Forest Research

Research Note

The carbon balances of two contrasting forest stands growing in the UK

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The removal of carbon dioxide from the atmosphere by trees is central to current plans to expand forest and woodland cover in the UK and international efforts to mitigate the impacts of climate change. Understanding the carbon balances of different forest types in the UK and how these are impacted by both management and the climate is essential for the development of effective climate change mitigation strategies. This Research Note summarises recent research on the carbon balances of two forest stands: an upland Sitka spruce plantation in Harwood Forest in the northeast of England, and a lowland deciduous oak plantation in Alice Holt Forest in southeast England. Overall total carbon stocks, including tree stems, roots, litter and soils, were higher at the spruce forest compared with the oak forest and soils at the spruce forest contained a larger proportion of the total carbon (62%) compared with the oak site (49%). The evergreen spruce forest remained photosynthetically active all year round, including over the winter period when the deciduous oak forest was leafless. The average overall long-term net ecosystem carbon dioxide uptake was 53% higher at the spruce forest compared with the oak forest. There were also differences between the two sites in the balance between carbon dioxide absorbed through photosynthesis and that lost to the atmosphere via respiration. Annual carbon dioxide emissions from the forest floor were larger at the oak forest compared with the spruce forest, which also accounted for a larger fraction of total ecosystem respiration (67% vs 40%).

Introduction

Continuing international efforts to limit the concentration of greenhouse gases (GHG) in the atmosphere are urgently required if further climate changes, including rises in global temperatures and dangerous changes to weather patterns, are to be avoided. At the national scale, the UK Government has accepted the recommendation of the independent Climate Change Committee and is committed to achieving 'net zero' national GHG emissions by 2050. Achieving this target will require not only further deep cuts in GHG emissions across all sectors, but also active GHG removal from the atmosphere to balance those emissions that cannot be avoided. Increasing the strength of our natural carbon sinks (Box 1) through a range of 'nature-based solutions', such as large-scale tree-planting programmes and peatland restoration, can potentially contribute to the national net zero target (Bradfer-Lawrence *et al*., 2021). Acknowledging this, across the UK, all four governments have set out ambitious plans and strategies to deliver an acceleration in tree-planting rates via The England Trees Action Plan, Scotland's Forestry Strategy 2019–2029, Woodlands for Wales and Forests for our Future in Northern Ireland.

This Research Note uses the case studies of two typical but contrasting managed forest stands to explain key aspects of the carbon balance of woodlands. These case studies are drawn from long-term research at these two woodlands, both of which are managed as commercial plantations. This research is informing the development of forest carbon models to study climate change impacts and to assess the effects of different woodland creation and management options (e.g. Matthews *et al*., 2022). The Research Note is intended as a resource for those involved or interested in woodland and forestry carbon assessments, management and related policy development.

At both forest sites – Harwood Forest and the Straits Inclosure – eddy covariance 'flux towers', along with meteorological and environmental measurement systems, including soil gas exchange chambers, have continually measured, hourly and daily, the uptake and release of carbon dioxide (CO_2) as weather conditions change, enabling seasonal comparisons within and between both sites. These 'flux' measurements have been complemented by periodic manual measurements of tree growth, soil carbon stocks and other variables that enable quantification of the movement of carbon between different components of these contrasting forest stands. Further details of the research on carbon and GHG at these two sites can be found in Wilkinson *et al*. (2016) and Xenakis *et al*. (2021). Here, we quantify the carbon stocks in the trees and other elements of these woodlands, summarise the ecosystem-scale CO_2 exchanges and their component fluxes, including from the soil, and highlight both the similarities and differences in the carbon balances between an evergreen coniferous and a deciduous broadleaved forest growing in the UK's temperate, oceanic climate.

Forest carbon cycle

Forests play a key role in the global carbon cycle, storing carbon in trees, other plants and soils. When carbon uptake from the atmosphere through photosynthesis is greater than that lost by respiration (including decomposition processes), fire or harvest over a year or longer periods, a forest stand is described as a net sink for carbon; conversely, when carbon losses are greater than the net uptake from the atmosphere, a stand is a net source of carbon. Further terminology is provided in Box 1.

Study sites

Harwood Forest is a large area of mostly coniferous woodland in northeast England, lying adjacent to the much larger Kielder Forest and partially within Northumberland National Park. This upland forest covers 3500 ha and was originally moorland used for livestock grazing. Tree planting began on the site in the 1930s, with subsequent harvesting and replanting of mature stands, which are managed on a patch clearfell system. Harwood Forest has been an active research site for the past 20 years; the most recent flux tower was constructed by Forest Research in 2013 in a second rotation Sitka spruce (*Picea sitchensis* (Bong.) Carr.) stand planted in 1973. The stand is situated at 290 m above sea level (asl) on a peat-gley soil and has no understorey. However, those measurements ceased in November 2021 because of the severe damage that Storm Arwen caused to the stand.

The Straits Inclosure is a 90 ha stand of lowland deciduous woodland that forms part of the much larger Alice Holt Forest covering 850 ha of the South Downs National Park in southeast England. The Straits Inclosure was originally part ancient semi-natural woodland and part parkland, but was replanted from 1920 to 1943 using a strip planting approach (with the aim of providing frost protection to the newly planted trees); evidence of these strips can still be seen in current aerial images of the site. As the hub for environmental research in Alice Holt Forest, the Straits Inclosure has been the site of numerous research projects over many years. In addition to the detailed measurements summarised here, the Straits Inclosure combines both an International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) Level II long-term forest monitoring plot and is also part of the Alice Holt Forest component of the UK

Box 1 Key definitions and meanings of terms used in forest carbon research

Autotrophic Respiration (RA): the rate of CO_2 lost by trees and other plants above and below ground due to respiration.

Brash mats: small logs and branches that are laid in tracks to minimize soil disturbance and compaction that could otherwise occur due to repeated trafficking by heavy machinery.

