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The Potential Contribution of Agroforestry to Net Zero Objectives

School of Water, Energy and Environment

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Photo of trees outside woodland in the Blackdown Hills, Devon by Paul Burgess

Acronyms and abbreviations

C	Carbon
CARBINE	A woodland carbon accounting model
CCC	Committee on Climate Chang
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
CSORT	A woodland carbon accounting model
Dbh	Diameter at breast height (e.g. 1.3 m)
GHG	Greenhouse gas
GWP	Global warming potential
ha	Hectare
kt	kilotonne, i.e., a thousand tonnes
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land use, land use change and forestry
Mt	Megatonne, i.e., a million tonnes
N	Nitrogen
N_2O	Nitrous oxide
SAB	Sycamore, ash, or birch
SOC	Soil organic carbon
t	Tonne
UK	United Kingdom
YC	Yield class
yr	Year

Executive Summary

The aim of this report, for the Woodland Trust, is to examine the potential contribution of agroforestry to net zero objectives in the United Kingdom over the next 40-50 years, with a focus on 2050. As part of the drive to net zero greenhouse gas emissions, the UK Government and the Committee for Climate Change has proposed an expansion in tree cover of 30-70,000 hectares a year across the UK. These are above any level of tree planting seen in the UK in recent years and the majority of such planting will need to occur on farmland. Agroforestry, the integration of trees on farms, whilst sustaining agricultural production, is one approach to increase tree cover whilst supporting other objectives such as the maintenance of livelihoods, provision of wildlife habitats, and reduced nutrient pollution. The report draws on and synthesises previously published literature in journal papers, academic reports, and on-going research.

The report comprises six main sections. The first section provides the over-arching context for this study. Although the project examines how farmland trees can support the drive to net zero greenhouse gas (GHG) emissions, the expansion of tree cover needs to be balanced with the need to maintain food production, rural livelihoods, and biodiversity. Agroforestry is defined as the "practice of deliberately integrating woody vegetation (trees or shrubs) with crop and/or animal systems to benefit from the resulting ecological and economic interactions". Three key agroforestry practices that can be expanded in the UK are shelterbelts and hedgerows, silvoarable systems, and silvopasture systems.

The second section focuses on the current baseline of greenhouse gas emissions. Total UK emissions (excluding aviation and shipping) declined from 809 Mt CO_2e in 1990 to 454 Mt CO_2e in 2019. Of UK emissions in 2019, 10% (46 Mt CO_2e) was derived from agriculture and 1.2% (~6 Mt CO_2e) associated with land use, land use change, and forestry (LULUCF). If the ongoing reduction in soil organic carbon in settlements (~6 Mt CO_2e) is ignored, the net emissions from rural LULUCF is close to zero. Dividing the UK agricultural emissions by the area of cropland and grassland in the UK results in mean emissions of about 2 t CO_2e ha^{-1} yr^{-1} for cropland and about 4 t CO_2e ha^{-1} yr^{-1} for grassland. It should be noted that these values do not include upstream emissions such as fertiliser manufacture and imported feeds.

Section 3 examines the effect of expanding tree cover on the storage of organic carbon in soils. There are particular issues with tree planting on peat soils and these are not a focus of this report. Planting shelterbelts and hedges on cropland was assumed to increase soil organic carbon by a mean of the equivalent of 1.8 t CO_2 ha^{-1} yr^{-1} over 40 years. Planting trees on arable soils in a silvoarable system was assumed to result in a mean sequestration equivalent to 1.1 t CO_2 ha^{-1} yr^{-1} over 30 years. Evidence suggested that planting trees on grassland with mineral soils has variable effects including non-significant increases and significant decreases in the first 10-40 years after planting. For this report we assumed no net effect of planting trees on soils under grassland, but this remains an area for research. In all cases, any tree planting should seek to minimise soil disturbance which can cause carbon losses.

Section 4 examines the effect of planting trees and hedgerows on the storage of biomass carbon, both above- and below-ground. The report firstly considers boundary agroforestry systems such as new shelterbelts and managed hedgerows. An important assumption in calculating carbon benefits is the assumed ratio between "tree" and "grass" areas. We assumed that a 6 m wide shelterbelt (a 3 m wide tree strip and 3 m of grass margins) could sequester 69 t C ha^{-1} over 40 years, equivalent to 6.3 t CO_2 ha^{-1} yr^{-1}, and a managed 2 m tall hedgerow could sequester 65 t C ha^{-1} over 50 years (6.1 t CO_2 ha^{-1} yr^{-1}). Increasing the height

of a managed hedge from 2 to 3 m over 5 years could result in a one-off gain of 1.4 t C ha^{-1} yr^{-1} (5.1 t CO_2 ha^{-1} yr^{-1}).

Two types of in-field agroforestry were considered using field measurements to 19-24 years and models after that to predict changes to 30-40 years. A narrow-alley silvoarable system with about 150 trees per hectare was predicted to sequester 63 t C ha^{-1} as biomass within 30 years (7.7 t CO_2 ha^{-1} yr^{-1}) whilst sustaining 26% of crop production. A silvopasture system with 400 trees ha^{-1} was able to sequester 195 t C ha^{-1} as biomass after 40 years (17.9 t CO_2 ha^{-1} yr^{-1}), whilst maintaining about half the level of grass production over that period.

Section 5 integrates the baseline emissions (Section 2), the soil carbon change (Section 3), and change in vegetation biomass (Section 4) to describe the potential change in greenhouse gas emissions of planting shelterbelts, hedgerows, silvoarable systems, and silvopasture systems. The use of in-field agroforestry systems can allow some of the sequestration benefits of woodland planting whilst enabling continued food production on the same land. Over 40 years, the 400 trees ha^{-1} silvopasture system provided the greatest carbon sequestration (16 t CO_2e ha^{-1} yr^{-1}), new shelterbelts and hedgerows on cropland and a 156 tree ha^{-1} silvoarable systems provided a mean abatement of 7 to 8 t CO_2e ha^{-1} yr^{-1}, and the mean abatement from hedges and shelterbelts on grassland was about 6 t CO_2e ha^{-1} yr^{-1}.

The implications of planting 10,000 ha of the silvopasture systems in, say, 2023 was predicted to result in a mean net greenhouse gas reduction of just under 200 kt CO_2e yr^{-1} over the subsequent 40 years. The predicted equivalent value for 10,000 ha of silvoarable, shelterbelt or hedgerow systems was about 100 kt CO_2e yr^{-1}. The net greenhouse gas abatement by shelterbelts and hedgerows on grassland were similar to that on cropland as the assumed reduction in livestock numbers provided a similar benefit to the end of soil cultivation.

If the tree are planted incrementally over time, rather than planting the total area in Year 1, then the carbon sequestration benefits are deferred. For example, the effect of planting 1,000 ha each year in years 1-10, rather 10,000 ha in year 1 was to move the peak in greenhouse gas abatement by 5 years, to reduce the peak by 4%, and to reduce the emission reduction within the next 40 years by 12%.

The reported current level of greenhouse emissions from UK agriculture is 46 Mt CO_2e yr^{-1}. Balancing these emissions, on average, over the next 40 years, could be achieved by the immediate planting of 2,230,000 ha of silvopasture agroforestry, equivalent to 21% of the UK grassland area. This contrasts with the Committee of Climate Change's estimate (2020a, page 8) that agroforestry, presumably on 10% of agricultural land (~1,600,000 ha), would provide a benefit of 6 Mt CO_2e yr^{-1} by 2050. The difference between the values could be due to differences in the assumed scheduling, the assumed tree density, and temporal changes.

