.7 (17.5–19.9)	27.7 (25.5–29.9)
	Prunus spinosa	14	499.9 (494.5–505.3)	26.4 (23.8–28.9)	19.5 (17.5–21.4)
	Acer pseudoplatanus	1	496.4	32.0	15.5
	Alnus glutinosa	2	525.7	30.7	17.2
	Corylus avellana	1	498.7	31.7	15.7
	Fraxinus excelsior	1	483.0	30.7	15.7
	Ilex aquifolium	1	529.5	26.1	20.3
	Malus sylvestris	2	507.0	24.4	21.4
	Quercus robur	1	524.9	28.5	18.4
	Rosa canina	4	486.6 (479.3–494.0)	22.4 (18.2–26.6)	21.9 (17.6–26.3)
	Salix aurita	1	524.9	28.8	18.2
	Sambucus nigra	3	475.0 (457.0–493.0)	42.0 (36.5–47.5)	11.34 (9.58–13.1)
	Sorbus aucuparia	1	508.7	25.5	20.0
	Viburnum opulus	1	500.5	22.8	22.0
Root	*Crataegus monogyna*	4	468.3 (443.4–493.3)	10.5 (7.0–14.0)	47.4 (30.8–64.0)
	Prunus spinosa	4	484.5 (466.4–502.7)	10.3 (4.6–16.1)	51.6 (22.9–80.3)

For instance, we can calculate the cumulative sequestered C in scenario business-as-usual by the year 2050 as $Seq_{BaU}(27) = 161{,}744.7$ Mg C (0.16 Tg C).

For each scenario, the total C and CO_2 sequestered by hedge AGB are given for the year 2050, and the total C and CO_2 sequestered by hedge AGB + BGB + SOC are given for 2063, 40 years after planting. As we did not measure BGB in this study, we estimated the BGB C sequestration rate of 39 year old hedges based on the BGB:AGB C stock ratio of 1 found by Axe et al. (2017) in hawthorn dominated, mature, managed hedges. Thus, we used the average annual AGB C sequestration rate of 39 year old hedges for their BGB C sequestration rate. We used the SOC sequestration rate of 0.22 Mg C km^{-1} yr^{-1} based on 37 year old hedgerows (Biffi et al., 2022) to estimate SOC stocks for all age categories. This more conservative estimate was used instead of SOC sequestration rates by age category as the displacement of the soil profile when planting a new hedgerow (Laganière et al., 2010) can bias the SOC sequestration of younger hedges, overestimating the long-term effects of hedgerow planting on SOC.

3. Results

3.1. Carbon and nitrogen content of different woody components of hedgerow species

The elemental analysis of woody material by plant component and plant species shown in Table 2 indicated that there was little difference in C and N content among woody plant species, particularly for C. On average, hawthorn stems contained 495.4 g C kg^{-1} (C_{con}). Across all species, C content did not differ between shoot (500.3 g kg^{-1}, 496.9–503.6) and stem (498.4 g kg^{-1}, 496.0–500.8) samples, with an average of 499 (497–501) g C kg^{-1} across shoot and stem samples. In contrast, N content was significantly higher in shoot (23.5 g kg^{-1}, 21.8–25.2, $p < 0.001$) than stem samples (9.4 g kg^{-1}, 8.3–10.6). The C to N ratio was therefore significantly higher in stem samples (61.7, 56.5–67.0, $p = 0.003$) than in shoot samples (23.0, 21.3–24.6, $p < 0.001$). Average C content in both aboveground and belowground plant material was higher in woody hedgerow species than in grass ($p < 0.001$). In contrast, the average N content did not differ between woody hedgerow species and grass.

Hawthorn and blackthorn C content was significantly lower in root than in shoot (hawthorn: $p < 0.001$; blackthorn: $p < 0.01$) and stem samples (hawthorn: $p < 0.001$; blackthorn: $p < 0.01$), while N content was significantly higher in shoot than in stem ($p < 0.001$) and root samples ($p < 0.001$, Table 2). Hawthorn and blackthorn C content did not differ among hedge age categories. The N content of hawthorn was significantly higher in 12 year old hawthorn stem samples (15.2 g kg^{-1}) compared to 39 year old (7.8 g kg^{-1}, $p = 0.018$) and Old (7.9 g kg^{-1}, $p = 0.018$). The N content in 3–6 years old category was 10.3 g kg^{-1} and did not differ to the other age categories. The N content of blackthorn did not change among hedge age categories.

3.2. Aboveground biomass C stock and sequestration rates of hedges of different ages

The biomass and AGB C stock of hedges increased with age (Table 3) with a sharp increase from sapling to young hedges (3–6 year and 12 year old) and a smaller increase once hedges reached maturity (39 year and

Table 3
Average AGB and AGB C stock (and 95 % confidence intervals) of hedges of different ages. Values expressed in km refer to a hedge of 1.5 m width, the 'favourable condition' threshold for hedges (DEFRA, 2007). Different letters in a column indicate statistically significant differences among age categories ($p < 0.05$)

	AGB_{dry}		AGB C stock							
Age	Mg km^{-1}	Sig.	kg C m^{-3}	Sig.	Mg C ha^{-1}	Sig.	Mg C km^{-1}	Sig.	Mg CO_2 km^{-1}	Sig.
Sapling	1.15 (0.96–1.35) e^{-3}	*d*	0.95 (0.83–1.08) e^{-3}	*c*	3.80 (3.16–4.45) e^{-3}	*c*	0.57 (0.47–0.67) e^{-3}	*c*	2.09 (1.74–2.45) e^{-3}	*c*
3 – 6 years	1.92 (0.15–3.68)	*c*	0.59 (0.17–1.01)	*b*	8.34 (3.12–13.57)	*b*	1.25 (0.47–2.03)	*b*	4.59 (1.72–7.47)	*b*
12 years	5.64 (2.05–9.24)	*bc*	1.16 (0.72–1.6)	*ab*	21.92 (9.03–34.8)	*ab*	3.29 (1.35–5.22)	*ab*	12.06 (4.97–19.16)	*ab*
39 years	8.07 (5.60–10.54)	*ab*	1.36 (0.60–2.12)	*ab*	33.41 (19.31–47.51)	*a*	5.01 (2.9–7.13)	*a*	18.39 (10.63–26.15)	*a*
Old	12.8 (4.82–20.79)	*a*	1.87 (0.67–3.07)	*a*	40.42 (11.36–69.47)	*a*	6.06 (1.7–10.42)	*a*	22.25 (6.25–38.24)	*a*

Table 4

Estimated average annual C sequestration rates by hedge AGB of different age categories (AGB C_{seq}), and the respective sequestration rate showing the change in AGB C stock over time among age categories (ΔAGB C_{seq}). Values expressed in km refer to a hedge of 1.5 m width, the 'favourable condition' threshold for hedges (DEFRA, 2007).