Carbon flux: the rate of exchange of carbon between different components, or in and out of a set of pools, such as those comprising a forest stand or woodland. Fluxes are usually expressed as mass change per unit ground area per unit time (e.g. t CO_2 ha^{-1} y^{-1}).

Carbon pools: the different components of the system.

Carbon sink and sources: a carbon sink is any system that causes a carbon transfer from the atmosphere to the system, and a carbon source is one that releases it. A net sink is one that absorbs more carbon from the atmosphere than it emits. A growing forest stand is normally a net carbon sink, but there are situations when forests can become a net carbon source (e.g. through harvesting, deforestation or fire).

Carbon stock: the amount of carbon in the system or its components at a given time, such as within biomass, soil, deadwood or litter. It is usually defined as mass of C per unit land area (e.g. t C ha^{-1}).

Eddy covariance 'flux towers': Eddy covariance is a micrometeorological method used to determine the rate of exchange of trace gases and energy between ecosystems such as forest or agricultural fields and the atmosphere.

Gross Primary Productivity (GPP): the total rate of CO_2 taken up by plants from the atmosphere through photosynthesis.

Heterotrophic Respiration (RH): the rate of CO_2 lost by animals and microorganisms. In terrestrial ecosystems, this includes CO_2 emitted by soil and litter organisms.

Net Ecosystem Exchange (NEE): the net rate of exchange of CO_2 between an ecosystem and the atmosphere. NEE is usually defined as negative when CO_2 is removed from the atmosphere (NEE = Reco – GPP).

Net Ecosystem Productivity (NEP): is equal to the opposite sign of NEE (NEP = –NEE, or = GPP – Reco).

Net Primary Productivity (NPP): refers to the net uptake of carbon into plant tissues, such as woody stems, leaves, roots and seeds (NPP = GPP – RA).

Soil gas exchange chambers: enclosures that sit on the soil surface used to measure changes in the concentration of trace gases over short periods, therefore enabling the exchange or flux from or into the soil to be calculated.

Total Ecosystem Respiration (Reco): the sum of all autotrophic and heterotrophic respiration rates in the ecosystem (i.e. Reco = RA + RH).

Yield Class (YC): an index used in Britain of the potential productivity of even-aged stands of trees. It is based on the maximum mean annual increment of cumulative timber volume achieved by a given tree species growing on a given site and managed according to a standard management prescription. It is measured in units of cubic metres per hectare per year (m^3 ha^{-1} yr^{-1}).

Note: to convert from stock or flux units of C to units of CO_2, multiply by 44/12 (the ratio of their molecular weights).

Environmental Change Network. This stand is situated 80 m asl, on a surface-water gley soil, which is 80 cm deep and overlies Cretaceous clay. Among the tree species present, *Quercus robur* L. predominates, with some *Fraxinus excelsior* L., *Quercus petraea* (Matt.) Liebl. and *Quercus cerris* L.; a few small groups of *Cryptomeria japonica* (L.f.) D.Don. are also present. In contrast to the Harwood Forest stand, a varied shrub understorey of *Corylus avellana* L. and *Crataegus monogyna* Jacq. occurs, with a ground flora of herbs, grasses, tree seedlings, brambles, roses and honeysuckle also present in patches. Regular thinning is carried out approximately every ten years in different parts of the Straits Inclosure to promote and enhance the composition of native tree species. Since 2007, the thinning operations at the Straits Inclosure have been carried out in the eastern and western half separately (Wilkinson *et al.*, 2016).

Both Harwood Forest and the Straits Inclosure (Figure 1) are managed by Forestry England as part of the nation's forests; their main site characteristics are summarised in Table 1.

Methods

Biometric surveys have been carried out at both sites using established mensuration techniques for stand characteristics such as tree height, tree girth and crown size within plots of a known area. Where these measurements have been repeated over time, they can be used to quantify changes in different above-ground carbon pools.

Soil sampling has been carried out at various times across both stands to assess soil carbon stocks. Samples have been taken using an auger, to allow the different soil horizons to be distinguished and separated and the carbon content determined. At the Straits Inclosure, as part of the ECN protocols, an in-depth soil sampling and profile description has been carried out every 20 years, with less comprehensive soil characterisation carried out every five years. These surveys cover the major elements found in the soil that are important for tree nutrition, as well as the carbon content, particle size distribution, mineralogy and bulk density. Litterfall and litter

Figure 1 Towers from the ground and instruments at the top at (a) Alice Holt Forest in Hampshire and (b) Harwood Forest in Northumberland.