The final section provides seven recommendations. Firstly, initiatives to reduce greenhouse gas emissions require a systematic approach that considers food, profitability, and livelihoods alongside greenhouse gas emissions to ensure that the best decisions are made. Second, it is essential that farm businesses start to establish carbon inventories and accounts of greenhouse gas flows to determine future progress. The process of achieving net zero requires a portfolio of approaches, and methods to reduce nitrous oxide and methane emissions need to be pursued alongside tree-planting and management. The choice of tree species is important as carbon sequestration rates can vary at least three-fold depending on whether a species is suited for a particular site or not. The report also highlights the temporal nature of carbon sequestration. An observation that the Yield-SAFE agroforestry model tends to predict earlier carbon sequestration than the woodland models with the Woodland Carbon Code is worthy of further study. The continued production of crops and/or livestock with agroforestry means that carbon sequestration by the trees is more likely to be used to ensure that a farm itself achieves net zero, rather than sold to other businesses through carbon trading schemes. Lastly, it is important to remember the need for skilled people to enable the above goals to be achieved.

1 Introduction

1.1 The food – climate – biodiversity – livelihood nexus

For centuries, farmers and landowners in the UK, and worldwide, have used their skills and experience to produce food and fibre whilst securing a livelihood. However looking forward, business as usual is not possible. Farmers and landowners need to continue producing food whilst securing a livelihood, but this must now be combined with a contribution to net zero greenhouse emissions and enhanced biodiversity (Figure 1) (National Food Strategy 2021). Balancing these demands is difficult and it will require new regenerative approaches within agriculture. One definition of "regenerative agriculture" is "a system of principles and practices that generates agricultural products, sequesters carbon, and enhances biodiversity at the farm scale" (Burgess et al. 2019).

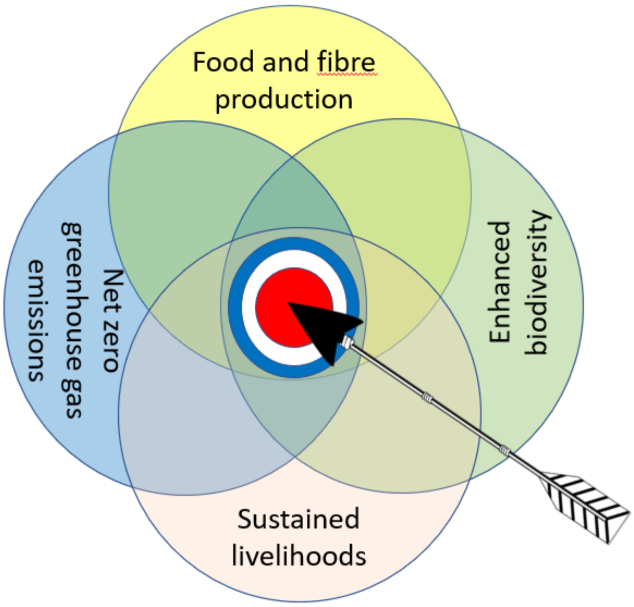

Figure 1. UK farmers and landowners need to combine food and fibre production and sustained livelihoods with approaches to achieve net zero greenhouse gas emissions and enhanced biodiversity.

1.2 Agroforestry

The focus of this report is on the potential role of agroforestry on UK farms to support continued food and fibre production and sustained livelihoods, whilst moving towards net zero greenhouse gas emissions. Biodiversity is not explicitly covered in this report, but it should be considered in farm-level decisions. In general, the greater integration of trees on farms is considered to improve on-farm biodiversity (Torralba et al. 2016).

Agroforestry has been defined as the "practice of deliberately integrating woody vegetation (trees or shrubs) with crop and/or animal systems to benefit from the resulting ecological and economic interactions" (Burgess and Rosati 2018). It can include the integration of livestock and crops into tree-only systems, and the integration of trees into crop, livestock, and mixed farms. In the context of supporting net zero greenhouse gas emissions, the focus of this report is on the integration of trees on farms.

There are three main agroforestry practices possible on agricultural land: ii) hedgerows and shelterbelts (which can also include riparian buffer strips), ii) silvoarable systems, and iii) silvopasture systems (Table 1).

Table 1. Agroforestry practices can be linked to dominant land use categories (agriculture, forest or peri-urban). This report focuses on agricultural systems (Mosquera-Losada et al. 2017)

Land use and agroforestry practice		Examples	Brief examples and descriptions
AGRICULTURE	Silvopasture	Wood pasture and parkland	Typically areas used for forage and animal production that includes non-agricultural trees and shrubs.
		Meadow orchards	Typically areas of agricultural trees and shrubs (e.g. fruit orchards, olive groves, vineyards) which are grazed.
	Hedgerows, shelterbelts and riparian buffer strips	Hedgerows, windbreaks and riparian buffer strips	Here the woody components are planted to provide shelter, shade, or parcel demarcation to a crop and/or livestock production system. Riparian buffer strips are typically created to protect water quality and can be silvopasture or silvoarable.
	Silvoarable	Alley-cropping systems	Widely spaced woody perennials inter-cropped with annual or perennial crops. As the tree canopy develops, the crops may be replaced with a grass understorey.
FOREST	Silvopasture	Forest grazing	Although the land cover is described as forest, the understory is grazed and delivering agricultural products
	Forest farming	Forest farming	Forested areas used for production or harvest of naturally standing speciality crops for medicinal, ornamental or culinary uses
URBAN AND PERIURBAN	Homegardens	Homegardens	Combining trees/shrubs with vegetable production usually associated with peri-urban or urban areas

1.3 Approach

As indicated, balancing food and fibre production, sustainable livelihoods, and net zero greenhouse gas emissions is not easy. It requires a systematic approach because of the various trade-offs between these factors.

The first step in a systematic approach is to understand the current baseline for any farm (Figure 2). What is the level of food and fibre production? What is the current status of financial and natural capital? What is the current level of greenhouse gas emissions? The actual reduction in net greenhouse gas emissions achieved by increased tree cover on farms is very context specific and will depends on the climate, the soil, the tree species, the form of management, and the permanence of any harvested wood (Forster et al., 2021).

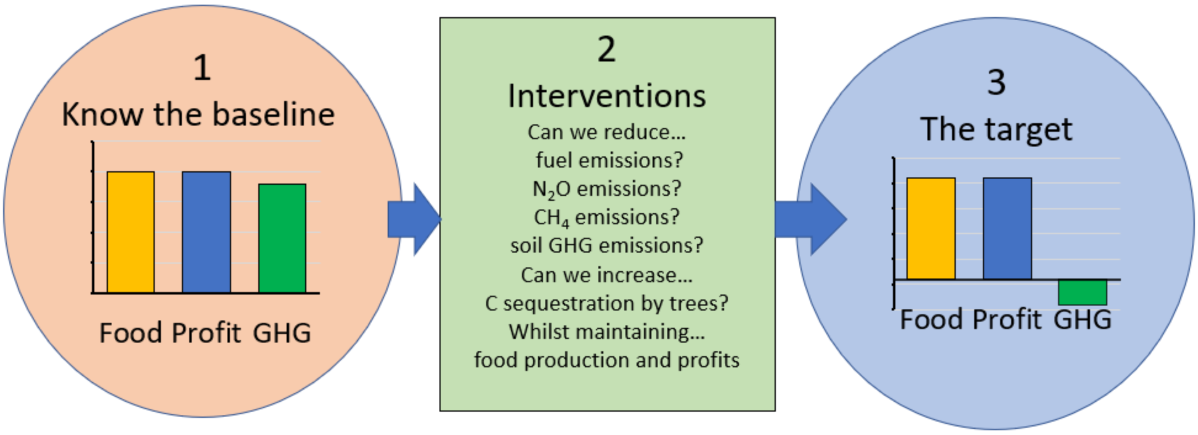

Figure 2. A systematic approach to reducing net greenhouse gas requires a systematic approach that starts with a clear consideration of the baseline (food and fibre, balance sheet, and carbon inventories and greenhouse gas emissions) and then considers how emissions can be reduced and carbon sequestration increased.