Age	AGB C_{seq}					ΔAGB C_{seq}	
	kg C m^{-3} yr^{-1}	Mg C ha^{-1} yr-1	Mg C km^{-1} yr^{-1}	Mg CO_2 ha^{-1} yr^{-1}	Mg CO_2 km^{-1} yr^{-1}	Mg C ha^{-1} yr^{-1}	Mg C km^{-1} yr^{-1}
3–6 years	0.15 (0.04–0.25)	2.09 (0.78–3.39)	0.31 (0.12–0.51)	7.65 (2.86–12.45)	1.15 (0.43–1.87)	2.09	0.31
12 years	0.1 (0.06–0.13)	1.83 (0.75–2.9)	0.27 (0.11–0.43)	6.7 (2.76–10.64)	1.01	2.26	0.34
39 years	0.03 (0.02–0.05)	0.86 (0.5–1.22)	0.13 (0.07–0.18)	3.14 (1.82–4.47)	0.47 (0.27–0.67)	0.43	0.06

Old) and were regularly trimmed to consistent dimensions (~1.90 m wide by 2.10 m high, see Table 1). The largest rate of increase in AGB occurred between planting the saplings and 3–6 years old hedges, then AGB biomass increased by 163 % from 3 to 6 year old to 12 year old hedges, by 51 % between 12 year old and 39 year old hedges, and by 21 % between 39 year old and Old hedges. The stock of 1 m^3 of hedge increased by 217 % from 3 to 6 year old to Old age category.

Table 4 shows the average AGB C sequestration rate for each hedge age category. Our results show that average sequestration rate was highest in 3–6 year old hedges (2.09 Mg C ha^{-1} yr^{-1}) and lowest in 39 year old hedges (0.86 Mg C ha^{-1} yr^{-1}). The latter average sequestration rate was also used for estimating BGB C stock in the upscaling scenarios. ΔAGB C_{seq} was highest in hedges up to 12 years old, after which the change in AGB, and the relative ΔAGB C_{seq} decreased substantially from ~ 0.3 Mg C km^{-1} yr^{-1} to 0.06 Mg C km^{-1} yr^{-1}. The estimated C sequestration in annual shoot growth for 39 year old and Old hawthorn hedges was 0.94 (0.582–1.31) Mg C km^{-1} yr^{-1} and 0.96 (0.44–1.48) Mg C km^{-1} yr^{-1}, respectively.

3.3. Hedgerow planting rates and climate change mitigation potential of planting hedges

In England, a total of 5264.9 km of hedges were planted within AES between 2004 and 2022, of which 94 % were planted around improved grassland (2441 km) and arable (2497 km) fields (Fig. 2). There has been a strong increase in the annual planting rate in recent years with 2.6 times as many hedges (3816.7 km) planted in 2019–2022 compared to 2004–2018 (1448.2 km). The highest planting rate yet, 1375.3 km yr^{-1}, was achieved in 2022. During the entire 2004–2022 period, the average length planted per agricultural holding was 0.68 (0.65–0.70) km. However, 25 % of holdings planted >0.8 km, and the average length of planting for this group was 1.78 (1.70–1.87) km per holding. Thus, these 25 % of farms were responsible for planting almost twice the total length of hedges compared to the remaining 75 % of agricultural holdings that, on average, planted 0.31 (0.31–0.32) km each.

Gapping-up has also contributed significantly to increasing overall hedgerow length. Between 2004 and 2022 a total of 1843.8 km of hedges were restored via gapping-up, contributing a further 35 % to total hedgerow planting efforts. Again, 94 % of these agreements took place in arable and improved grassland landscapes. If we consider hedgerow planting and gapping up together, the planting rate in 2022 was 1778.8 km yr^{-1} (Fig. 2).

Other major planting schemes, that we are aware of, have also contributed to national hedge planting efforts, although to a lesser degree than AES planting (Fig. 2). MOREhedges planted 450 km between 2014 and 2022, with increasing planting rates over time with ~100 km being planted between 2021 and 2022. Close the Gap planted 43 km between 2021 and 2022. Thus, over the period 2004 to 2022 a total of 7602 k m of hedges were planted across England via the schemes and initiatives presented in Fig. 2.

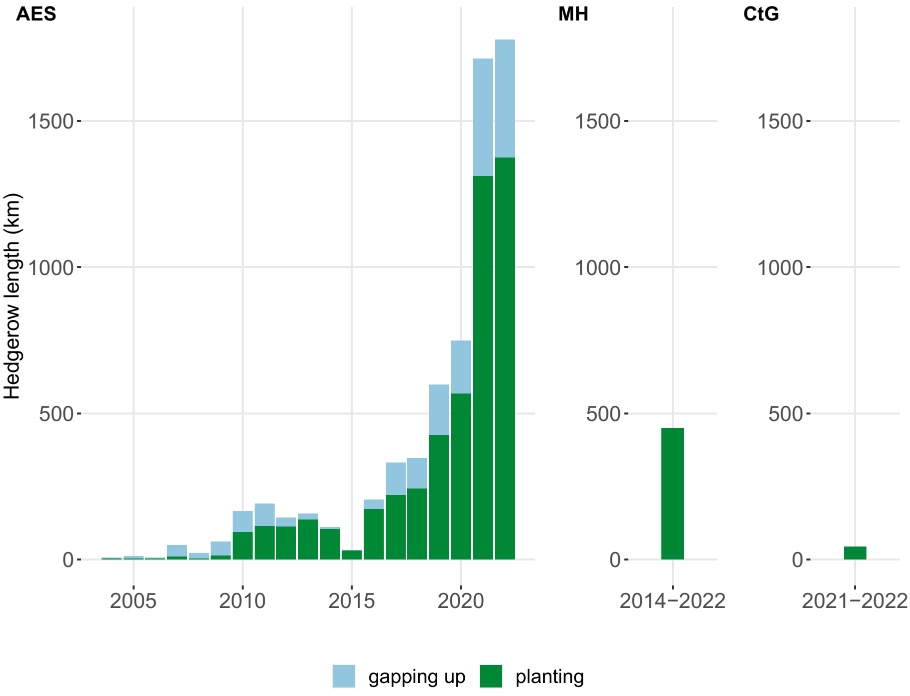

Fig. 2. Annual length of hedgerow planting and gapping up by AES schemes (Environmental Stewardship and Countryside Stewardship) in arable and improved grassland landscapes between 2004 and 2022, and total hedgerow planting by MoreHedges (MH, Woodland Trust), and Close the Gap (CtG, TheTreeCouncil).