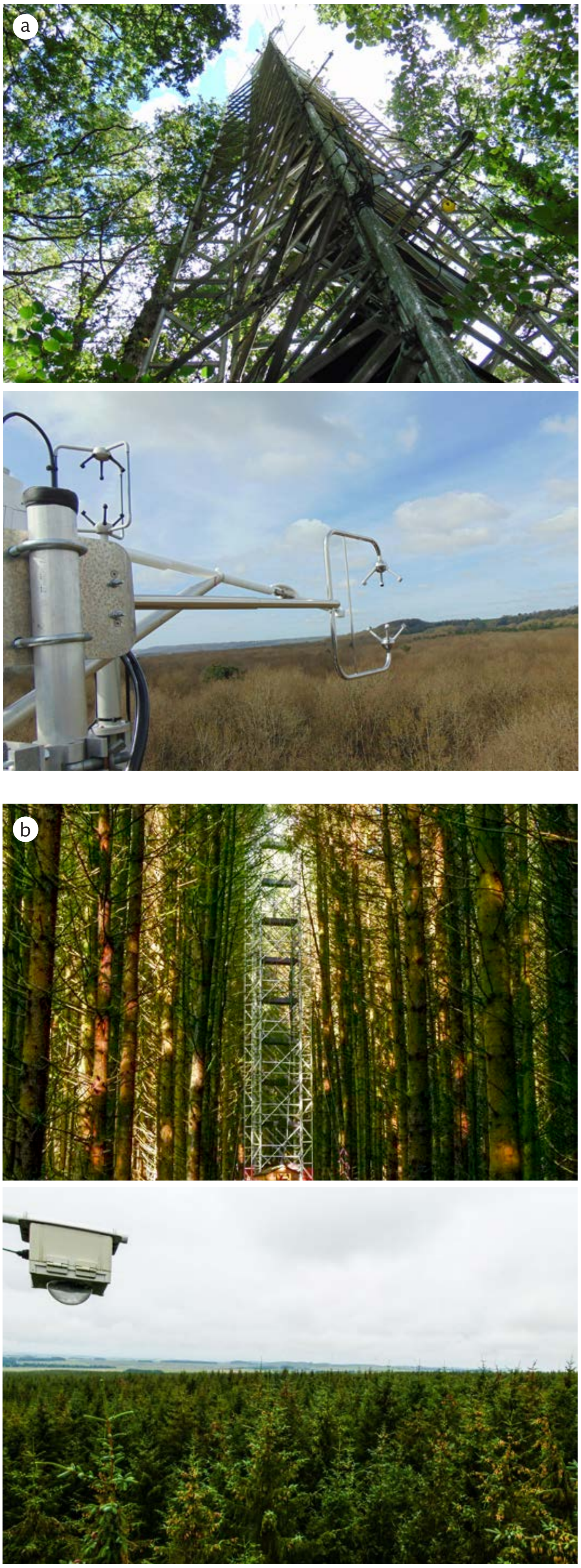


Table 1 Main characteristics of the research stands.

	Alice Holt Forest, the Straits Inclosure	Harwood Forest
Location (latitude and longitude)	51°07′N, 0°51′W	55°10′N, 02°3′W
Region	SE England	NE England
Main tree species	*Quercus robur* >85%	*Picea sitchensis*
Elevation (m above sea level)	80	290
Stand height (m)	22	26^{A}
Tree density (stems/ha)	275 (East) 300 (West)	1348
Understorey	Coppice of *Corylus avellana* and *Crataegus monogyna*	None
Ground flora	Herbs and grasses	Little or none, some mosses
Planting year	1920–1943	1973
Mean peak Leaf Area Index (m^2/m^2)	5.1	5.7
Soil type	Surface water gley	Peaty-gley
Mean annual air temperature (°C)	9.9^{B}	7.6^{B}
Mean annual precipitation (mm)	798^{B}	904^{B}

Measured in: A 2018; B 1981–2011.

decomposition is also an important component of forest carbon cycles and is one of the main pathways of nutrient fluxes and carbon into the soil. Litterfall therefore has a strong influence on both organic soil carbon stocks and on forest floor CO_2 fluxes. Detailed assessments of litterfall were made at both sites using standard protocols (ICP Forests Manual [icp-forests.net]). In brief, litter was collected periodically from conical shaped traps with a collecting surface area of 0.3 m^2 and at a height of 1.5 m at both sites. Litter falling into these traps was separated into the different fractions, and the dry weights of all fractions, as well as the leaf surface area, were measured. The carbon stocks in various components of deadwood (coarse woody debris, stumps, standing dead trees) have also been assessed at the Straits Inclosure (e.g. Tenner, 2013).

The net exchange of CO_2 between the forest ecosystems and the atmosphere has been continuously measured at both sites using the eddy covariance technique, using instruments mounted within and above the forest canopy on towers. This is now a standard approach for measuring landscape-scale CO_2 exchange and is used across a range of different ecosystems around the world. The tower-based eddy covariance measurements commenced in 1999 and 2013 at the Straits Inclosure and Harwood Forest, respectively.

Two different soil gas flux chamber designs have been used, 'static' and 'dynamic', both of which use measurements of changes in the concentration of CO_2 in the chambers over a short period of time to calculate the gas flux. At the Straits Inclosure, chamber measurement was also adapted to measure the CO_2 released from tree stems.

Results

Tree carbon stocks

Across all types and ages of UK woodland, the calculated average tree carbon stock is 81 t C ha^{-1}, and the total average carbon, including soils, is 356 t C ha^{-1} (Morison & Matthews, 2023). Periodic biometric surveys at both sites enabled a comparison between these stands and with the UK averages. Biomass expansion factors, based on established allometric relationships between diameter at breast height and above-ground and below-ground biomass (AGB and BGB, respectively), were used with timber density values and C fraction to estimate C stocks (Table 2).

Despite Sitka spruce having a lower timber density than oak (e.g. 0.33 vs. 0.56 t m^{-3}; Morison *et al*. 2012, Appendix 4), the much higher stocking density and total basal area of the conifer stand resulted in higher tree AGB carbon stocks (122.2 t C ha^{-1}) at Harwood Forest compared with both the eastern (77.1 t C ha^{-1}) and western (83.9 t C ha^{-1}) sectors of the Straits Inclosure. These estimates for the Straits Inclosure are lower than those given previously by Morison *et al*. (2012), who reported AGB and BGB tree carbon stocks at the Straits Inclosure of 95 and 38 tC ha^{-1}, respectively. However, the figures presented in Morison *et al*. (2012) included areas that had not been thinned for >20 years and, since then, substantial thinning operations have been carried out (e.g. in 2007 and 2019: East; and in 2014 and 2021: West), resulting in a lower tree stocking density.

Table 2 Tree measurements data and carbon stocks.

	Straits Inclosure East	Straits Inclosure West	Harwood Forest
Year	2020	2015	2018
Tree density (tree ha^{-1})	275	300	1 348
Mean DBH (cm)	26	30	24
Timber (t C ha^{-1})	50.4^{A}	57.6^{A}	88.1^{B}
AGB (t C ha^{-1})	77.1^{A}	83.9^{A}	122.2^{B}
BGB (t C ha^{-1})	23.4^{C}	31.8^{C}	61.0^{B}
Total tree stock (t C ha^{-1})	**100.5**	**115.8**	**183.2**

AGB, above-ground biomass; BGB, below-ground biomass; DBH, diameter at breast height.