1.4 Summary

- Farmers and landowners need to continue producing food and securing a livelihood whilst moving towards net zero greenhouse emissions and enhanced biodiversity
- There are three main agroforestry practices possible on agricultural land: ii) hedgerows, shelterbelts and riparian buffer strips, ii) silvoarable systems, and iii) silvopasture systems.
- An important step in a systematic approach to address the above questions is to first understand the baseline greenhouse gas emissions of the current systems used by farmers.

2 Understanding the baseline

Understanding the current baseline level of greenhouse gas emissions on any farm, or group of farms, is critical before considering the role of agroforestry.

2.1 Units

In the section focused on the benefits of reducing greenhouse gas emissions, the sequestration of carbon is reported in terms of tonnes of carbon dioxide equivalents per hectare (t CO_2e ha^{-1}), to allow direct comparison with greenhouse gas fluxes. To change the mass of carbon in the soil to the mass of carbon dioxide, the carbon masses should be multiplied by the molecular weight of CO_2 divided by the weight of carbon, i.e. 44/12.

2.2 UK national baselines

The UK Government has been tracking the level of greenhouse gas emissions since at least 1990. Primarily as a result of the closure of coal power stations, UK territorial emissions of CO_2e have declined from 809 Mt CO_2e in 1990 (not including aviation and shipping) to 454 Mt CO_2e in 2019 (BEIS 2021). The plan is to reduce net emissions to zero by 2050 (Figure 3).

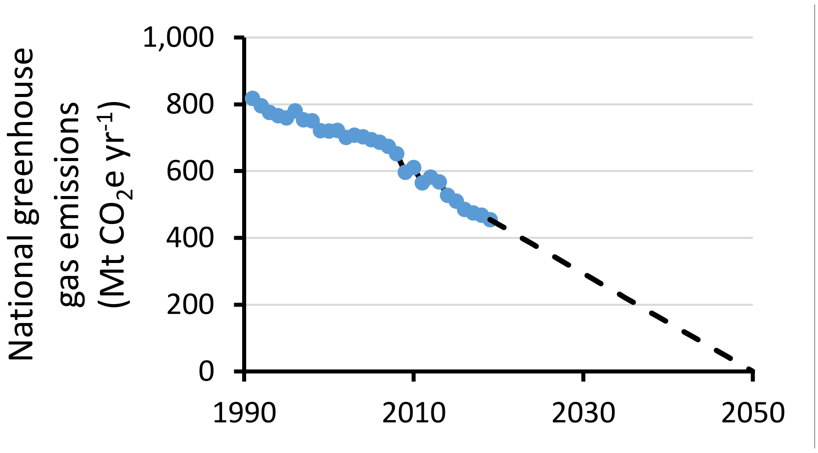

Figure 3. UK greenhouse gas emissions have declined from 809 Mt CO_2e in 1990 to 454 Mt CO_2e in 2019 (BEIS, 2021)

2.3 UK agriculture and land use

Greenhouse gas emissions from land use and farms are typically considered in two sections: emissions from "agriculture" and emissions from "land use, land use change, and forestry" (LULUCF) (Table 2).

Table 2. Two principal sources of agricultural and agricultural-related greenhouse gas emissions (BEIS 2021)

Sector	Description
Agriculture	"Emissions of greenhouse gases from livestock, agricultural soils (excluding carbon stock changes which are included in the LULUCF sector) and agricultural machinery". The categories include combustion from engines, enteric fermentation primarily from ruminant livestock, livestock waste, direct soil emissions, and other practices including liming.
Land use, land use change and forestry (LULUCF)	"Emissions/removals of CO_2 from changes in the carbon stock in forestland, cropland, grassland, wetlands, settlements and harvested wood products, and of other greenhouse gases from drainage (excl. croplands and intensive grasslands) and rewetting of soils, nitrogen mineralisation associated with loss and gain of soil organic matter, and fires. Because the impact of biomass harvest on carbon stocks in ecosystems is included in this sector, any emissions of CO_2 from burning biomass (regardless of the country of origin) are excluded from other sectors to avoid double counting them".

There are different categories of greenhouse gas emissions on farms. Scope 1 emissions include direct emissions of CO_2 from machinery, methane from livestock, nitrous oxide from fertilizer, and carbon sequestration by newly planted trees (Harrison 2021). Scope 2 emissions include on-farm electricity use. This study primarily focuses on Scope 1 emissions.

In 2019, UK agriculture emitted 46.3 Mt CO_2e (Figure 4) and UK land use, land use change and forestry (LULUCF) emitted 5.9 Mt CO_2e (BEIS 2021). Hence agriculture is a source of 10% of UK emissions, and LULUCF was a net source of 1.2% of emissions. It could be argued that rural land use if not carbon neutral, as the continued change of soil carbon in settlements was equivalent to 5.9 Mt CO_2e (BEIS 2021) (Figure 5).

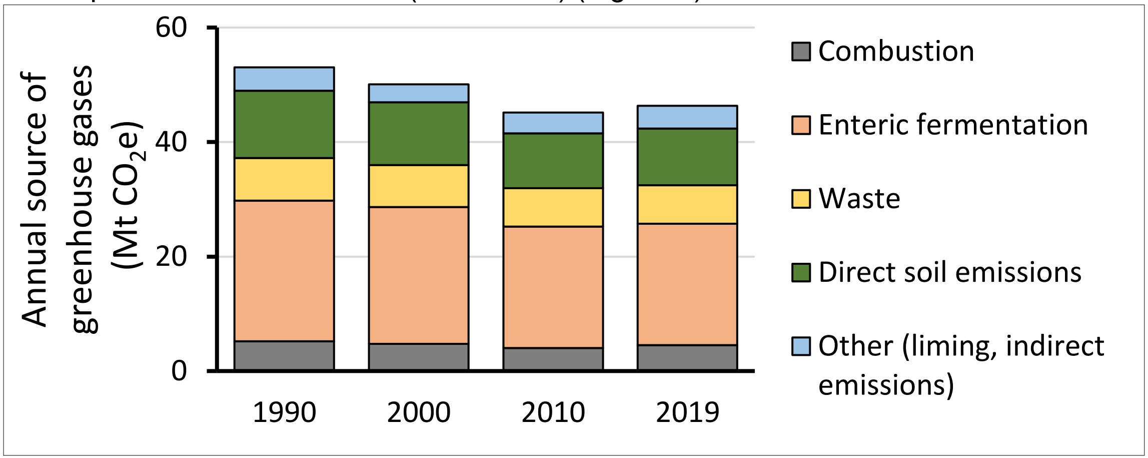

Figure 4. UK agricultural emissions declined from 53.1 Mt CO_2e in 1990 to 50.1 Mt CO_2e in 2000, 45.2 Mt CO_2e in 2010, and rose to 46.3 Mt CO_2e in 2019. There has minimal decline in waste and other emissions (BEIS, 2019)