If planting rates remain constant at 1778.8 km yr^{-1}, hedge AGB will sequester 0.60 Tg CO_2 by 2050 and 1.03 Tg CO_2 by the end of 2063 (Table 5). If we account for C sequestration by AGB, BGB, and in the soil, then total C sequestration associated with planting hedges at the current rate increases to 2.87 Tg CO_2. However, if planting rates increase to meet the Climate Change Committee goal of a 40 % increase in hedgerow length, which requires the planting of an additional 193,000 km of hedgerows, the C sequestration potential will increase depending on the planting scenario. For scenario A, the optimal but unrealistic scenario where all new hedgerows are planted in one year (193,000 km yr^{-1}), hedge AGB will sequester 3.40 Tg of CO_2 by 2050. For scenario B, where planting occurs over 27 years (7148.1 km yr^{-1}), hedge AGB will sequester 27 % less CO_2 by the end of 2050 than scenario A. Thus, 4.1 times more CO_2 could be sequestered by hedge AGB by 2050 if planting increases from current rates to those presented in scenario B, and 3.5 by 2063. If we include C sequestration by BGB and soil as well as AGB, the total CO_2 sequestered over 40 years associated with planting 193,000 km of new hedgerows is 13.87 and 10.13 Tg for scenario A and B, respectively.

4. Discussion

4.1. Carbon and nitrogen content of hedge species

Our results provide a reference for the C and N content of different components of the woody biomass of hedge species commonly found in temperate climatic regions. The C content of the stem and shoot component of the hedge species did not differ and ranged between 467 and 535 g C kg^{-1}, with an average of 499 (497–501) g C kg^{-1}. This average value was higher than the C content reported by Milne and Brown (1997) of 460 g C kg^{-1} for woody broadleaf species in England, but similar to the IPCC tier 1 guidelines for 'increase in stocks in living biomass' which suggest a default C fraction of dry matter of 500 g C kg^{-1} (IPCC, 2019). However, this value has been shown to introduce some degree of systematic overestimation in forest C stock estimates, as wood C content can vary across species of the same provenance (Thomas and Martin, 2012). Indeed, we found that C_{con}, the average stem C content for hawthorn, was 495 g C kg^{-1}, 5 % lower than our average C content across all hedge species. This C content measure was higher than that reported for hawthorn by Axe et al. (2017) of 484 g C kg^{-1} for stem and shoot samples combined.

Although we did not measure the C stock in BGB, it should be noted that the C content of the coarse root component of hawthorn and blackthorn were significantly lower than in the stem. The C content of roots has also been shown to vary with size, with finer roots having higher C concentration than thicker ones (Axe et al., 2017). Therefore, to improve the accuracy of C stocks in hedgerow biomass, the C content of different components of the biomass, as well as the species distribution of the hedgerows should ideally be considered.

Table 5

Estimated C and CO_2 uptake and storage in aboveground biomass (AGB) over 27 years (end of 2050) and estimated C and CO_2 uptake and storage in AGB and soil organic carbon (SOC) over 40 years (end of 2063). Estimates are shown if current planting rate (1778.8 km yr^{-1}) is kept constant, and if the 40 % increment in existing hedgerow length in England, which means planting an additional 193,000 km of hedgerows, is achieved in one year (by the end of 2024, scenario A, 193,000 km yr^{-1}) or 27 years (by the end of 2050, scenario B, 7148.1 km yr^{-1}). All estimates are based on a hedge width of 1.5 m, the 'favourable condition' threshold for hedges (DEFRA, 2007). BGB estimates are based on a BGB:AGB C stock ratio of 1 (Axe et al., 2017) for 39 year old hedges.

Scenario	Component	2050 (year 27)		2063 (year 40)	
		Tg C	Tg CO_2	Tg C	Tg CO_2
Business-as-usual	AGB	0.16	0.60	0.28	1.03
	BGB			0.19	0.70
	SOC			0.31	1.14
	Total			0.78	2.87
A: goal over 1 year	AGB	0.93	3.40	1.08	3.96
	BGB			1.00	3.67
	SOC			1.70	6.24
	Total			3.78	13.87
B: goal over 27 years	AGB	0.67	2.47	0.93	3.41
	BGB			0.68	2.50
	SOC			1.15	4.22
	Total			2.76	10.13

We found the N content to be three-times higher in shoot (23.5 g N kg^{-1}) compared to stem (9.9 g N kg^{-1}) samples across all hedge species sampled. This disproportionate allocation of N in new plant growth is to be expected, as N is translocated from the plant stores to the leaf biomass before the start of leaf expansion to increase photosynthetic capacity (Hikosaka, 2004). Shoot N fraction of hawthorn and blackthorn were respectively 18.7 and 26.4 g kg^{-1} of dry mass, a result comparable to the average reported for the same species in the TRY database (17.6 ± 2.9 and 23.9 ± 5.3 g kg^{-1}, Kattge et al., 2020, Trait 14). Although blackthorn retranslation (the re-absorption of foliar N from senescing leaves, Brant and Chen, 2015) has been shown to be slow (Del Arco et al., 1991), the difference in shoot N content does not necessarily reflect disproportionate N input through leaf litter of blackthorn and hawthorn. Hedge trimming usually occurs during winter dormant period (October/November), when most foliar N has been already retranslated before foliar abscission. However, climate change can lengthen the abscission duration period (Gunderson et al., 2012) and may affect N inputs form litter into soil when hedges are trimmed. Moreover, the lower C:N in shoot compared to stem samples suggests that trimmed new growth may decompose quicker than stems, as C:N affects microbial respiration (Nicolardot et al., 2001; Jílková et al., 2020). Further research is needed on the N dynamics of hedgerows and how they might affect the decomposition rate of woody biomass and the accumulation of C in the soil, versus its release into the atmosphere as CO_2.

4.2. Carbon stocks in aboveground biomass of managed hedgerows

As far as we are aware, this is the first study to quantify the AGB C stocks of young hedges, which are not yet trimmed regularly, and to compare them to the AGB C stock of mature and regularly managed hedge that are trimmed every few years. We found that the AGB C stock increased sharply from that found in saplings (average = 0.0038 Mg C ha^{-1}) to that in 3–6 year old hedges (average = 8.34 Mg C ha^{-1}), reflecting that fact that the maximum height increment of woody plants occurs in the first few years of growth (Bond, 2000). The AGB C stock of the 12 year old hedges (21.9 Mg C ha^{-1}) was 2.6 times greater than that in 3–6 year old hedges. After 12 years, hedge growth slowed but total AGB C stock nearly doubled between 12 year old and Old hedges due to changes in hedge volume and AGB C density as the hedge matured. We found the average AGB C stock of mature hedges to be 33.4 and 40.4 Mg C ha^{-1} for 39 year old and Old hedges, respectively, showing that the increase in AGB C stocks slows considerably once a hedge reaches 40 years. Our results indicate that the AGB C stock of mature managed hedges is approximately a tenth of that of UK's temperate forests, which have been estimated recently to store 409.9 Mg C ha^{-1} (Calders et al., 2022) and a third of the AGB C stock of 30 year old native broadleaved woodland, which is estimated to be on average 114 Mg C ha^{-1} (Gregg et al., 2021). Comparatively, permanent grassland in the country yields an average of 8.7 Mg dry matter ha^{-1} (Qi et al., 2018), which, if we consider our grass C content of 449.5 g C kg^{-1}, corresponds to a C stock of 3.9 Mg C ha^{-1}. This estimate is close to the AGB C stock of grassland estimated by Beka et al. (2023) for two replicate fields (3.2 and 2.5 Mg C ha^{-1}). It should be noted, however, that most AGB is removed from grassland by grazing and/or harvesting, reducing the effective AGB C stock of this habitat.

