The carbon pool in a British semi-natural woodland

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Summary

A comprehensive, generally non-destructive quantification of carbon in all significant above- and below-ground forest components for five contrasting stands was undertaken in Monks Wood, south-east England. The total carbon content of the five selected stands varied from 346 to 616 t ha^{-1}. The mean carbon content of the forest components was approximately 2 t ha^{-1} for deadwood, 3 t ha^{-1} each for foliage and ground vegetation/litter, 18 t ha^{-1} for understorey shrubs and small trees, 28 t ha^{-1} for all roots, 78 t ha^{-1} for overstorey trees, and 335 t ha^{-1} for soils. The results of this study suggest that if the stands sampled at Monks Wood were representative of broadleaved woodlands in Great Britain and, if understorey vegetation were considered, they would contain 92.6 Mt carbon. This contrasts with a previous estimate of 61.9 Mt carbon, which excluded understorey vegetation. The results highlight the importance of broadleaved woodlands as carbon stores and will be informative to current and future initiatives for developing British woodlands to offset greenhouse gas emissions.

Introduction

Since the beginning of the industrialized era, global atmospheric levels of carbon dioxide have risen from 280 to 367 p.p.m. in 2000 and could reach between 478 and 1099 p.p.m. by 2100 (IPCC, 2000). This increase is attributable to fossil fuel combustion and land-use change such as deforestation. It is with this rationale that the UN Framework Convention on Climate Change recognizes, along with a requirement to reduce carbon dioxide emissions, a need to preserve and enhance the amount of carbon stored in the terrestrial biosphere (UNFCCC, 1997). In particular, Article 3.3 of the 1997 Kyoto Protocol allows changes in stored carbon, due to afforestation and reforestation, to be used to meet targets for net emission reductions.

In Great Britain, woodlands represent a considerable carbon store. Milne and Brown (1997) estimated that, although covering only 11 per cent of the total rural land area (Barr *et al.*, 1993), woodlands may hold as much as 80 per cent of the total carbon contained in British terrestrial vegetation. However, these estimates only considered the carbon contained in the dominant overstorey species. If shrubs and understorey trees were included, it would significantly increase the total store in broadleaved woodlands, as the understorey vegetation can account for as much as 12 per cent of the above-ground biomass (Satchell, 1971).

Several European studies have provided data and methods for estimating biomass and carbon stored in overstorey and understorey trees, litterfall and deadwood of temperate forest ecosystems (i.e. Satchell, 1971; Hamilton, 1975; Swift *et al*., 1976; Cannell, 1982; Vogt, 1991; Matthews, 1993). However, although Satchell (1971) estimated the total biomass of some forest components in Meathop Wood (a woodland similar to Monks Wood in species composition and structure, located in Cumbria, England), there do not appear to be any comparable studies for semi-natural woodlands in Britain where the carbon content for all significant carbon pools, including soil, has been estimated and compiled. This paper presents a comprehensive and mainly non-destructive quantification of carbon in the overstorey, understorey, foliage, roots, ground vegetation/litter (GVL), deadwood and soils of a British deciduous woodland.

Materials and methods

Fieldwork was undertaken in July 2000 at Monks Wood National Nature Reserve, a 157-ha temperate woodland located in Cambridgeshire, UK (52° 24′ N, 0° 14′ W). The dominant tree species are ash *Fraxinus excelsior* L., oak *Quercus robur* L., field maple *Acer campestre* L., elm *Ulmus carpinifolia* Gleditsch. and aspen *Populus tremula* L., while the dominant shrub species are hawthorn *Crataegus monogyna* Jacq., hazel *Corylus avellana* L., blackthorn *Prunus spinosa* L., dogwood *Cornus sanguinea* L., and wild privet *Ligustrum vulgare* L. The majority of overstorey trees are 70–80 years old. The soils are gleyed brown calcareous and surface water gley resting on impervious clay (Hodge *et al*., 1973).

Five contrasting stands were selected, each defined as an identifiable spatial compartment of trees with relatively homogeneous species composition, environmental characteristics and structure. The contrasting stands were chosen to be representative of the diversity of the wood (Table 1). Each stand was divided into 10 equal areas (eight in stand 5) and one sample plot of 20 × 20 m (0.04 ha) was located randomly within each of these areas (Hamilton, 1975). This combined random and systematic sampling was intended to avoid sampling bias due to spatial trends and features (e.g. ridges or depressions).