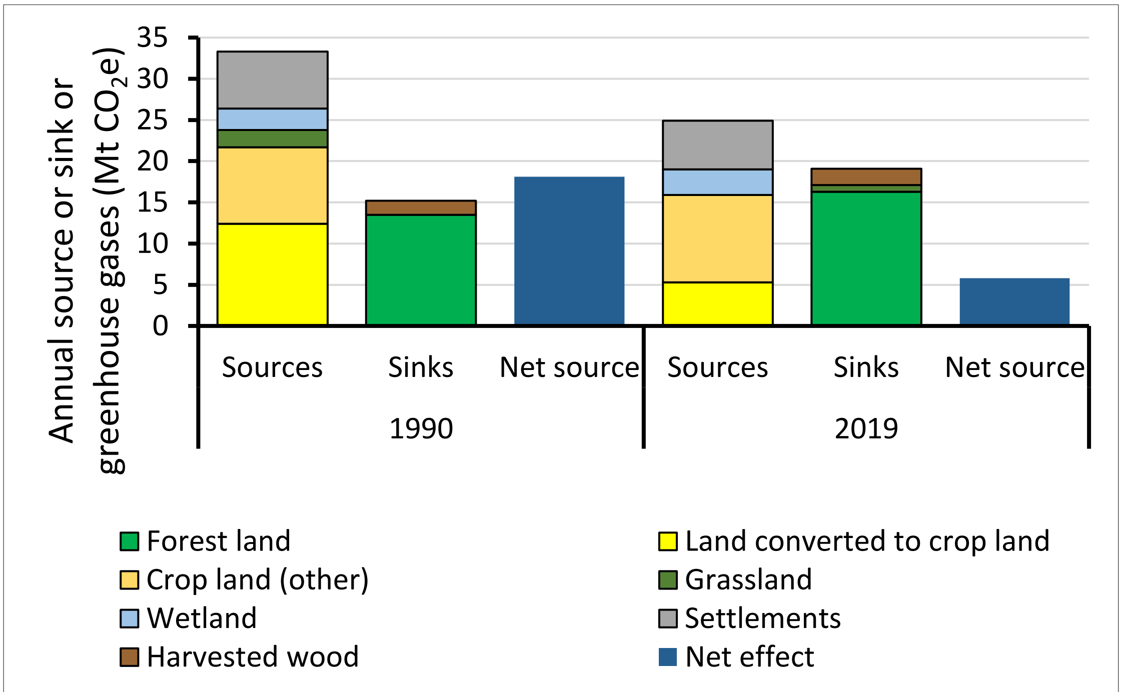

Figure 5. Due to the increase of forest land as a sink, grassland becoming a net sink, and reduced emissions from the historic conversion of forest and grassland to cropland; LULUCF has reduced from 18.0 Mt CO_2e in 1990 to 5.9 Mt CO_2e in 2019. The historic emissions from settlement land was 5.9 Mt CO_2e in 2019 (BEIS, 2019)

2.4 Estimates of greenhouse gas emissions from individual farms

Whilst national estimates of agricultural and LULUCF emissions are useful, we found few reports of benchmarks for agricultural and LULUCF emissions from individual farms, estates, or businesses. Hence a key recommendation of this report is that the UK Government should support farming businesses in establishing the carbon inventory and current levels of greenhouse gas emissions from individual holdings.

UK agricultural land can be split in three main categories: cropland (4.84 million ha) temporary grassland (1.22 million ha), and permanent grassland (9.96 million ha) (Table 3).

Table 3. UK land areas in 2021 (Defra 2021b)

Land type	Area ('000 ha)
Cropland	4,839
Temporary grassland	1,217
Permanent grassland	9,965
	16,021
Rough grazing	1,194
Woodland	1,076
Other	340
	18,631

2.4.1 CO_2 emissions from combustion

As demonstrated in Figure 4, carbon dioxide from combustion of mobile and stationary machinery contributes 4.50 Mt CO_2 yr^{-1}, equivalent to about 10% of UK agricultural emissions. If we assume that these emissions primarily occur on cropland, then the mean annual level of combustion emissions is 0.93 t CO_2 per hectare of cropland (Table 6). Note that the value does not include the emissions associated with the manufacture of fertilizer, pesticides or machinery. Including such parameters can double arable emissions to, for example, 2.40 t CO_2 ha^{-1} yr^{-1} (Giannitsopoulos et al. 2020).

2.4.2 Emissions from fertiliser

As demonstrated in Figure 4, direct soil emissions contribute 9.90 Mt CO_2 yr^{-1}, equivalent to about 21% of UK agricultural emissions. The level of nitrous oxide (N_2O) emissions from cropland and improved grassland can also be based on the nitrogen application rates reported in the British Survey of Fertiliser Practice for 2019 (Defra, 2020b), and the IPCC (2013) Tier 1 method that includes direct N_2O emissions from fertilizer application, and indirect emissions from leached nitrate and volatilised ammonia and nitrous oxides (Table 4). The calculated N_2O emissions were converted into Global Warming Potential over 100 years (GWP_{100}) of 298 (IPCC 2007). For the calculation, it was assumed that 30% of the grassland is less than five years old.

Table 4. Assumed nitrogen application rates on land types in England and Wales and consequent greenhouse gas emissions from nitrous oxide emissions

Land type	Nitrogen application rate (kg N ha^{-1} yr^{-1})	Total N_2O emissions (t CO_2e ha^{-1} yr^{-1})
Crop land	141	0.94
Grass less than five years old	98	0.65
Grass five years and over	42	0.28
Rough grazing	0	0

2.4.3 *Emissions from livestock*

Methane produced from rumen fermentation contributes 21.2 Mt CO_2e yr^{-1}, equivalent to about 45% of UK agricultural emissions (Figure 4). The number of dairy cattle, beef cattle, and sheep in the UK is about 1.9 million, 1.5 million, and 32.7 million respectively (Table 5) (Defra et al. 2021b). Livestock also produce nitrous oxide from urine and manure. Table 5 includes estimates of methane and nitrous oxide emissions from grazing livestock (Adrian Williams, 2021 personal communication) using IPCC Tier 1 methods and coefficients per livestock type appropriate for the UK climate and animal production systems. Methane emissions from managed manure were calculated from typical animal liveweights, coefficients for volatile solids per unit liveweight, and expected housing periods (1 month for sheep, 7 months for dairy cattle and 6 months for other cattle) (Table 5). Nitrous oxide from direct deposition of excreta and managed manure were derived using similar methods to those for nitrous oxide from fertiliser in the previous section.

Table 5. Emissions from nitrous oxide (N_2O) and methane (CH_4) per animal type

Livestock type	Number (million)	Greenhouse gas emission (kg CO_2e $head^{-1}$)			
		Enteric methane	Methane from manure	N_2O emissions	Total
Dairy cattle	1.9	3,150	76.7	1,494	4,721
Calves, beef cattle, horses	7.7	1,300	25	673	1,998
Sheep and deer	32.7	175	1	158	334

2.4.4 *Counterfactual*

This indicative analysis suggests that combustion, fertiliser and livestock-related emissions from the mean UK arable farm are about 1.87 t CO_2e ha^{-1} yr^{-1}, and those from grassland farms about 2.34 t CO_2 ha^{-1} yr^{-1}. If waste and other emissions of 11.07 Mt CO_2e (Table 7) are equally distributed across the grassland area of 11.18 million ha, then that results in an additional 0.99 t CO_2e ha^{-1} yr^{-1} (Table 6). Any focus on a farm achieving net zero should focus on ways to reduce these emissions, ideally without reducing food production or damaging farm profitability. There are a range of methods to reduce greenhouse gas emissions, but not all methods offer economic, environmental, and social benefits (Harrison et al. 2021).