In Appendix C, we compare our results to the few studies that have also used destructive biomass sampling for hedgerows with similar species composition to determine AGB C stock in hedges, often to estimate biofuel production from coppicing of unmanaged hedges. In Germany, hedgerows of primarily hawthorn, hazel, and willow were found to store 44.9–47.7 Mg C ha^{-1} (Lingner et al., 2018a, 2018b; Drexler et al., 2021), which is very similar to the 40.42 Mg C ha^{-1} we found in Old hedges. However, the hedgerows sampled in Germany had a substantially higher AGB cross section volume than the managed hedges in our study, which averaged 3.0 (2.4–3.6) m^3 per 1 m length for hedges of 12 years and older (Fig. 3, Table 1). Drexler et al. (2021) examined hedgerows (recently coppiced to 10–15 years after coppicing) with an average 1 m cross section volume of 16.1 (13.9–18.3) m^3 m^{-1}, while the average in Lingner et al. (2018a, 2018b) was 48.1 (26.3–69.9) m^3 m^{-1}. The considerably larger hedge AGB volumes in the German studies, suggest that these hedges would be considered treelines in the UK. The AGB C stocks in mature hedges 36.9 (24.2–49.6) Mg C ha^{-1} in our study was very similar to the average AGB C stock of 37.3 Mg C ha^{-1} across the three hedges sampled by Axe et al. (2017) in the UK. Using LiDAR scanning estimates of biomass density on primarily hawthorn hedges in Ireland and assuming a C_{con} of 50 %, Black et al. (2014) reported an average AGB C stock of 20.5 (range 0.01–350) Mg C ha^{-1}, with most having a low AGB stock of 4 Mg C ha^{-1}. However, these modelled estimates were not accompanied by direct AGB measurements and relied on forestry-derived methods based on naturally occurring tree forms, while hedges shrubs are altered by regular management. Interestingly, a similarly low value was reported by Falloon et al. (2004), who estimated hedge AGB C stock to be 5 Mg C ha^{-1} based on forestry data.

Our results contribute critical insights to the AGB C stock density of managed hedges, which are structurally different from unmanaged hedges, thus contributing to national C stocks inventories for climate change mitigation modelling. Fig. 3 displays AGB C stock and AGB C stock densities in recent studies on hedgerows with similar composition and with data available for AGB C stock and hedge height and width per hedge (also shown in Appendix C). When considering an equal surface area of hedge (e.g. 1 ha), there is a linear relationship between total AGB C stock and hedge height, with taller hedgerows containing higher C stock (panel A). However, AGB C stock in managed hedges in our study and Axe et al. (2017) increase more rapidly with hedge height than unmanaged hedges, as shown by the different slopes of the lines in Fig. 3. Moreover, when considering a 1 m wide cross section of their volume, hedges show discrepancy in AGB C stock density with their size and management (panel B). On average, our AGB C stock density changed among hedgerow age categories from 0.59 kg C m^{-3} in 3–6 year old hedges (not shown in plot) and 1.87 kg C m^{-3} in Old hedges. Although Axe et al. (2017) did not report AGB C stock density, we can derive density values from the three replicate AGB C stock measurements of the three hedges considered in the study. The resulting average AGB C stock density of 1.46 kg C m^{-3} is very similar to the density of 39 year old hedges in our study (1.36 kg C m^{-3}). Unmanaged, large hedgerows in Lingner et al. (2018a) and Drexler et al. (2021), instead, showed a lower AGB C stock density, which averaged 0.90 and 0.86 kg C m^{-3}, respectively. A recent study on managed hedges in Ireland reported a much higher AGB density of 6.4–7.6 Kg m^{-3} (average height = 1.3 m, Black et al., 2023), which, assuming a C_{con} of 495 g C kg^{-1} (Table 2), would equate to a AGB C stock density of 3.2–3.8 kg C m^{-3}. Such high density per hedge volume ratio has not been observed by any of the studies shown in Fig. 3, while their reported AGB density for unmanaged hedgerows (1.9 kg m^{-3}), would equate to a C stock density of 0.94 kg C m^{-3}, in line with the results of Lingner et al. (2018a). The variation in AGB density in managed and unmanaged hedgerows and treelines is crucial when developing national inventories of C stocks and assessing changes in AGB C stocks over time (Cardinael et al., 2018). Our results provide benchmark measurements for UK managed hedges of different ages.

4.3. Carbon sequestration of aboveground biomass of managed hedges

This is the first study, as far as we are aware, to show the average annual AGB C sequestration rate of managed hedges of different ages, as well as the time series of the change in AGB C sequestration rate from planting to maturity. We found that the average annual AGB C sequestration is substantial in young hedges ≤12 years old, which sequester 2.0 Mg C ha^{-1} yr^{-1} in their AGB, while mature (39 year old), regularly managed hedges, sequestration rate is ~60% lower (0.86 Mg C ha^{-1} yr^{-1}). Our results also present a time series of the change in net AGB C sequestration rate of a hedge from planting to maturity, showing that a newly planted hedge can sequester 0.31 Mg C km^{-1} yr^{-1} in the first six years after planting, after which the sequestration rate increases slightly to 0.34 Mg C km^{-1} yr^{-1} from year 7 to 12 after planting. Once regular management starts, and the change in AGB C stock between hedge life stages decreases due to regular trimming, the ΔAGB C_{seq} decreases substantially to 0.06 Mg C km^{-1} yr^{-1}.