Note: totals include dead standing trees.

A Estimated from plot measurements and relationships established by E. Casella from destructive tree sampling in 2009.

B Estimated from allometric relationships derived for Sitka spruce (Xenakis, pers. comm., 2022).

C Estimated from McKay *et al*. (2003).

Large areas of the Straits Inclosure have a well-developed shrubby understorey dominated by hazel with some hawthorn present, although past management has resulted in it being highly diverse. The carbon stocks in different components of the hazel understorey, including shoots, stools and coarse roots, were estimated to be 7.7 t C ha^{-1}, with 70% (5.39 t C ha^{-1}) allocated above ground and the remaining 30% (2.31 t C ha^{-1}) below ground (Hasegawa, 2011). While we do not have detailed measurements for the lying deadwood component from Harwood Forest, Tenner (2013) estimated lying deadwood carbon stocks (standing deadwood is included in the tree measurement data) at the Straits Inclosure to be 25.8 t C ha^{-1} in unthinned areas and 4.1 t C ha^{-1} in parts of the forest that had been recently thinned. However, it is likely that the values from the recently thinned areas are a considerable underestimate because they did not include the carbon stocks in the brash mats used for the machinery movements that were left behind after thinning.

Soil and litter carbon stocks

Over the past 15–20 years, several studies have measured both soil and litter carbon stocks at or close to these two forest sites. At the Straits Inclosure, repeat soil surveys have been carried out as part of the ECN set of core measurements. From 1994 to 2009, mean carbon stock to a depth of 20 cm was 65.7 t C ha^{-1} (Benham, Vanguelova and Pitman, 2012), excluding the litter and fermentation layers. This is in close agreement with a more recent study conducted by Ražauskaitė (2019), who sampled additional areas of the Straits Inclosure, to the same protocol and depth, and reported a mean carbon stock of 67.2 t C ha^{-1} (Table 3). Carbon stocks contained in the litter and fermentation layer are typically 16.9 t C ha^{-1} (Morison *et al*., 2012). Although we do not have detailed contemporaneous soil and litter carbon stock measurements from the Harwood Forest tower site, other researchers have carried out soil sampling campaigns across the wider Harwood Forest and surrounding areas on similar soil types to the tower site. For example, Zerva and Mencuccini (2005) investigated changes in the carbon stocks across a range of different aged stands within Harwood Forest. They estimated the total soil and litter carbon stocks of a 30-year-old, second rotation Sitka spruce stand (18 years younger than the tower site stand) to be 249 t C ha^{-1} to a depth of 45 cm (Table 4). Swain *et al*. (2010) sampled one profile at the tower site and

Table 3 Comparison of soil carbon stock estimates for the Straits Inclosure.

Depth (cm)	1994	1999	2004	2009	Depth (cm)	2016 (t C ha^{-1})
	(t C ha^{-1})					
0–5	24.3	22.9	22.8	27.4	0–20	67.2
5–10	18.5	17.8	18.5	16.8	20–40	34.1
10–20	26.1	15.6	27.0	25.1	∑0–40	101.3
∑0–20	68.9	56.3	68.3	69.3	40–60	19.5
20–30	18.2	17.6	18.1	16.4	60–80	11.2
					80–100	5.8

Note: 1994–2009 data from Benham, Vanguelova and Pitman (2012) and 2016 data from Ražauskaitė (2019); neither of these studies included litter or fermentation layers.

Table 4 Comparison of soil carbon stock estimates for Harwood Forest.

Depth (cm)	2000/01 (t C ha^{-1})	Depth (cm)	2010 (t C ha^{-1})	Depth (cm)	2015 (t C ha^{-1})
0–7	27.7	0–10	120.3	0–20	234.2
7–21	173.3	10–20	144.4		
∑0–20	192.8	∑0–20	264.7		
21–45	48.4	20–30	11.5		
		30–45	155.7		
∑0–45	249.4	∑0–45	431.9		

Note: 2000/01 data from Zerva and Mencuccini (2005), and includes litter 2010 data from Swain *et al*. (2010) and 2015 data from Morison (pers. comm., 2021).

estimated the soil carbon stocks to be 432 t C ha^{-1} to a depth of 45 cm. Vanguelova *et al*. (2019) carried out an extensive survey of soil carbon stocks on peaty-gley soils in the wider Kielder forest, including both first and second rotation Sitka spruce plots. In their three 40-year-old, second rotation plots, total soil and litter carbon stocks were estimated to be 319 t C ha^{-1} down to a depth of 50 cm.