Table 6. UK greenhouse gas emissions expressed per hectare of cropland and grassland

Land Cover		Area (million ha)	Density (Head ha^{-1})	Greenhouse gas emissions (t CO_2e ha^{-1} yr^{-1})				
				Fuel CO_2	Fertiliser	Methane	Other	Total
Crop		4.84		0.93	0.94			1.87
Grass	Fertiliser (temp. grass)	1.22			0.65			
	Fertiliser (perm. grass)	9.96			0.28			
	Dairy herd		0.17			0.55	0.21	
	Calves and cattle		0.72			0.96	0.39	
	Sheep herd		2.92			0.51	0.39	
	Grassland total	11.18			0.32	2.02	0.99	3.33

Table 7. UK national greenhouse gas emissions for agriculture allocated to the area of cropland and grassland (based on BEIS 2019 and Defra 2021b)

Land cover	Area (million ha)	Total greenhouse gas emissions (Mt CO_2e yr^{-1})				Total
		CO_2	Fertiliser	Methane	Manure and other	
Cropland	4.84	4.50	4.55			9.05
Grassland	11.18		3.58	22.62	11.07	37.27
Total	16.02	4.50	8.13	22.62	11.07	46.32

2.5 Summary

- Current levels of greenhouse gas emissions from cropland and grassland areas in the UK provide a baseline from which to assess interventions to move to net zero.
- Baseline emissions were assumed to be a mean of 1.87 t CO_2e ha^{-1} yr^{-1} from arable farms, and a mean of 3.33 t CO_2e ha^{-1} yr^{-1} from grassland farms. In an early version of this report, the grassland emissions was estimated to a higher value of 3.94 t CO_2e ha^{-1} yr^{-1}, and this higher value is used later in this report.
- Any systematic attempt to reduce net greenhouse emissions should focus on ways to reduce these emissions without reducing food production or farm profitability.

3 Soil carbon emissions and sequestration

Having considered greenhouse gas emissions from machinery, fertiliser and manure use, and livestock, a next step is to consider the net rate of carbon sequestration by the soil. Carbon sequestration or emission rates of soil are difficult to determine by direct measurement because of the high inherent spatial variability of soil. However detailed research work has established some key principles.

3.1 Peat soils

In examining carbon sequestration by soil, it is important to determine if the soil at a site is a mineral soil, an organo-mineral soil, or peat. If the site is peatland or has an organo-mineral soil, then specific additional advice should be sought as the carbon emissions of such soils can be very high. For example, carbon emissions from peatland for cropped, grassland and forested soils typically range from 3 to 11 t C ha^{-1} yr^{-1} (Evans et al. 2017).

3.2 Arable soils

Tree and hedge planting on **arable mineral soils** generally has a positive effect on soil organic carbon (SOC) in the topsoil because soil carbon is no longer oxidised by regular cultivation. In the UK National Greenhouse Gas Inventory, Brown et al. (2020, page 789) reports that converting arable to forestry land increases the soil carbon by 31 t C ha^{-1}. If this change occurs over 100 years, a mean annual value over that period would be +0.3 t C ha^{-1} yr^{-1} (1.1 t CO_2e ha^{-1} yr^{-1}). Morison et al. (2012) in a Forest Research report highlighted that, although there are few definitive data, afforestation of mineral soils is expected to increase soil carbon at typical rates of between 0.14 to 0.46 t C ha^{-1} yr^{-1}. Falloon et al. (2004) estimated a mean increase in soil carbon of 0.53 t C ha^{-1} yr^{-1} from newly planted shelterbelts and hedgerows on arable land over 40 years (Table 8).

Table 8. Modelled annual soil carbon sequestration rates of newly planted tree shelterbelts and managed hedgerows on arable land based on Falloon et al. (2004)

		Soil C storage (0-30 cm) (t C ha^{-1})	Time (yr)	Net change (t C ha^{-1} yr^{-1})
Baseline	Arable	84.7		
6 m wide tree strip	4 m wide arable to grass	106.7	~40	
	2 m wide to trees	104.5	~40	
	Weighted mean change	21.3	~40	0.53
2 m wide managed hedgerow	0.5 m arable to grass	106.7	~40	
	1.5 m to hedge	106.0	~40	
	Weighted mean change	21.5	~40	0.54

Drexler et al. (2020) reported that new hedgerows on cropland could result in an additional SOC stock of 17 t C ha^{-1} over a 20-year period (0.9 t C ha^{-1} yr^{-1}), and suggested a lower mean increase of 0.3 t C ha^{-1} yr^{-1} over 50 years. For the purpose of this study, we assumed a mean value of **0.5 t C ha^{-1} yr^{-1}** for hedgerows and shelterbelts planted on cropland over 40 years.

Upson and Burgess (2013) reported that moving from arable to a silvoarable and then a silvopasture system resulted in an increase in soil carbon (0-150 cm) of 8.7 t C ha^{-1} over 19 years, equivalent to 0.46 t C ha^{-1} yr^{-1} (Table 9). Assuming that the soil carbon then stabilised, the increase over 30 years would be 0.29 t C ha^{-1} yr^{-1}. In a study across five silvoarable sites, Cardinael et al. (2017) reported a mean increase in SOC (generally 0-30 cm) of 0.24 t C ha^{-1} yr^{-1} over 6-42 years. Axe (2015) reported a SOC (0-30 cm) of 98.7 t C ha^{-1} below a hedge compared to 85.1 t C ha^{-1} in the field margin, but a time period for the increase was not available. For the purpose of progressing the analysis, we assumed the SOC sequestration of

0.29 t C ha^{-1} yr^{-1} over 30 years for silvoarable systems, based on the study by Upson and Burgess (2013).

Table 9. Reported soil annual carbon sequestration rates of a poplar (6.4 m x 10 m) silvoarable system over 19 years. Both the cropped and the agroforestry system were cropped for 11 years, and grass was grown for the last 8 years (Upson 2014, page 80)

	Soil carbon storage (0-150 cm) (t C ha^{-1})	Time period (yr)	Net carbon sequestration (t C ha^{-1} yr^{-1})
Control	215.6		
Agroforestry	224.3		
Net change	8.7	19	0.46
		30	0.29

The effect on soil carbon levels of planting trees on **grassland** is more mixed. Biffi et al. (2022) examined the increase in soil carbon storage of new hedgerows on grassland areas in Cumbria and reported that most of the increase occurred within 37 years of planting. At a depth of 0-30 cm, and assuming an equivalent soil mass, the stock increased from 97.3 t C ha^{-1} to 105.3 t C ha^{-1} at 2-4 years, 110.5 t C ha^{-1} at 10 years, 135.7 t C ha^{-1} at 37 years, and 146 t C ha^{-1} for "old" hedges (Biffi et al. 2022; Table 3). The increase of 38.4 t C ha^{-1} over 37 years is equivalent to 1.04 t C ha^{-1} yr^{-1}. By contrast in a meta-analysis of six studies, Drexler et al. (2021) reported no significant change in SOC stocks of hedgerows and those of grassland. Brown et al. (2020, page 789) report that a change from grassland to forest land in England is typically associated with an increase in soil carbon of 21 t C ha^{-1} (i.e. 77 t CO_2 ha^{-1}). Research by Beckert et al. (2016) at Glensaugh in Scotland reported a non-statistically significant increase in SOC (0-50 cm) over 24 years of 7-18 t C ha^{-1}, equivalent to 0.28-0.76 t C ha^{-1} yr^{-1} (Table 10). In Northern Ireland, Fornara et al. (2018) reported no significant change in the soil carbon (to 20 cm) between pasture and a silvopasture system with ash trees 26 years after planting.

Table 10. Reported soil carbon sequestration rates of three tree species (400 tree ha^{-1}) in a silvopasture system in Eastern Scotland over 24 years (derived from Beckert et al. (2016).

	Soil carbon storage (t C ha^{-1})	Time period	Net change (t C ha^{-1} yr^{-1})
Pasture control	64		
Agroforestry (Hybrid larch 400 trees ha^{-1})	82		
Net change	18	24	0.76
Agroforestry (Scots pine 400 trees ha^{-1})	71		
Net change	7	24	0.28
Agroforestry (Sycamore 400 trees ha^{-1})	72		
Net change	8	24	0.32

By contrast, Upson et al. (2016) in Bedfordshire reported that tree planting on grassland may initially (e.g. within the first 14 years) result in lower soil carbon levels (Table 11). Possible reasons for this include oxidation of carbon during planting, reduced carbon inputs from grass root turnover, and drier soil conditions. It should be noted that standard measurements of "soil carbon" will remove root material and litter. If root material and litter is added, then the effect of tree planting on below-ground carbon can be more positive. Research by Ashwood et al. (2019) suggests that over longer time periods (e.g. 100 years), soil carbon levels under woodland can be the same as or greater than values for grassland. Hence although tree planting can increase below-ground carbon storage in the form of roots (considered in the next section), for this assessment we take a conservative view and assume that the benefits of planting trees on grassland on soil carbon levels is minimal.