Vegetation

Monks Wood is a National Nature Reserve and, as such, destructive measurements were prohibited. Therefore, standard forestry mensuration methods for estimating volumes and mass were adopted (Hamilton, 1975). The species and diameter at 1.3 m above ground (diameter at breast height; d.b.h.) were recorded in all plots for all woody stems of 7 cm d.b.h. and above. A total of 2283 trees in 48 plots were measured. Trees were classified as overstorey (d.b.h. ≥ 18 cm), understorey (7 ≤ d.b.h. < 18 cm) or as saplings (d.b.h. < 7 cm). Regression equations from Crockford (1987) were used to estimate the above-ground woody volume of each overstorey tree and total dry mass for all understorey trees. These regressions are based on destructive measurements of dominant species (ash, oak and birch) and a selection of understorey/coppiced trees across Britain. Proxy models were defined for overstorey tree species for which no regressions were available. For birch, aspen and elm overstorey trees, the regression for ash was used. For field maple, regressions for ash and birch were used and the results were averaged. Estimation of dry mass and carbon content was then achieved using conversion factors based on studies conducted in woodlands of similar soil type, vegetation composition, structure, and management to Monks Wood. Table 2 summarizes the methodology and presents the conversion factors.

Foliage dry weights were obtained on a per species basis, as a percentage ratio of the above-ground woody dry weight for the respective species (Satchell, 1971). The mean percentage ratio from oak, ash, birch and sycamore was used as proxy value for both ash and elm, sycamore was used as proxy value for field maple, and hazel was used as proxy value for the understorey, as no values were available for these species or components. Likewise, root dry weights were derived as a percentage ratio of the total above-ground woody dry weight. This conversion factor was derived from Cannell (1982) as the average ratio of roots to total above-ground dry weight of 26 European deciduous woodlands. A 1 × 1 m^2

Table 1: Description of the five contrasting stands in Monks Wood National Nature Reserve

Stand details: total area of similar management within the wood	Vegetation structure and composition	Dry weight (t ha^{-1})
Stand 1: 2.57 ha **Class**: Non-interference **Total non-interference area**: 34.14 ha	**Overstorey**: field maple, oak, ash, well spaced and in equal numbers. **Understorey**: relatively mature consisting mainly of hawthorn, hazel, blackthornand small privet shrubs	271
Stand 2: 3.35 ha **Class**: Non-interference **Total non-interference area**: 34.14 ha	**Overstorey**: field maple, ash, well spaced **Understorey**: hawthorn and hazel	233
Stand 3: 2.83 ha **Class**: Field and glades **Total field and glades area**: 9.00 ha	**Overstorey**: few large trees, mixed composition: aspen, oak, field maple and ash occur at various stages of maturity **Understorey**: large thickets of hawthorn and occasionally blackthorn	148
Stand 4: 3.69 ha **Class**: Woodland **Total woodland area**: 57.89 ha	**Overstorey**: ash and oak, fairly dense and closed canopy **Understorey**: little understorey. Some privet shrubs and occasional hawthorn and hazel	215
Stand 5: 0.84 ha **Class**: Mixed and coppiced **Total mixed and coppiced**: 55.76 ha	**Overstorey**: mostly elms, densely packed, which have escaped Dutch elm disease Understorey: composed of elm saplings. Occasional hawthorn	413
Belgium	Oak 120 years old with coppiced understorey of hazel	384
Former Czechoslovakia	Oak and ash 96 years old, with lime (*Tilia* sp.) and field maple understorey	360
Russia	Oak and ash 48 years old, Norway maple (*Acer platanoides* L.) understorey	261
Russia	Aspen and birch sp. 45–55 years old, some Norway spruce (*Picea abies* (L.) Karst.)	231
United Kingdom	Oak, ash, some birch, varying ages up to 81 years old, hazel understorey	203

The class indicates past treatments applied to the stands (Steele and Welch, 1973). The table also includes the total dry weight (t ha^{-1}) of overstorey, understorey, roots and foliage for all stands in Monks Wood. Dry weight (t ha^{-1}) for woodlands of similar age (70–80 years) and species composition to Monks Wood located elsewhere in the world are also given (Cannell, 1982).