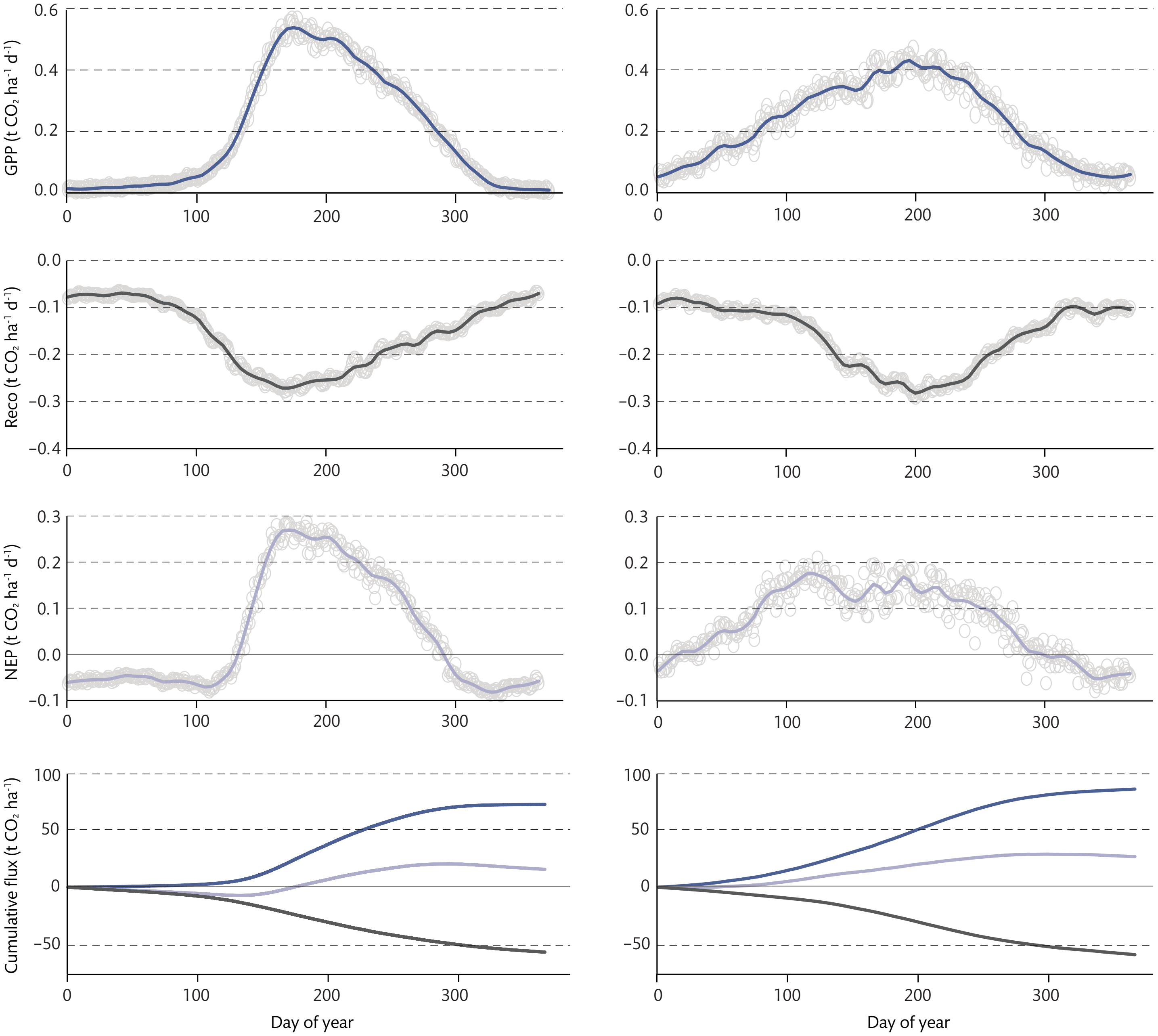
Ecosystem-scale CO_2 fluxes

The eddy covariance systems provide an integrated measure of the net exchange of CO_2 between the forest ecosystem and the atmosphere. Net ecosystem productivity (NEP) is the difference between the rate of CO_2 absorption by the forest through photosynthesis or gross primary productivity (GPP), and the rate of release by the respiration and decomposition processes within the forest ecosystem which is known as total ecosystem respiration (Reco), including soil, litter, deadwood, microbes and animals. Although neither GPP nor Reco can be measured directly, they can be derived from the NEP data using daytime and night-time differences and are important in understanding the magnitude and timing of processes affecting the carbon balances of these two contrasting forest sites. The annual pattern for each of these different CO_2 flux components for both sites, averaged for each day across several years, is shown in Figure 2. These CO_2 fluxes were the integrated response across large areas of each forest, typically hundreds to many thousands of square metres, depending on weather conditions. GPP is largely determined by the seasonal availability of solar energy, while Reco is mainly determined by the seasonal changes in air and soil temperature.

In general, for all the component CO_2 fluxes, the Straits Inclosure oak stand displayed a stronger annual cycle compared with the Harwood Forest spruce stand. In the deciduous oak stand, large seasonal differences occurred in these flux components, with rapid between-season changes. GPP only started to increase once the leaves of the understorey vegetation began to develop, which was then followed by the development of the tree canopy. GPP declined when the canopy senesced in autumn, so that there was no GPP in the winter (December, January and February). By contrast, the seasonal differences in the CO_2 flux components were smaller for the evergreen spruce stand. It is notable that the spruce stand remained photosynthetically active (i.e. there was some GPP) all year round (top panels in Figure 2), including over the cold winter period, with a gradual rise in the spring and early summer as the amount of solar radiation increased.

Peak summer photosynthetic activity occurred earlier at the oak stand (approximate day of year 170) than at the spruce stand (approximate day of year 200). Differences between the two stands were therefore evident in the NEP fluxes (third panels from top in Figure 2), with a stronger seasonal cycle for oak than spruce. The oak stand was a weak net source of CO_2 from early November to the end of April when Reco was the dominant component flux. In the spruce stand, photosynthesis during the winter, although low, combined with low rates of Reco due to cool conditions, resulted in a long net CO_2 uptake period from mid-February to early November. The average summer peak net daily uptake was slightly higher at the oak site (~ 0.3 t CO_2 ha^{-1} d^{-1} or 0.08 t C ha^{-1} d^{-1}) than at the spruce site (~ 0.22 t CO_2 ha^{-1} d^{-1} or 0.06 t C ha^{-1} d^{-1}). This is likely to be a result of the warmer conditions, combined with higher levels of sunlight in the south of England compared with Northumberland. The spruce forest also experienced moisture stress during the hot dry summer of 2018, when soil moisture levels at 10 cm depth were around 16% from June to September compared with the more usual 25–40%, which will have affected the average values shown. By contrast, the hot dry summer of 2018 did not affect the oak stand as severely, in part because of the