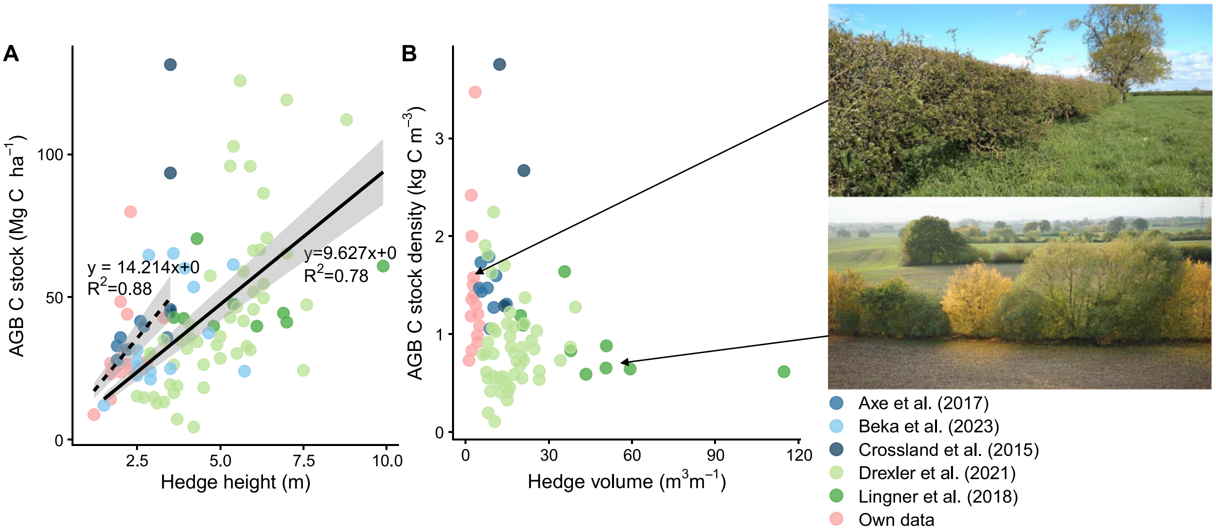

Fig. 3. AGB C stocks in managed and unmanaged hedges of similar species composition as reported in the literature (green = Germany, blue = UK) and in this study (red, only hedges ≥12 year old are included). (A) Relationship between AGB C stock of hedges per unit of surface area and hedge height. Lines are fitted using linear regression, with the dotted line including our study and Axe et al. (2017) (exclusively managed hedges), and the solid line including the other studies (largely unmanaged/coppiced hedges, with potentially some managed hedges in Beka et al. (2023), as management was not specified); (B) AGB C stock density in 1 m^3 of hedge as a function of the hedge volume in 1 m length of hedge. Beka et al. (2023) is not included in plot A, as hedge width was not reported. The top picture shows an example of a mature, regularly managed hedge in this study, and the bottom picture, reproduced with permission, is from Lingner et al. (2018b) and shows an example of an unmanaged hedge.

Few studies have attempted to provide estimates of annual AGB C sequestration rates of hedges, and most of these are based on hedgerows of unknown age or on woodland data. For mature hedgerows, Kay et al. (2019) reported a potential AGB C sequestration rate of 0.1–0.45 Mg C ha^{-1} yr^{-1} for hawthorn and blackthorn hedgerows in Atlantic silvoarable systems based on existing literature, while Robertson et al. (2012) estimated it to be 0.13–0.51 Mg C ha^{-1} yr^{-1} for ancient hazel and hawthorn hedges using Rothamsted forest data. Drexler et al. (2021) estimated a considerably higher AGB C sequestration rate of 4.3 Mg C ha^{-1} yr^{-1} and 1.7 Mg C ha^{-1} yr^{-1} for unmanaged hedgerows, which was obtained by hypothesizing a hedge age of 20 years and 50 years, respectively. Crossland (2015) estimated an even higher AGB C sequestration rate of 6.0 Mg C ha^{-1} yr^{-1} for unmanaged blackthorn hedgerows.

This study also provides an estimate of annual growth for mature hedges, which, however, is regularly removed from the AGB via trimming, and does not contribute to an increment in AGB C stock and thus an increase in C sequestration rate. Our results provide an indication of annual growth of mature hawthorn hedges, which was estimated to be ~0.9 Mg C km^{-1} yr^{-1}. This figure is based on the assumption that the growth will occur over the total lateral surface of the hedge, from ground level to its maximum height. This will depend on the height of herbaceous vegetation at the sides of the hedge, as well as state of the hedge, as, for example, “tall and leggy” hedges lack significant growth in the lower parts (DEFRA, 2007). A recent measurement of annual growth in managed hedgerows in Northern Ireland estimated it to be 3.7–13.0 Mg C ha^{-1} yr^{-1} (Blair, 2021), which equates to 0.55–1.95 Mg C km^{-1} yr^{-1} assuming a hedge width of 1.5 m. Our shoot biomass samples were taken before the end of the growing season and suggest that the yearly growth of managed hedges can be substantial. This annual growth is removed regularly and does not add to the AGB C stock of hedges, and thus is excluded from the AGB C sequestration rate. However, trimmed residues that are left on the ground to decompose are part of the dead organic matter carbon stock of hedges, and, together with litter, likely contribute to the higher SOC stocks observed beneath and close to hedgerows than in adjacent agricultural fields (Walter et al., 2003; Follain et al., 2007; Van Den Berge et al., 2021; Biffi et al., 2022).

The findings of this study suggest that the periodic management of established hedgerows in the UK is important to maintain their AGB C stock and C sequestration capacity over time. While Crossland (2015) assumed an AGB C sequestration rate of 0 Mg C ha^{-1} yr^{-1} for hedges coppiced every 15 years, due to the complete removal of their AGB, it is likely that hedge management has an impact on AGB density and on the long-term AGB C sequestration potential of managed hedges in this study. In England, mature hedges are traditionally laid every 20–30 years. Hedge laying involves removing part of the hedge AGB (brash) and laying the main shrub stems (pleachers) horizontally on the ground, entwining them to favour plant rejuvenation and increase wood density (Staley et al., 2015). While the removal of part of the biomass causes a temporary net loss of AGB C, hedgerow laying increases the complexity and the density of hedges' woody structure, allowing the AGB to continue sequestering C, although at a lower rate than in young hedges, after the hedgerow has reached maturity.

Hedge biomass is not limited to AGB, as BGB can double the C stock of shrubby plants. Although we did not measure the BGB of hedges, we can estimate the BGB C stock and BGB C sequestration rates from findings of previous studies on the ratio between BGB and AGB and using the hawthorn root C$_{con}$ found in our study. While forested biomes have a low BGB:AGB, as trees allocate 80 % of their resources aboveground, shrubs usually allocate around 50 % of their resources belowground (Mokany et al., 2006; Ma et al., 2021). Thus, the contribution of the root system to biomass C stock might be especially important for managed hedges, as their aboveground growth, and thus C sequestration rate, is hindered by regular trimming once they reach maturity. However, compared to AGB of hedges, little information exists about hedges' belowground biomass. Black et al. (2023) found that managed hedgerows had a higher BGB:AGB than unmanaged hedgerows, with an average of 0.49 for 1.3 m tall managed hedges compared to 0.28 for irregular less intensively managed ones. In the UK, Axe et al. (2017) harvested AGB and BGB of three 2.7–1.9 m tall hedges and found BGB:AGB C stock to be close to 1, suggesting that 39 year old and Old hedges in our study sequester similar amounts of C in their ABG and BGB, resulting in a total of $0.86 \times 2 = 1.72$ Mg C ha^{-1} yr^{-1} (0.94 Mg CO$_2$ km^{-1} yr^{-1}). By including the 1.48 Mg C ha^{-1} yr^{-1} SOC C stock of 37 year old hedges presented in Biffi et al. (2022), we can estimate that ~40 year old managed hedges have an average sequestration rate of 3.2 Mg C ha^{-1} yr (11.74 CO$_2$ ha^{-1} yr^{-1} or 1.76 Mg CO$_2$ km^{-1} yr^{-1}). This shows that hedge C sequestration equates to 80 % of the representative sequestration rate for 30 year old native mixed broadleaved woodlands, which is ~14.5 Mg CO$_2$ ha^{-1} yr^{-1} (Woodland Carbon Code, 2021).