Table 2: Summary of the methodology used for estimating the carbon content of the five stands

Forest components	Species and unit measured	Volumes (m^3)	Conversion to dry weight (DW)	Conversion of DW to carbon content (CC) (%)
			Woody AG DW/ total volume (%)	
Overstorey DBH ≥ 18 cm	Ash[a]	Total AG volume = 0.65002 – 0.063304.DBH^2 + 0.0022603.DBH2 (r^2 = 0.98)[a]	53[b]	49.3[f]
	Field maple	Stemwood volume = 0.48953 – 0.044703.DBH^2 + 0.0014869.DBH2(r^2 = 0.93)		
	Oak	Regressions for ash and birch used as proxy models. Results were averaged	56	50.0
	Birch	Total AG volume = 0.28191 – 0.031727.DBH + 0.0016827.DBH^2 (r^2 = 0.99)	49	49.0
	Aspen	Stemwood volume = -0.064351 +0.00082257.DBH^2 (r^2 = 0.99)		
	Elm	Regressions for ash used as proxy models	53	48.8
	Beech	Regressions for ash used as proxy models	36	49.9
		Regressions for ash used as proxy models	43	50.2
		Total AG volume = –0.2226 + 0.0014153.DBH^2 (r^2 = 0.97)	N.A	N.A
		Stemwood volume = –0.34177 + 0.023826.DBH + 0.00045029.DBH^2(r^2 = 0.99)		
Understorey 7 cm ≤ DBH < 18 cm	All species dealt with as one unit (total BA per plot)	Total AG volume = 14.8 + 6.776. BA (r^2 = 0.96)[a]	DW = 9.59 + 3.522. BA (r^2 = 0.93)[a]	49[g]
			Foliage DW/AG woody DW (%)	
Foliage	Ash	–	2.5[c]	45[h]
	Field maple		3.1	
	Oak		2.9	
	Birch		2.5	
	Aspen		2.7	
	Elm		2.7	
	Hazel		3.7	

Table 2: Continued

Forest components	Species and unit measured	Volumes (m^3)	Conversion to dry weight (DW)	Conversion of DW to carbon content (CC) (%)
			Roots DW/ AG woody DW (%)	
Roots	–	–	28.5[d]	For overstorey trees, see species specific CCs. For the understorey, see understorey CC.
			Deadwood DW/ deadwood volume (%)	
Deadwood	Standing dead tree with crown	Dealt with as either overstorey or understorey depending upon DBH values	26.7[e]	49[g]
	Standing dead tree without crown	Height and DBH used to estimate volume		
	Fallen branches: Mid-diameter ≥ 7 cm	Length and mid-diameter of pieces on the forest floor with mid-diameter ≥ 7 cm recorded per plot and used to calculate volume (Hamilton, 1975). Data for pieces > 3 m in length recorded as 3 m sections		
	Fallen branches: 4 cm ≤ mid-diameter < 7 cm	All fallen small branches, with mid-diameter between 4 and 7 cm counted and subsample used to derive mean dimensions of 5.5 cm diameter and 1 m length. Resulted in a volume of 0.0023m^3 per branch		
GVL	See text	See text	See text	45[h]

All conversion factors are shown to one decimal place only. GVL stands for ground vegetation and litter; DBH for diameter at breast height; BA for basal area; AG for above ground. There are no beech trees in Monks Wood but data required for proxy values. Units for DBH and BA are cm and cm^2, respectively.

Sources: [a] Crockford (1987), [b] Hamilton (1975). No values available for ash. Poplar used as proxy value. [c] Satchell (1971), [d] Cannell (1982). [e] The mean relative density of fallen dead wood obtained in Meathop Wood (Swift *et al*., 1976), [f] Matthews (1993), [g] Birdsley (1990) and Matthews (1993), [h] Ajtay *et al*. (1977) and Vogt (1991).

sample of living ground vegetation (including saplings) was also collected from the centre of each plot, together with all leaf and small woody litter. The sample was cut down to soil level, removed from the plot, air-dried and weighed to estimate dry mass and carbon content. Finally, all deadwood was measured and counted to estimate volume and carbon content.

Soils

Soils are spatially very heterogeneous (Brady, 1990), so spatial variability of both carbon content and bulk density across the plots and through the soil profile may be large. Consequently, a comprehensive study of the soil carbon pools in Monks Wood was beyond the scope of this study. However, a preliminary analysis was conducted which included an estimate of the soil carbon pool to a depth of 50 cm. Thomasson (1971) analysed a soil of the Hanslope series (a soil similar to that of Monks Wood) under pasture-land and showed that carbon content decreases from 5.6 per cent at 0–15 cm depth to 1.0 per cent at 15–51 cm depth. A depth of 50 cm is therefore likely to contain a high proportion of the total carbon. A core of soil to a depth of 50 cm was collected from a random location within each plot using a soil auger of 2.5 cm diameter. The soil core from each plot was oven-dried and 5-g subsamples ignited in a Muffle furnace, with loss on ignition used to calculate carbon content as a percentage of dry weight (Bengtsson and Enell, 1986). The average bulk density of each soil type was calculated from the dry weight and volume of four independent soil cores, each 7 × 50 cm, taken from random locations within each stand. Bulk density was multiplied by the carbon content of each plot sample and the estimates for all plots within a stand were averaged and used to calculate carbon content per hectare to a depth of 50 cm.