Figure 2 Average annual time course of Gross Primary Productivity (GPP), Ecosystem Respiration (Reco) and Net Ecosystem Productivity (NEP) for Alice Holt Forest (left columns) and Harwood Forest (right columns). The bottom panels show cumulative carbon dioxide (CO_2) fluxes for each component averaged over 21 years for Alice Holt Forest and 5 years for Harwood Forest, with the same colours as the above graphs.



deep clay soil and deeper rooting of the oak trees. Overall, the stand-scale CO_2 flux measurements showed that the average annual cumulative NEP (the end point of the light blue line in the bottom graphs in Figure 2) was higher at the spruce site (26.4 t CO_2 ha^{-1} y^{-1} or 7.2 t C ha^{-1} y^{-1}) than at the oak forest (15.4 t CO_2 ha^{-1} y^{-1} or 4.2 t C m^{-2} y^{-1}) (Table 5).

Table 5 Average annual CO_2 fluxes from the Straits Inclosure oak and Harwood Forest spruce stands.

	Straits Inclosure 1999–2018	Harwood Forest 2015–2018	Straits Inclosure: Harwood Forest ratio
GPP (t CO_2 ha^{-1} y^{-1})	71.4 ± 1.9	84.6 ± 2.6	0.84
Reco (t CO_2 ha^{-1} y^{-1})	55.9 ± 1.5	58.2 ± 2.0	0.96
Reco:GPP	0.78	0.69	1.13
NEP (t CO_2 ha^{-1} y^{-1})	15.4 ± 1.0	26.4 ± 7.7	0.58

CO_2, carbon dioxide; GPP, gross photosynthetic productivity; NEP, net ecosystem productivity; Reco, total ecosystem respiration.
Note: ± represents the standard error of the mean.

Components of total ecosystem respiration

Reco comprises several different CO_2 sources, both above and below ground. The substantial flux of CO_2 from the forest floor into the atmosphere is a mixture of the below-ground components of plant respiration (RA) and microbial and animal respiration (RH), which includes that from the decomposition of soil organic matter and litter on the surface. The mean annual cycle of CO_2 released from the forest floor in both stands is shown in Figure 3 (left panel). Forest floor CO_2 fluxes from both stands displayed a similar seasonal pattern, with lower rates over the cooler winter period and higher emissions over the warmer summer months (June–September) when the plants are metabolically more active and soils are at their warmest. Within this seasonal pattern, the fluxes were consistently higher in the oak stand, probably because of generally warmer soil temperatures combined with relatively large amounts of annual litter input from the deciduous trees and shrubs. On average, the annual cumulative forest floor CO_2 fluxes (Figure 3, right panel) were larger at the Straits Inclosure, which had an estimated total flux of 37.5 t CO_2 ha^{-1} y^{-1} (average for 2013–2020), making up approximately 67% of the total Reco compared with Harwood Forest, which had an estimated total flux of 23.5 t CO_2 ha^{-1} y^{-1} (2015–2018), 40% of the total Reco.

Earlier work at the Straits Inclosure (Heinemeyer *et al*., 2012), measuring different components of soil and forest floor CO_2 fluxes, showed that the heterotrophic respiration, including the litter and soil organic matter decomposition, contributed approximately 44% to the total forest floor CO_2 flux. Information about the different components of soil and forest floor CO_2 fluxes is not available from the Harwood Forest site. In a comparable study, across eight afforested peatland sites in southwest Ireland (Jovani-Sancho, Cummins and Byrne, 2018), heterotrophic respiration, including soil organic matter and litter decomposition, was estimated to have contributed approximately 55% to the total soil CO_2 flux.

Tree stems also act as a net source of CO_2 to the atmosphere, emitting CO_2 produced within the stem tissues, roots and soil, and transported in stem sap flow. To quantify the size of this flux and its contribution to the overall Reco, a limited measurement campaign was carried out at the Straits Inclosure from July 2014 to October 2015, using a chamber strapped to the side of each tree. These measurements were carried out on trees across a range of sizes at a height of 1.5 m above the ground. The mean annual CO_2 flux emitted by the oak tree stems was 1567 g CO_2 m^{-2} of stem surface area per year, similar to the rates of 1107 ± 832 and 2079 ± 1246 g CO_2 m^{-2} y^{-1}, respectively, from mature beech forests in Germany and the Czech Republic (Maier *et al*., 2018), thus providing confidence in these measurements. Although we do not have similar measurements from the Harwood Forest spruce stand, where comparable measurements have been made in other coniferous forests, the rates of stem CO_2 emissions were slightly lower than our measured rates at the Straits Inclosure. For example, Darenova *et al*., (2020) reported a mean rate of stem CO_2 emissions of 1242 g CO_2 m^{-2} of stem surface area per year from a Norway spruce (*Picea abies* (L.) Karst) forest located 875 m asl in the Czech Republic. To estimate the contribution of stem CO_2 losses to the total Reco flux for each forest (Table 6), we assumed that the flux did not vary with height and estimated the tree stem surface area per hectare from the biometric survey data, assuming that the tree stems were cone shaped.

These assumptions are likely to overestimate the stem CO_2 flux per individual tree, as declines with height have been found in some studies (e.g. Acosta *et al*., 2008). Conversely, we are not

Figure 3 Average annual time course of forest floor carbon dioxide (CO_2) fluxes for Alice Holt Forest and Harwood Forest (left panel) and average cumulative forest floor CO_2 fluxes (right panel). Blue lines are data from Alice Holt Forest, while the black lines are for Harwood Forest. Open circles in the left panel are monthly sums interpolated from intra-monthly measurements; the lines in the left panel are a fitted local polynomial regression.