4.4. Hedgerow planting rates and climate change mitigation goals

National planting efforts within AES must continue to increase in order to reach the 20 % increment in hedgerow length by 2035 and a 40 % increment by 2050 set by the UK Climate Change Committee. The highest hedgerow planting and gapping-up rate within AES (1778.8 km yr^{-1} in 2022) was within the same order of magnitude, but four times lower, than the rate needed to reach the planting goal by 2050 (7148.1 km yr^{-1}). Although the rate of planting between consecutive years has been variable, there was a strong increase in planting efforts over the 2019–2022 period, which exhibited the highest planting rates across AES. Although hedgerow restoration via “gapping up” has also contributed to increasing overall managed hedgerow length, further substantial efforts in increasing planting rates are needed. Other major national planting schemes also contributed to hedgerow planting, although to a much smaller degree than AES. These schemes offer greater flexibility than AES and may encourage planting by farmers who are deterred by the bureaucratic aspects of AES (Brown et al., 2020; Westaway et al., 2023). It should be noted that these planting figures do not encompass the entirety of hedges planted in the country. For instance, a recent national survey of 1160 farmers conducted in 2022 found that 60 % of participants had planted hedges in the past 10 years (of which over half had been planted in the last 3 years, which is in line with the increase in hedge planting observed in AES in 2019–2022). Of the total farmers surveyed, 56 % received financial support through AES, or, to a lesser degree, by private schemes, while 44 % contributed to hedge planting through self-funding (CPRE, 2022). Thus, individual farmers and landowners are contributing to national planting efforts outside of public and private sector funded schemes; however, it is not possible to quantify the extent of this contribution.

Our findings show that hedgerow planting and restoration in agricultural landscapes is a tool for climate change mitigation, but depending on the rate at which hedges are planted incrementally over time, their C sequestration benefits are deferred over a longer period, with repercussions for the contribution that hedgerow planting can make to the UK's net-zero targets. At current planting rates, it would take nearly 110 years to plant 193,000 km of hedges. This would result in only 1.03 Tg CO$_2$ being sequestered over the next four decades by AGB, or 2.87 Tg of CO$_2$ being sequestered by AGB and BGB C and SOC stocks. Current annual CO$_2$ emissions from agriculture are estimated at stocks 5.6 Tg yr^{-1} in England (DEFRA, 2019). Thus, our findings indicate that 40 years after planting, the AGB of hedgerows planted within the business-as-usual scenario will have sequestered 18 % of 5.6 Tg CO$_2$, representing an annual offset of 0.5 % (0.03 Tg CO$_2$ yr^{-1}) of agricultural emissions for four decades, or 1.3 % (0.07 Tg CO$_2$ yr^{-1}) when considering AGB, BGB and SOC stocks together. In scenario A, the optimal –but unrealistic– scenario in which the total length of 193,000 km of hedges is planted over the course of one year, we found that it would allow an offsetting potential of 3.96 Tg CO$_2$ in hedge AGB over 40 years, or 13.87 Tg CO$_2$ when considering AGB, BGB, and SOC stock together. This would represent an annual offset of 1.8 % (0.09 Tg

CO_2 yr^{-1}) of agricultural emissions for four decades, or 6.2 % (0.35 Tg CO_2 yr^{-1}) when considering AGB, BGB and SOC stocks together. Planting scenarios B, which is more achievable, as it is based on a planting rate four times higher than current planting rates (7148.1 km yr^{-1}), still offered a notable contribution of hedgerow planting to reaching net-zero goals. Scenario B offered a 4.5 % (0.25 Tg CO_2 yr^{-1}) offset of annual agricultural CO_2 emissions in their total biomass and in the soil for four decades if the planting goal is reached over the course of 27 years, by the end of 2050.

Financial and production factors may hinder progress in increasing hedgerow planting rates from 1778.8 km yr^{-1} to 7148.1 km yr^{-1} and reaching the UK Climate Change Committee goal of a 40 % increase in hedgerow length. The main barriers for farmers and landowners are likely of financial nature, either directly tied to planting costs, or relating to potential income losses. Farmers may be less likely to plant hedgerows if they perceive that current subsidies do not cover a sufficient proportion of hedgerow planting costs. However, the Countryside Stewardship capital grant for hedgerow planting has recently doubled from £11.60 to £22.97 per meter (Rural Payments Agency, 2023), with potential positive outcomes against planting costs barriers. Private sector investment, either with individual supply chain schemes tying hedgerow planting to a guaranteed price for product (e.g. Milk Plan, Biffi et al., 2022), or collaborative initiatives between private and public sector (e.g. Landscape Enterprise Networks, Gosal et al., 2020), may also present opportunities to abate some of the financial barriers to hedgerow planting. Another barrier may be farmer concern for potential loss of land productivity associated with hedgerow planting (CPRE, 2022); however, the UK average grass yield of permanent pasture is estimated to be 8.7 Mg ha^{-1} of (Qi et al., 2018) and planting a 1.5 m wide hedge across a grassland field would equate to a marginal loss of 1.3 Mg of dry matter yield per km of hedge (0.13 metric tonnes every 100 m planted). Importantly, in both grassland and arable systems, new hedges are usually planted around existing field boundaries and over historical hedge boundaries, a requirement that has been made part of recent AES (Rural Payments Agency, 2022). Moreover, a 40 % increment in hedge length would represent only 11 % of existing arable and grassland field boundaries in England without the need to reduce field size (Biffi et al., 2022). Thus, yield loss should not be considered a strong barrier for hedgerow network expansion at the national scale. There may be also barriers related to the supply of hedgerow plant sapling from UK nurseries. The provenance of saplings has been shown to be crucial for the successful development of hawthorn shrubs in the UK, with imported saplings being less successful than native ones (Jones et al., 2001). Assuring local provenance of planted saplings is crucial to maintain expected AGB growth rates and contribute to net-zero goals.