Carbon content in British natural deciduous woodlands

Milne (1992) and Milne and Brown (1997) have estimated the total carbon content held in British woodlands using a Forestry Commission census of woodlands (Locke, 1987). Stemwood volumes per species were categorized in 10-year bands of forest age and divided by the equivalent land area. This provided average stemwood volumes per unit area for each age/species group. To convert stemwood volume to complete carbon content of trees (including roots), they estimated carbon density using a factor χ of 0.38 t m^{-3}. This factor was obtained as $\chi = \rho\omega ø$ where ρ is the mean specific density of broadleaved species (0.55 t m^{-3}), ω is the mean ratio of total volume of wood to the stemwood volume (1.5) and $ø$ is the fraction of wood mass which is carbon (0.46). However, this method does not differentiate between broadleaved woodlands with different stand structures, e.g. between plantation/commercial stands and semi-natural or native woodlands. Consequently, to estimate a factor for more natural broadleaved woodlands, results from the study in Monks Wood were used. Stemwood volumes (V_{stem}) and total volumes (V_{tot}) were calculated using the regressions presented in Crockford (1987) (Table 2), from which the mean ratio of total volume (V_{tot}, including roots) to stemwood volume (V_{stem}) was derived. Root volume was derived from above-ground vegetation volume using the proportional relationship between root dry weight and above-ground vegetation dry weight (Table 2). Finally, a factor (χ) to convert stemwood volumes to carbon content was obtained using V_{stem} and the average carbon held in the vegetation of the five stands.

Results

Vegetation and soils

The highest carbon content per hectare, excluding soil, occurred in stand 5 (213 t ha^{-1}) and the lowest in stand 3 (78 t ha^{-1}), with a range of 135 t ha^{-1}. When the soil carbon pool to 50 cm depth is included, the range between the stands increases to 270 t ha^{-1} (Table 3). The quantity of carbon in the soil to a depth of 50 cm was considerably greater than the quantity of carbon in all other forest components combined. Forest components, in order of decreasing mean carbon pool size, were as follows: soils, overstorey wood, roots, understorey wood, GVL, foliage, deadwood. The smallest three carbon pools were approximately equal in size.

Figure 1 shows interval plots for the carbon content of soils; of all components excluding soils;

Table 3: Carbon content of all stand components (t ha^{-1})

	Overstorey			Understorey							
Stand	WAG	Fol	Rts	WAG	Fol	Rts	DWD	GVL	Total	Soils	Total
1	85	2.2	24.3	16	0.9	4.5	0.9	4.6	138	346	484
2	70	1.6	19.9	18	0.6	5.0	1.6	3.1	119	331	450
3	38	1.0	10.9	18	0.6	5.0	2.5	2.3	78	268	346
4	53	1.3	15.1	27	0.9	7.8	1.7	3.4	111	327	437
5	143	3.5	40.7	14	1.7	4.0	3.4	3.1	213	402	616
Mean	78	1.9	22.2	19	0.9	5.3	2.0	3.3	132	335	467

WAG stands for woody above ground; Fol for foliage; Rts for roots; DW for deadwood and GVL for ground vegetation and litter.
All figures rounded to the integer or the first decimal in accordance to the resolution of the measurements.

and of all components excluding soils, roots and foliage. Since only limited destructive sampling was possible, the estimates of carbon are generally based on allometric relationships developed for other woodlands. Hence, quantification of the overall error in the final carbon estimate is not possible. However, confidence limits at the 95 per cent level are given for the carbon content of soils and for the carbon content of all components excluding soils, roots and foliage. No confidence limits are given for the carbon content of all components excluding soils, as root and foliage carbon contents were estimated as functions of other components. These confidence limits are based on the measurements collected at Monks Wood and do not include error introduced from other sources.

Figure 2 is a scatterplot showing above-ground carbon content and soil carbon content for each plot in the stands, along with stand averages (large, black symbols). The results show that at the stand scale, the size of the above-ground carbon pool is strongly correlated with the size of the soil carbon content (0.97, $P < 0.05$). However, when all the plots from all the stands are considered, the correlation is still significant but much weaker (0.34, $P < 0.05$), reflecting the heterogeneity within each stand.