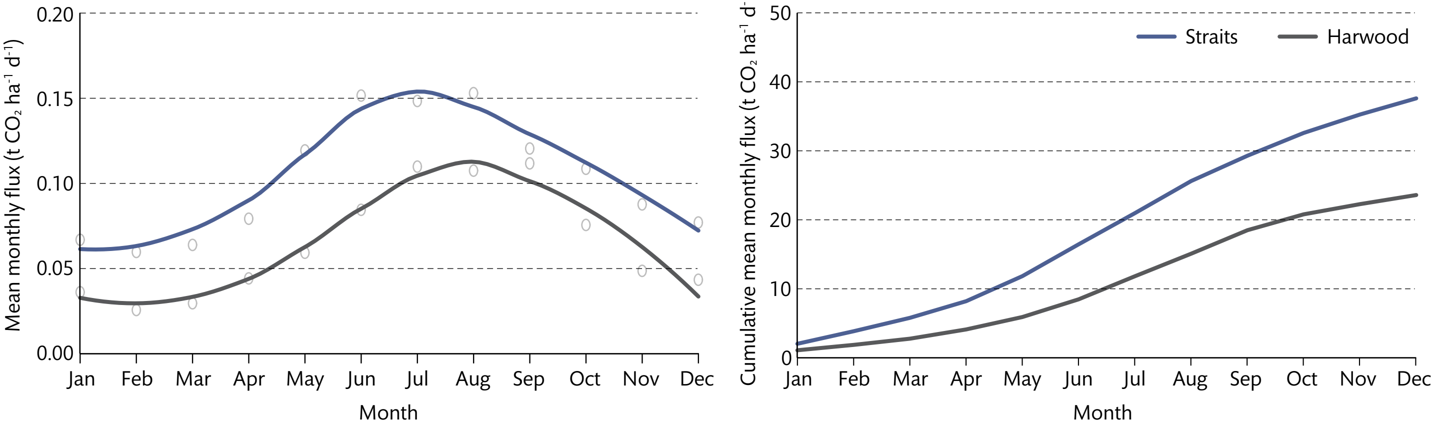


Table 6 Tree stem CO_2 fluxes.

Site	Mean DBH (cm)	Assumed stem height (m)	Tree density (trees ha^{-1})	Stem surface area (m2 ha^{-1})	Stem emissions (t CO_2 ha^{-1} y^{-1})	% of annual total Reco
Harwood Forest*	24	26	1 348	13 278	16.5	27.2
Straits Inclosure East	26	22	275	2 486	3.9	6.9
Straits Inclosure West	30	22	300	3 132	4.9	8.7

CO_2, carbon dioxide; DBH, diameter at breast height; Reco, total ecosystem respiration. *Estimated using stem emission rate values from the literature.

including any emissions from branches that represent a larger area in the oak stand than the conifer, nor are we including the contribution from the understorey shrub stems. Thus, it is likely that the stem emissions component in the Straits Inclosure is larger than this estimate. Despite lower assumed rates of stem CO_2 flux, the higher stem density at Harwood Forest resulted in a larger estimated release of CO_2 compared with the Straits Inclosure and a higher estimated proportion of total Reco emissions from the forest.

Forest litter

In forests, litterfall is a key process for the cycling of carbon and nutrients. The total amount of carbon that accumulates and is stored in the litter layer depends on the quantity and decomposition rate. Rates of carbon input to the forest floor from canopy litterfall were measured at both sites over several years using litterfall traps; the results are shown in Tables 7 and 8.

Table 7 Annual forest floor litter inputs for Straits Inclosure.

	2017 dry weight (g m^{-2})	2018 dry weight (g m^{-2})	2019 dry weight (g m^{-2})	Carbon content^{B} (%)	Average dry weight (g m^{-2})	Average carbon flux (t C ha^{-1} y^{-1})
Oak leaves	396.5	321.7	390.5	47.3	369.6	1.75
Twigs	126.0	103.9	395.7^{A}	47.7	313.0	1.45
Frass	91.7	68.1		50.2		
Oak buds and flowers	38.1	31.2		46.8		
Acorns	2.3	69.3		46.8		
Ash keys	1.5	11.2		47.2		
Hazel leaves	90.8	63.6	87.4	47.3	80.6	0.38
Ash leaves	11.4	8.6	60.5	47.3	26.8	0.13
Total annual litter flux	**758.3**	**677.6**	**934.1**	**–**	**790.0**	**3.75**

A Twigs, oak buds and flowers, acorns and ash keys, were not analysed separately in 2019. B Carbon content from Ma *et al*. (2018).

Table 8 Annual forest floor litter inputs for Harwood Forest.

	2014 dry weight (g m^{-2})	2015 dry weight (g m^{-2})	2016 dry weight (g m^{-2})	Carbon content^{A} (%)	Average dry weight (g m^{-2})	Average carbon flux (t C ha^{-1} y^{-1})
Needles	182.3	527.4	181.5	53.1	297.1	1.58
Flowers	20.9	1.7	–	53.9	11.3	0.06
Twigs and frass	25.0	79.9	94.9	53.3	66.6	0.35
Budscales	–	3.8	22.4	53.7	13.1	0.07
Cones	–	155.6	94.6	51.9	125.1	0.65
Total annual litter flux	**228.2**	**768.4**	**393.4**	**–**	**463.3**	**2.71**

A Carbon content from Ma *et al*. (2018).

Mean annual litter inputs from the forest canopy to the soil surface were 3.75 t C ha^{-1} y^{-1} at the Straits Inclosure (2017–2019) and 2.71 t C ha^{-1} y^{-1} at Harwood Forest (2014–2016), with foliage in the form of oak leaves and spruce needles making up the largest single component of total litter (46.7% and 58.3%, respectively).