Table 11. Measured soil organic carbon storage (0-150 cm) of a 14 year old woodland and silvopasture system relative to a pasture control (Upson et al. 2016)

	Soil carbon storage (t C ha^{-1})	Time period	Net change (t C ha^{-1} yr^{-1})
Pasture control	59.6		
Agroforestry	59.4		
Net change	-0.2	14	-0.01
Woodland	46.2		
Net change	-13.4	14	-0.96

3.3 Summary

- If the site is peatland or has an organo-mineral soil, then specific additional advice should be sought as the carbon emissions of such soils can be very high.
- Tree and hedgerow planting on **arable mineral soils** generally has a positive effect of soil carbon in the topsoil because soil carbon is no longer oxidised by regular cultivation. We assumed a mean value of 0.50 t C ha^{-1} yr^{-1} over 40 years for hedgerows and shelterbelts on cropland, and 0.29 t C ha^{-1} yr^{-1} over 30 years for a silvoarable system.
- Tree and hedgerow planting on **grass mineral soils** has a mixed effect. Benefits of 0.28-0.76 t C ha^{-1} yr^{-1} over 24 years, and 1.04 t C ha^{-1} yr^{-1} over 37 years have been reported, but also losses of 0.96 t C ha^{-1} yr^{-1} over 14 years. Because of the substantial variability we assumed no net effect on SOC of planting trees and hedgerows on grassland.
- Methods focused on carbon sequestration should seek to minimise soil disturbance during tree planting.

4 Carbon sequestration by trees

4.1 Shelterbelts and lines of trees

Whereas hedgerows are typically managed, an increasing proportion of hedges in the UK are being left unmanaged resulting in “lines of trees” (Figure 6). Carey et al. (2008) reported that across an estimated 700,000 km of lines of trees and hedgerows in Great Britain, there was a 6% loss in managed hedgerow length between 1998 and 2007, with a large proportion turning into lines of trees and relict hedges. Drexler et al. (2021) reported that C stocks in such tree lines were similar to stocks found in forests on a per tree area basis.

Figure 6. Line of trees within hedges, with parkland in the foreground (Burgess 2012)

These lines of trees can store significantly more carbon than a managed hedge and Falloon et al. (2004) assumed a mean above-ground tree biomass of 140 t C per hectare of the tree line (excluding the grass areas to the side) after 50 years. However including 2 m width of grass to the side of each tree line resulted in a carbon gain of 46 t C ha^{-1}, equivalent to 0.92 t C ha^{-1} yr^{-1} over 50 years (Table 12).

Table 12. Above-ground carbon sequestration rates of newly planted 6 m tree shelterbelt based on modelling by Falloon et al. (2004), and a meta-analysis by Drexler et al. (2021)

		Above-ground C storage (t C ha^{-1})	Time (yr)	Net change (t C ha^{-1} yr^{-1})
New shelterbelt (Falloon et al. 2004)	Baseline arable	2.2		
	4 m wide arable to grass margin	2.4		
	2 m wide to trees	140.0		
	Weighted mean change	46.1	50	0.92
Coppiced hedge (Drexler et al. 2021)	Hedge <5 years after coppice	~20.0		
	Hedge 10-15 yr after coppice	~47.0	10	2.70

Drexler et al. (2021) in a European meta-analysis reported that the mean above ground carbon storage of hedges changed from about 20 t C ha^{-1} less than five years after coppice to about 47 t C ha^{-1} 10-15 years after coppice (Table 12). This implies mean annual sequestration rate of 2.7 t C ha^{-1} yr^{-1} over 10 years, similar to the annual value reported by Falloon et al. (2004) if only based on the tree area.

Establishing the time series: the Woodland Carbon Code (2020) presents annual carbon sequestration rates for a range of tree species, including roots and debris in addition to the above-ground vegetation biomass. A critical assumption in determining the carbon sequestration of a tree row is the assumed ratio of the tree row to the grass margin. The width of the tree row varies with the time from the last harvest, trim, or coppice. For example, a hedge may have a width of 3.5-6.0 m before coppicing and 0.5-1.5 m after coppicing (Crossland 2015).

Assuming a Yield Class 6 for beech, but reduced to half of the value, assuming that on average 3 m out of 6 m is taken up by the tree row would result in a cumulative carbon sequestration (above and below ground) of 81 t C ha^{-1} by year 50 (Figure 7), which is comparable to the above-ground carbon value of 48 t C ha^{-1} by year 50 modelled by Falloon et al. (2004). The mean carbon sequestration over 40 years of the same system was 69 t C ha^{-1}, equivalent to **1.72 t C ha^{-1} yr^{-1}.** The beech model provides values between those for oak, and the sycamore, ash, and birch (SAB) species.

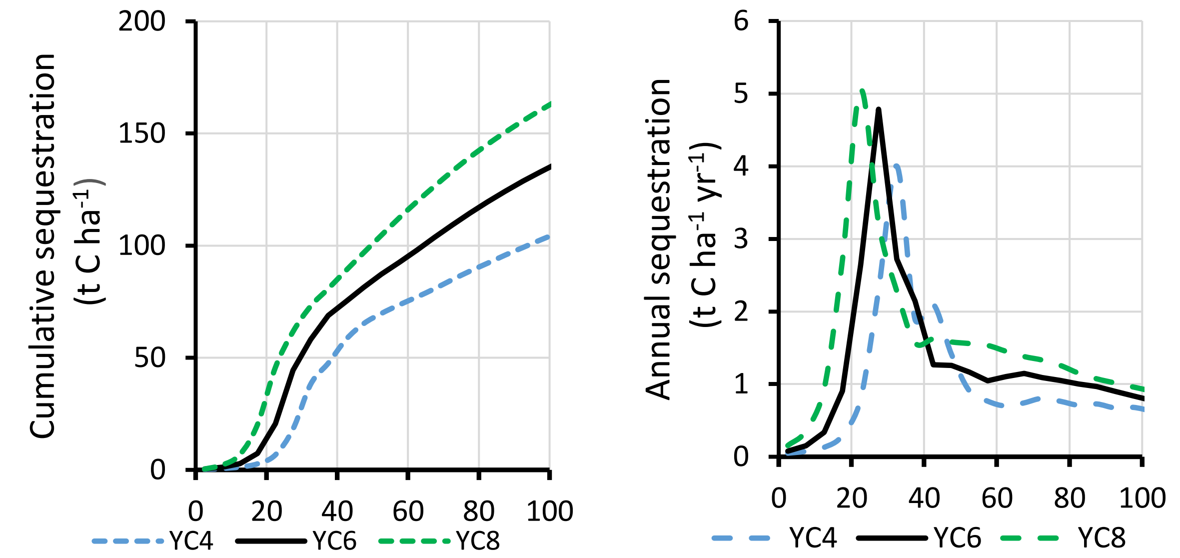

Figure 7. Predicted rate of carbon sequestration for a shelterbelt (comprising 3 m width of trees and 3 m width of grass) based on beech (standing trees and debris) (unthinned, Yield Class (YC) = 4, 6, and 8, initial spacing = 2.5 m) (after Woodland Carbon Code 2020)

4.2 Carbon storage of new managed hedgerows

There is a wide range of hedge types and a wide range of estimates for the carbon stored in hedge biomass ranging from small volumes of blackthorn to substantial Devon hedges (Figure 8). In Great Britain, 4% of the hedges sampled in the Countryside Survey of 2007 were less than 1 m, 46% were 1-2 m, and 50% were greater than 2 m (Carey et al. 2008). In a modelling study, Falloon et al. (2004) assumed a very low value of only 5 t C ha^{-1} for a hedge, based on a value for set-aside reported by Adger and Subak (1996) (Table 13). This value seems low, but in Ireland, Black et al. (2014, page 24) reported that more than 50% of the hedgerows they sampled had a biomass of less than 4 t C ha^{-1}".