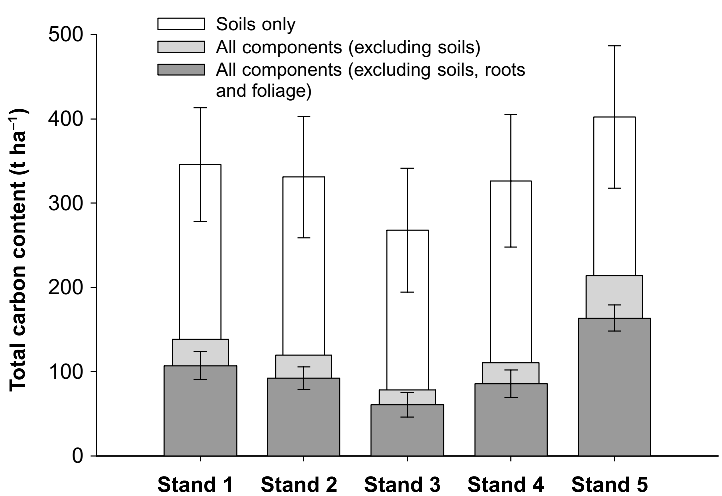

Figure 1. Interval plot showing the carbon content of soils; of all components excluding soils; and of all components excluding soils, roots and foliage (t ha^{-1}).

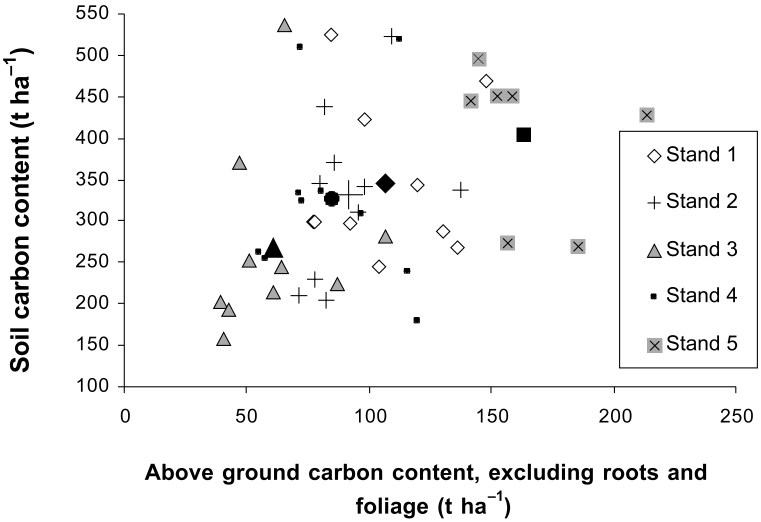

Figure 2. Scatter plot showing above-ground carbon content and soil carbon content for the five stands. Larger, black symbols represent stand averages.

An estimate of the total carbon content of Monks Wood was obtained by weighting the carbon content per hectare per stand to the total area of the wood, falling within the same management class (Table 1). This suggests that Monks Wood contains a total of 79 kt of carbon and 23 kt if soils are excluded.

Carbon content in British natural deciduous woodlands

Finally, the biomass expansion factor for converting stemwood volumes to total volumes and the factor for converting stemwood volumes to carbon content per hectare are presented in Table 4. The mean ratio of total volume to stemwood volume (ω) is 2.12. Considering the overstorey, understorey, foliage, roots, GVL and deadwood components, the conversion factor from stemwood volumes to carbon content (χ) is 0.57.

Discussion

Total dry weights of overstorey, understorey, roots and foliage for stands 1–5 in Monks Wood are generally within the observed range of European dry-biomass figures. However, stand 5 was slightly higher (Table 1). Differences between the dry-biomass estimates of the European woodlands and stands 1–5 reflect not only differences in species composition and age, but also in factors such as stem density, climate, and soil type or fertility.