4.5. Limitations and future research

If managed well, hedges remain in the landscape as permanent linear features, which can continue to sequester and store C in their biomass and soil. However, their C sequestration capacity will change over time depending on their age and what stage of the management cycle they are in. The results of this study show that management has an impact on the amount of C sequestered by hedgerows, as young hedges sequester C in their AGB at twice the rate of mature, regularly trimmed hedges (Table 4). We cannot provide a complete timeline of AGB C sequestration by hedgerows, which are typically laid ~20 years after being planted, as our chronosequence does not include an age category of 20 year old hedges. Thus, we do not know how the AGB C stock changed between 12 year old and 39 year old hedges, despite knowing that the 39 year old hedges were laid at 20 years old and were in the process of being laid for the second time at the time of sampling. This gap in our chronosequence has repercussions on the upscaling of our results to assess the impact of hedgerow planting on climate mitigation goals, as we assumed that hedges sequestration rate remained constant at 0.06 Mg C km^{-1} yr^{-1} between 12 year old and 39 year old hedges. In reality, net sequestration will have oscillated between minimal levels in regularly trimmed hedges and maximum levels during periods of fast growth following laying or coppicing. The inclusion of a 20 year old age category for mature hedges would have allowed us to make a more precise estimates of AGB C sequestration changes among hedge life stages and, as a result, more accurate estimates of their climate change potential. However, the results presented in this study represent a substantial improvement of hedge C sequestration estimates over time than previously available.

As we did not sample the root system of hedgerows in this study, we could not account for changes in BGB between age categories or determine how the C sequestration rate of BGB changed with time since planting. The BGB sequestration rate used in our upscaling scenarios is based on a 1 to 1 ratio of BGB to AGB and the annual average sequestration rate of 39 year old hedges. The net annual BGB C sequestration rate of hedgerows likely changes among life stages, with younger hedges accumulating BGB at a faster rate than older ones (Claus and George, 2005). For example, the BGB:AGB of the saplings in this study was 0.57, as the average BGB was 0.612 g and AGB was 1.151 g, suggesting a rapid growth of BGB to reach the BGB:AGB ratio of 1 found in mature hedges. Further research is therefore needed to determine the effective sequestration potential of managed hedgerow root system. Our upscaling scenarios, used the BGB sequestration rate for 39 year old hedges, thus conservatively estimating C sequestration, as potentially higher C sequestration rates by BGB in the first few years after planting were not taken into account.

Our hedgerow planting scenarios for 2050 and 2063 assume that planting rates will remain constant over time. As Fig. 2 shows, this is unlikely to be the case, as planting rates vary over time depending on subsidies availability, as well as on other barriers to planting covered in Section 4.4. As the first 12 years after planting are the ones where most net C sequestration potential resides, fluctuations in planting rates will affect the final sequestration potential of the hedge increment. Moreover, we assumed that planted saplings successfully grew into mature hedges, which, depending on hedge management, might not always be the case, particularly under increased drought conditions in the light of climate change (Neumann et al., 2017; Banin et al., 2022). Scenario A and B represent two possible outcomes of reaching the 40 % increase in hedge length goal, but it will only be possible to calculate total C sequestration retrospectively, once effective planting rates and survival rates are known. It should also be noted that the upscaling figures in this study are based on a conservative hedgerow width estimate of 1.5 m, which is the threshold for ‘favourable condition’ for hedgerows in England (DEFRA, 2007). Mature hedgerows are often wider, for example, the mature hedges in our study were close to 2 m wide (Table 1).

Finally, regular hedgerow management has potential implications on the net C sequestration of hedges at different life stages, as there are CO_2 emissions associated with the use of machinery for trimming and laying hedges. Reducing the trimming frequency from 1 to 2 years to 3 years may decrease some of the costs associated to hedge management, as well as some of the CO2 emissions, while increasing provisioning of food resource for biodiversity (Staley et al., 2012; Froidevaux et al., 2019b). Alternatively, hedges could be managed by coppicing on an approximately 15–20 year time scale for biofuel (Crossland, 2015; Westaway and Smith, 2020), reducing the use of machinery for trimming (although wood-chipping fuel consumption should be considered). Life-cycle analyses of different types of management regimes are urgently needed to provide recommendations on how to optimize hedge management for the preservation of C stock and C sequestration, especially in the light of potential co-benefits or trade-offs for the delivery of multiple ecosystem services by hedgerows.

5. Conclusions

Assessing changes in C stock over time in agroforestry practices, for example as a result of hedgerow planting, is crucial for accurate climate change mitigation modelling and to account for the contribution that woody vegetation in agricultural landscapes can make towards reaching net-zero targets. Increasing hedgerow length has been identified as one of the changes needed to reach net-zero by 2050 in the UK, but to date, we lack information on the rate at which C is sequestered by hedge biomass and, thus, on the climate change mitigation potential associated with hedge planting. This study conducted destructive sampling of managed hedgerows of known ages to determine their AGB C stock and average annual C sequestration rate. We found that AGB C stock increased with hedge age from sapling to mature hedges, and that young hedgerows (≤ 12 years) sequestered on average ~2.0 Mg C ha^{-1} yr^{-1}, while mature, 39 year old hedgerows sequestered 0.86 Mg C ha^{-1} yr^{-1}. We used the change in AGB C stock among age categories and their relative AGB C sequestration rates to estimate the medium and long-term climate change mitigation potential of planting 193,000 km of hedgerows to increase by 40 % the length of existing hedgerows. We found that current planting rates need to increase substantially to achieve this planting goal by 2050. Planting hedgerows at the current rate of 1778.8 km yr^{-1} will sequester by 2063 2.87 Tg CO_2 in hedge aboveground and belowground biomass and in the soil beneath them. However, if planting rates increase to meet the 40 % increment in hedge length goal, depending on the planting scenario, this increment will sequester between 10.13 and 13.87 Tg CO2 in hedge biomass and in the soil over 40 years. This represents between 3.5 and 4.8 times more CO_2 than if current planting rate remains constant over the next 40 years, annually offsetting between 1.5 and 4.5 % of UK annual agricultural CO_2 emissions.

When considering the role that agriculture can play in climate change mitigation, the inclusion of woody species in agricultural landscapes for atmospheric C sequestration cannot be the only contributing factor of the agricultural sector, as GHG emissions reduction, land-use changes, and SOC sequestration in agricultural soils will also be needed to reach agricultural net-zero. However, hedgerows provide a wide range of ecosystem services while occupying a small area of land around agricultural fields, making them a promising option for climate change mitigation and for the delivery of multiple benefits to farmed landscapes.

CRediT authorship contribution statement

Sofia Biffi: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Pippa J. Chapman:** Conceptualization, Supervision, Methodology, Writing – review & editing, Project administration. **Richard P. Grayson:** Conceptualization, Methodology. **Guy Ziv:** Conceptualization, Supervision, Writing – review & editing, Funding acquisition.