Figure 8. Example of a managed hedge surrounded by grassland (Photo: Paul Burgess)

Table 13. Modelled annual above-ground carbon sequestration rates of newly planted hedgerows by Falloon et al. (2004)

	Above-ground C storage (t C ha^{-1})	Time (yr)	Net change (t C ha^{-1} yr^{-1})
Baseline arable	2.2		
0.5 m wide to grass	2.4		
1.5 m wide to hedgerow	5.0		
Weighted mean	4.4	~40	0.10

Axe (2015) measured the biomass carbon storage of a mature 2 m tall hedge with an above-ground biomass of 27.8 t C ha^{-1}, and a below-ground biomass of 38.7 t C ha^{-1}. This above-ground biomass is similar to the mean above ground biomass of 20.5 t C ha^{-1} measured using LiDAR data across 228 hedgerows in Ireland, reported by Black et al. (2014). It is difficult to determine a carbon sequestration rate for the hedge described by Axe (2015), but for the purposes of argument if we assumed that the carbon accumulation took place over 40 years, the mean carbon sequestration rate would be 1.49 t C ha^{-1} yr^{-1} (Table 14).

Table 14. Measured carbon levels of a 2 m high hedge by Axe (2015) and Axe et al. (2017), and assuming a 40 year time period for illustrative purposes

			C Storage (t C ha^{-1})	Time (yr)	Rate (t C ha^{-1} yr^{-1})
Measured hedge (Axe 2015)	Baseline margin	Above-ground biomass	2.6		
		Below-ground biomass	4.0		
	2 m high hedge	Above-ground biomass	27.8		
		Below-ground biomass	38.7		
		Net change	59.9	~40	**1.49**

Biffi et al (2022) reported that a 37 year old hedgerow in Cumbria, assumed to be about 1.75 m tall and 1.70 m wide, had an above- and below-ground biomass storage of 70 t C ha^{-1}, suggesting a sequestration rate of 1.89 t C ha^{-1} yr^{-1} (Table 15). In Ireland, Black et al. (2014) reported above-ground biomass for non-managed hedges of 39 and 47 t C ha^{-1}, and assuming a 50 year period assumed a carbon sequestration rate of 0.78 and 0.90 t C ha^{-1} yr^{-1} for above-ground biomass respectively (Table 15). Looking at existing hedgerows they quoted a mean above ground biomass sequestration of 0.18 t C ha^{-1} yr^{-1} for hedgerows and 0.66 t C ha^{-1} yr-^{1} for shrubland. Black et al. (2014) also reported an above-ground sequestration of 0.44 t C ha^{-1} yr^{-1} for an existing hedgerow.

Table 15. Reported annual carbon sequestration rates of above-ground (AG) and below-ground (BG) of managed hedgerows by Biffi et al (2022) and Black et al. (2014)

		C Storage (t C ha^{-1})	Time (yr)	Rate (t C ha^{-1} yr^{-1})
New hedgerow (Biffi et al. 2022)	Change in total biomass	70.0	37	**1.89**
New hedgerow (Black et al. 2014, pg 24)	Change in AG biomass	39.0	50	**0.78**
	Change in AG biomass	47.0	50	**0.94**
Existing hedgerow (Black et al. 2014)	Change in AG biomass	20.5		**0.18**
Existing scrub (Black et al. 2014)	Change in AG biomass	~20-30		**0.66**
Existing hedgerow (Black et al. 2014 p 36)	Change in AG biomass			0.44
	Change in BG biomass			0.08
	Change AG and BG			**0.52**

Establishing the time series: determining a time series for the cumulative carbon sequestration of a managed hedgerow is difficult. In the absence of a bespoke model, we assumed a carbon sequestration profile of beech with a yield class of 6 until it reached the mature managed hedgerow biomass of 65 t C ha^{-1}, as reported by Axe (2015), after which we assumed no further increase (Figure 9). These assumptions imply an accumulation of **1.66 t C ha^{-1} yr^{-1}** over 40 years, similar to the shelterbelt. This is within the range of 0.16 to 2.80 t C ha^{-1} yr reported for vegetation growth in five boundary systems across Europe as reported in the Appendix (Table 24).

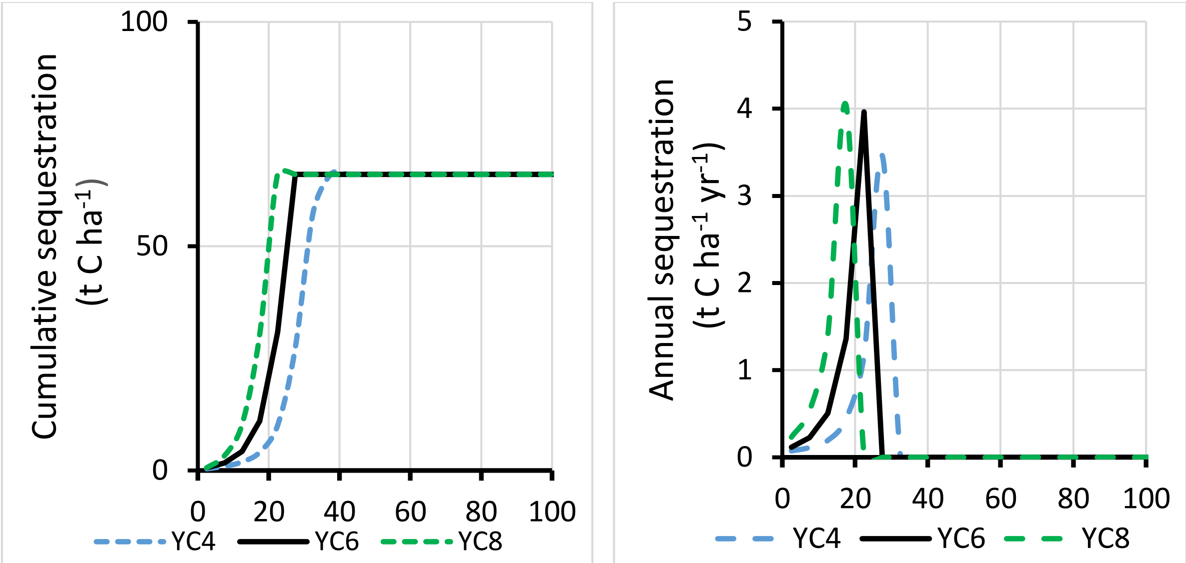

Figure 9. The predicted rate of carbon sequestration for a managed hedgerow (comprising 1.5 m trees and 0.5 m grass) based on beech (standing trees and debris) (unthinned, Yield Class (YC) = 4, 6, and 8, initial spacing = 2.5 m) (after Woodland Carbon Code 2020). The assumption is that once the hedge reaches a biomass of 66 t C ha^{-1}, gains in biomass are matched by losses due to hedge maturity and management.

4.3 Carbon sequestration by mature hedgerows and height increases

Axe et al. (2017) provides some data on how changes in hedge height could affect carbon storage, based on hawthorn hedges in England (Figure 10). Using a logarithmic regression line forced through the origin, the mean above-ground carbon storage was 33 t C ha^{-1} for a hedge height of 2 m and 40 t C ha^{-1} for a hedge height of 3 m. Hence assuming that this could be achieved over 5 years, this represents an increase of **1.4 t C ha^{-1} yr^{-1}**.