Comparison of the carbon content and the bulk density of soils in Monks Wood with those

Table 4: Derivation of factors to convert stemwood to total carbon content

Stands	V_{stem}[a] (m^3 ha^{-1})	V_{tot}[a] (m^3 ha^{-1})
1	190	482
2	215	422
3	67	279
4	194	387
5	494	888
Av.	232	492
CC_{tot}[b]	132 t ha^{-1}	
ω	$= V_{tot}/V_{stem} = 2.12$	
χ	$= 0.57$ t m^{-3} (CC_{tot}/V_{stem})	
	$= 0.38$ t m^{-3} (Milne, 1992)	

[a] Includes overstorey and understorey woody volumes (including roots).
[b] Includes all vegetation carbon.

of soils elsewhere show similar results (Table 5). In addition, 232 t ha^{-1} has been estimated as an average carbon content for soils in England and Wales (Milne and Brown, 1997). The results for stands 1–5 fall within these values. Both the Ragdale woodland soil at Melton Mowbray and the Hanslope/Ragdale soil in Monks Wood have a higher average carbon content than the soils under pasture or grass. A woodland soil is expected to have a higher carbon content than a soil on pastureland, due to the transfer of leaf litter and deadwood residues to the soil (Brady, 1990). The Monks Wood soil had a lower carbon content than the Ragdale soil under woodland. Soil type and woodland structure may account for these differences.

According to Cannell and Milne (1995), broadleaved woodlands account for 46.8 per cent of the estimated total 113.8 MtC in British vegetation, despite covering just 4.1 per cent of the total rural land area. Conifers cover 6.1 per cent of the land area, but contain only 25.4 per cent of the total carbon. These figures were calculated on the basis that broadleaved woodlands hold, on average, 61.9 tC ha^{-1} in trees compared with 21 tC ha^{-1} for conifer forests (Cannell and Milne, 1995). The mean carbon content per hectare excluding soils for stands 1–5 in Monks Wood is 132 tC ha^{-1}, about 47 per cent greater than Cannell and Milne's (1995) average for broadleaved woods in Britain. Cannell and Milne's (1995) figures are based on a method (see Milne 1992, also Cannell 1999; Milne and Brown 1997, 2000) which does not include the carbon present in the understorey, deadwood or GVL, as it was designed to estimate the carbon content of commercial woodlands. For stands 1–5 in Monks Wood, these components averaged 30 t ha^{-1}, representing nearly 25 per cent of the total carbon contained in the wood (soil excluded). When the average stemwood volume for stands 1–5 at Monks Wood (Table 4) is converted into carbon content using the Milne and Brown (1997) method, the result is 88.1 t ha^{-1}. This is close to

Table 5: Bulk density and organic carbon content of Hanslope and Ragdale soils in the Melton Mowbray district in Britain (Thomasson, 1971) compared with stand 1 and 4 (bulk density and organic carbon content are also given for separate soil samples taken from stand 1 and 4 which fall into the Hanslope/Ragdale complex at Monks Wood)

Soil type and land-use	Depth (cm)	Bulk density (g cm^{-3})	Carbon content (%)
Ragdale under oak/hazel woodland	0–23	0.8	5.6 (combined)
	23–43	1.2	
	43–66	1.6	
Ragdale under pasture	0–18	1.2	4.3
	18–30	1.3	1.1
	30–56	1.4	NA
Hanslope under pasture	0–15	1.1	5.6
	15–51	1.2	1.0
Hanslope temporarily under grass	0–18	1.3	2.6
	18–33	1.5	0.8
	33–60	1.6	0.7
Stand 1: Hanslope/Ragdale complex	0–50	1.1	5.4
Stand 4: Hanslope/Ragdale complex	0–50	1.1	4.7

The mean organic carbon content was calculated separately from six and four samples each from stands 1 and 4, respectively.
The mean bulk density was calculated from four samples taken from stands 1 and 4.

the average they present for broadleaved trees aged 70–80 years (i.e. the majority of overstorey trees found in Monks Wood) of 76.8 t ha^{-1} but contrasts with our 132 t ha^{-1} average. This indicates that although an ω factor of 1.5 may be appropriate for commercial broadleaved woodlands, where the stemwood volume constitutes a high proportion of the total woody volume; this may not be the case for trees in more natural woodland where understorey trees and shrubs represent non-negligible standing carbon pools. Consequently, information on the proportions of natural and commercial broadleaved woodlands is required to accurately assess how the results of this study might affect estimates of the total stock of carbon in British woodlands.

Conclusion

The results of this study illustrate the importance of Monks Wood and similar woodlands as important carbon reservoirs. If trees are to be grown in the future with the aim of making a long-term contribution to carbon sequestration, then these results support current government policy which encourages the establishment of different types of broadleaved woodland. Plantations plus their products can potentially equal the carbon storage of a mature woodland, but only if harvested timber and their products decay slowly (Cannell and Milne, 1995). Carbon sequestration is an important benefit of broadleaved woodland in addition to their high conservation and aesthetic value.

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