Data availability

Data available from the University of Leeds Research Data repository: carbon and nitrogen content (https://doi.org/10.5518/1337), aboveground biomass carbon storage (https://doi.org/10.5518/1338).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Example of a typical managed hedge

Fig. 1. Example of a typical managed hedge in England to indicate the provenance of stem and shoot samples. The permanent hedge biomass is distinguishable from the new growth, which is removed by regular trimming.

Appendix B. Species sampled by age category

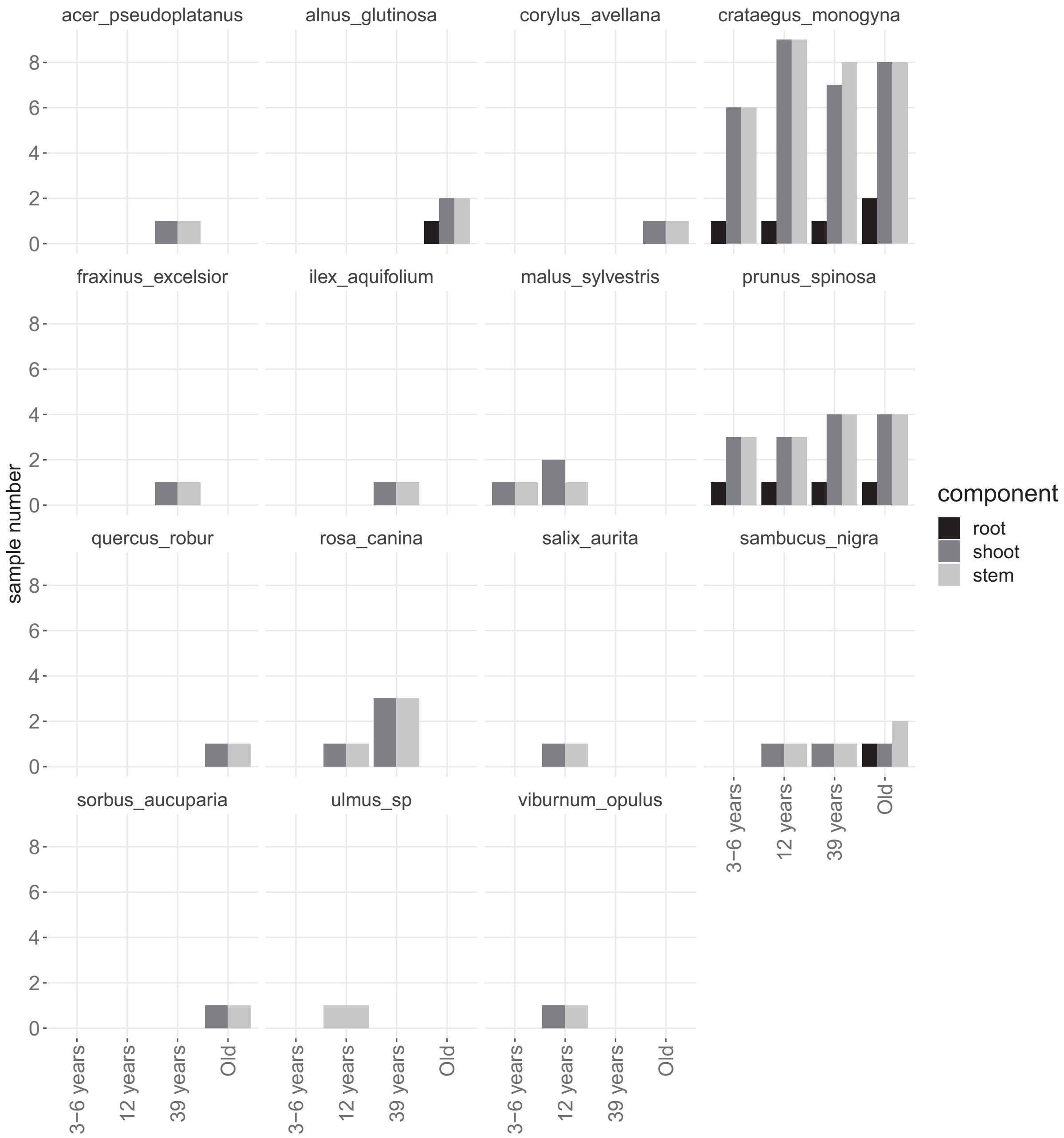

Fig. 1. Number of individual species sampled across the study by hedge age category.

Appendix C. Comparison with previous literature

Table 1
Comparison of our study and other studies with similar species composition that have available data per hedge. AGB C stock density was calculated from available data.

Reference	Country	Species	Sample	Height	Width	Age	AGB C stock	
			(n)	(cm)	(cm)		(kg C m^{-3})	(Mg C ha^{-1})
Own data	England	Hawthorn (*Crataegus monogyna* Jacq.), blackthorn (*Prunus spinosa* L.)	5	100–280	40–170	3–6 years	0.6 (0.2–1.0)	8.3 (3.1–13.6)
			5	120–230	100–130	12 years	1.5 (1.1–1.9)	31.9 (22.5–41.3)
			5	200–330	100–160	39 years		
			5	170–230	100–220	Old	1.6 (1.0–2.2)	36.9 (24.2–49.6)

(continued on next page)

Table 1 (*continued*)

Reference	Country	Species	Sample	Height	Width	Age	AGB C stock	
			(n)	(cm)	(cm)		(kg C m^{-3})	(Mg C ha^{-1})
Crossland (2015)	England	Hawthorn, blackthorn, hazel (*Corylus avellana* L.)	3	350	350–600	Mature	2.57 (−0.5–5.65)	90.0 (−17.6–198.0)
Axe et al. (2017)	England	Hawthorn, blackthorn	3	190–350	260–420	Mature	1.46 (1.28–1.64)	37.3 (32.6–41.9)
Lingner et al. (2018a, 2018b)[a]	Germany	blackthorn, fly honeysuckle (*Lonicera xylosteum* L.), hazel	9	360–990	530–1160	Mature	0.90 (0.27–0.63)	47.7 (39.4–55.9)
Drexler et al. (2021)	Germany	blackthorn, hazel, willow (*Salix* sp.)	49	250–880	100–600	Mature	0.86 (0.13–0.73)	44.9 (36.3–53.5)
Beka et al. (2023)[b]	England	Hawthorn, blackthorn, hazel	15	150–570	n.a.	10–40	n.a.	37.0 (26.8–47.3)

[a] Drexler et al. (2021) calculation from biomass data by Lingner et al. (2018a, 2018b), using 47.5 % C_{con}.

[b] Reported measurements from Westaway and Smith (2020) and a personal correspondence dataset for Crowmarsh Battle Farm.

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