Generally, litter inputs from conifers are smaller than for deciduous forest species (e.g. Neumann *et al*., 2018), as found here, and our estimates are comparable with previously published values of litter inputs into similar forest types. For example, Zerva *et al*. (2005) estimated total carbon input to the soil surface from litterfall in a first rotation 40-year-old Sitka spruce stand, close to the current Harwood Forest tower site, at 1.9 t C ha^{-1} y^{-1}. The long-term mean (2002–2020) litterfall at the Coalburn Level II Forest monitoring plot, a Sitka spruce plantation on an organo-mineral soil approximately 35 km southwest of Harwood Forest, was 3.1 t C ha^{-1} y^{-1} (SE = 0.76) (Benham, pers. comm., 2022). At the Straits Inclosure, Neumann *et al*. (2018) reported mean annual litter inputs of 3.41 t C ha^{-1} y^{-1} from the Level II forest monitoring plot approximately 450 m northwest of the flux site. Annual litter inputs to the forest floor were therefore equivalent to approximately 37% and 42% of the annual CO_2 flux from the forest floor at the Straits Inclosure and Harwood Forest, respectively.

Dissolved organic carbon

Carbon can also be lost from forest soils in solution as dissolved organic carbon (DOC). Soil DOC fluxes have been regularly assessed at the Straits Inclosure in the nearby Level II plot. These DOC fluxes for a mineral soil with a low C content are very small; for example, Benham, Vanguelova and Pitman (2012) reported a DOC flux of approximately 1 kg C ha^{-1} y^{-1} (or 3.7 kg CO_2 ha^{-1} y^{-1}) for the A and B soil horizons combined. We do not have contemporaneous measurements from the Harwood Forest stand, but where comparable measurements have been made in other coniferous forests on similar organo-mineral soils, the DOC fluxes are much larger. For example, Vanguelova *et al*. (2019) reported a DOC flux of approximately 60 kg C ha^{-1} y^{-1} (or 220 kg CO_2 ha^{-1} y^{-1}) at the Coalburn Level II forest monitoring plot (see above). While annual fluxes from organo-mineral soils such as at Coalburn and Harwood Forest are larger than on a mineral soil at the Straits Inclosure, they are still only very small (<1%) relative to the cumulative forest floor CO_2 efflux.

Conclusions

Forest type, species composition, soil type and management history all have major influences on the carbon stocks held within different components of forests and on the magnitude of the fluxes between those components. Drawing on a variety of sources, including our own original research and previously published literature, this Research Note has summarised recent research on the carbon balances of two contrasting forest stands, an upland Sitka spruce plantation in northeast England and a lowland deciduous oak plantation in southeast England. A summary of the data is provided in Table 9.

Overall, total carbon stocks, including tree stems, roots, litter and soils (to a depth of 50 cm), were higher in the more densely stocked upland spruce forest on an peaty-gley soil compared with the lowland oak forest on a mineral soil. The carbon stocks in the above- and below-ground biomass of the spruce trees alone were approximately 1.7 times larger than in the older oak trees, and the carbon-rich soils at the spruce forest contained 2.5 times as much carbon as the mineral soils at the oak site.

Table 9 Summary of the main average annual carbon fluxes (t CO_2 ha^{-1} y^{-1}) and stocks (t C ha^{-1}) at the Straits Inclosure and Harwood Forest.

	Straits Inclosure	Harwood Forest
Carbon fluxes (t CO_2 ha^{-1} y^{-1}): Ecosystem-scale CO_2 fluxes		
GPP	71.4	84.6
NEP	15.4	26.4
Respiration flux components		
Forest floor respiration (inc. litter)	37.5	23.5
Foliage respiration (by difference)^{A}	18.4	34.7
Total ecosystem respiration	55.9	58.2
Soil dissolved organic carbon flux	0.004	0.22
Carbon stocks (t C ha^{-1})		
Soil C stocks (to 50 cm depth)	114.7^{B}	281.1^{C}
Litter layer C stocks	16.9	37.9
Tree C stocks (above ground)	80.5	122.2
Tree C stocks (below ground)	27.6	61.0
Understorey C stocks	7.7	–
Sum of carbon stocks	**247.4**	**502.2**

C, carbon; CO_2, carbon dioxide; GPP, gross primary productivity; NEP, net ecosystem productivity.
A For the Straits Inclosure, foliage respiration includes that of understorey and ground vegetation, which are not present at the Harwood Forest stand. For both sites, stem respiration estimates have been omitted due to their uncertainty.
B Extrapolated from Ražauskaitė (2019).
C Data from Vanguelova *et al*. (2019).

A more pronounced seasonal cycle in CO_2 uptake was evident at the deciduous oak site, and the long-term record revealed considerable inter-annual variation due to changes in weather patterns, management and periodic outbreaks of defoliating caterpillars. The average annual net ecosystem CO_2 uptake was higher at the spruce forest compared with the oak forest, partly as a result of the dense evergreen canopy at the spruce forest that remained photosynthetically active all year round. Warmer air and soil temperatures, combined with large annual inputs of readily decomposable leaf litter, resulted in higher annual CO_2 emissions from the forest floor at the oak forest compared with the spruce site, despite the latter being on a peaty-gley soil and having a much higher total carbon content.

Detailed case studies on forest carbon balances, like those presented here, are scarce under UK conditions. While these case studies cannot be used to generalise the merits of one woodland type over the other, the understanding of the carbon balance components that have resulted from these sites is invaluable for developing models needed to assess the carbon benefits of forestry at other locations across the UK. As new tools and technologies are developed to measure and monitor forest carbon stocks and fluxes – for example, the European Space Agency's planned 2024 BIOMASS mission to determine the worldwide distribution of forest AGB – direct measurements have never been more important. Long-term observations that measure and quantify both the natural inter-annual variations in carbon fluxes and the response of forest to extreme weather events are crucial to improve our understanding of the processes that control forest carbon balances.

In the future, our work in this field at Forest Research will increasingly seek to combine the information from these sites with comparable sites across Europe and other areas of the temperate forest zone, to further advance our understanding of the impacts of the changing climate, extreme weather events and forest management on forest carbon and GHG balances.

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