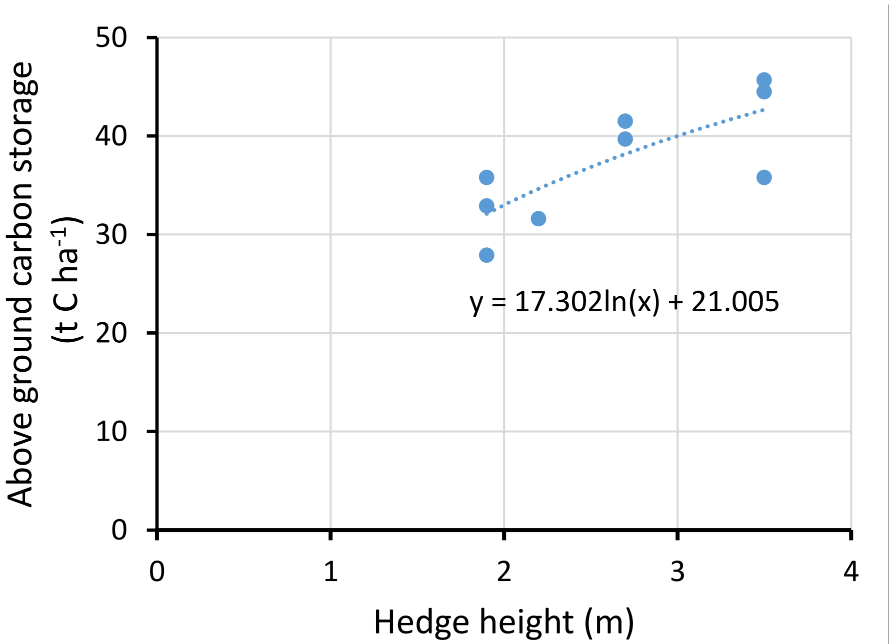

Figure 10. Relationship between hedge height and above ground carbon storage (from Axe et al. 2017)

4.4 High stem silvoarable agroforestry

There is a continuum between the lines of trees described in Section 4.1 and the establishment of silvoarable agroforestry systems. Silvoarable systems can range from widely-spaced alley systems where arable cropping continues indefinitely, to narrow alley systems where arable cropping may only be maintained for 5-10 years (Figure 11, Figure 12). The type of system has important implications on the continuation of food production and the carbon sequestration rates. The carbon storage by silvoarable systems vary greatly and is dependent on the location, the tree species, the tree spacing, and the tree management (Kay et al., 2019). Unlike the values for tree lines on field boundaries, the values presented below relate to **the whole field**.

a) Wide alley

b) Narrow alley

Figure 11, Contrasting silvoarable systems with a) 24 m alleys and 3 m tree strips, and b) 8 m alleys and 2 m tree strips (Photos by Paul Burgess)

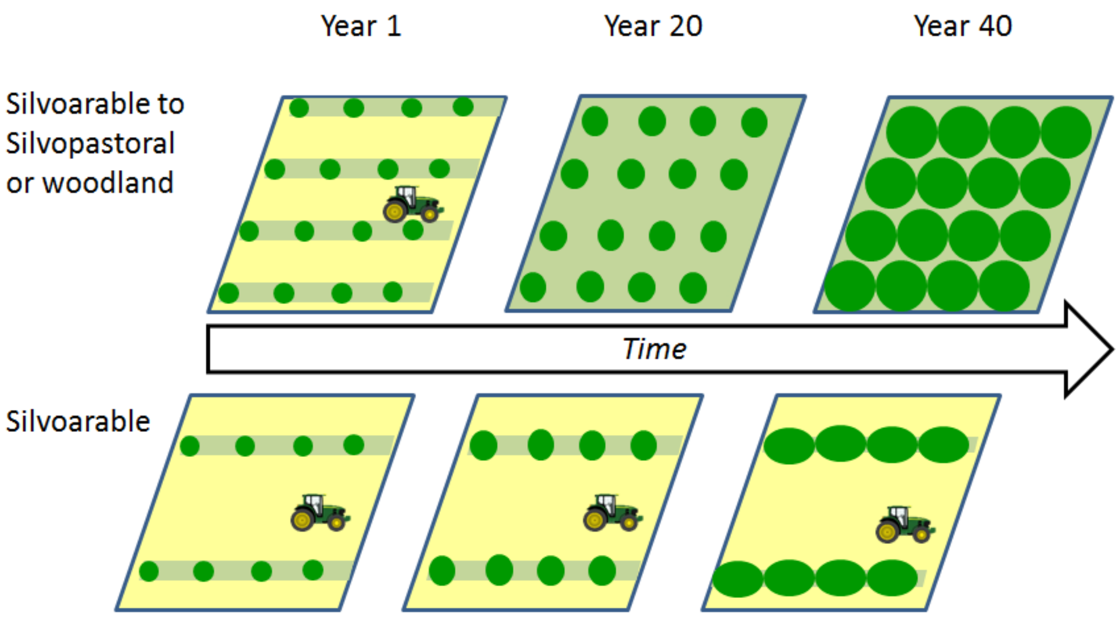

Figure 12, Schematic diagram showing the two types of silvoarable system

An example of a 24 m wide alley silvoarable system is the apple agroforestry system established at Whitehall Farm near Peterborough by Stephen Briggs (Figure 11a). In October 2009, 52 ha on the organic farm with a peat soil were converted to an agroforestry system using 4,500 apple trees (i.e. 86 trees ha^{-1}), covering 13 varieties (Franchella et al., 2016). Winter oats, wheat, vegetables, and legume fertility-building leys have been grown in 24 m-wide crop alleys and 3 m tree strips sown with wild flowers (total width = 27 m). The apples are harvested and used to produce direct sale or juicing.

An example of a narrow alley poplar silvoarable system was the planting of poplars at a 10 m x 6.4 m spacing on arable land as part of the UK silvoarable network (Burgess et al. 2003). Upson (2014) reported a net carbon sequestration in vegetation biomass of 156 poplar trees ha^{-1} of 33.6 t C ha^{-1} (Table 16), equivalent to 1.65 t C ha yr^{-1} over 19 years. This is within the range of 0.16 to 2.80 t C ha^{-1} yr^{-1} reported for the vegetation biomass sequestration across four high-stem silvoarable systems in Europe in the Appendix (Kay et al. 2019).

Table 16. Reported annual carbon sequestration rates of a poplar (10 m x 6.4 m) silvoarable system over 19 years. Both the cropped and the agroforestry system were cropped for 11 years, and grass was grown for the last 8 years (Upson, 2014 and Upson and Burgess, 2013).

		Carbon storage (t C ha^{-1})	Time period (years)	Net carbon sequestration (t C ha^{-1} yr^{-1})
Control	Fine roots (0-150 cm) (page 73)	1.4		
	Understorey vegetation (page 151)	0.7		
	Total	2.1		
Agroforestry	Above-ground tree (Page 164)	23.6		1.24
	Understorey vegetation (page 151)	0.5		-0.01
	Below-ground tree (Page 164)	6.9		0.36
	Fine roots (0-150 cm) (page 73)	2.6		0.06
	Sub-total	33.6		
	Net change	31.5	19	**1.65**

Establishing the time series for biomass carbon: determining a time series for poplar agroforestry was determined using the Yield-SAFE agroforestry model (van der Werf et al. 2007). The model predicts an increase in vegetation carbon of 34.8 t C ha^{-1} after 19 years, compared to 33.6 t C ha^{-1} measured in the field (Figure 13). After 30 years, the predicted biomass carbon is about 63 t C ha^{-1}, equivalent to **2.1 t C ha^{-1} yr^{-1}**. This is lower than a proposed mean sequestration of 2.75 t C ha^{-1} yr^{-1} reported by Aerstens et al. (2013) in a European modelling study.

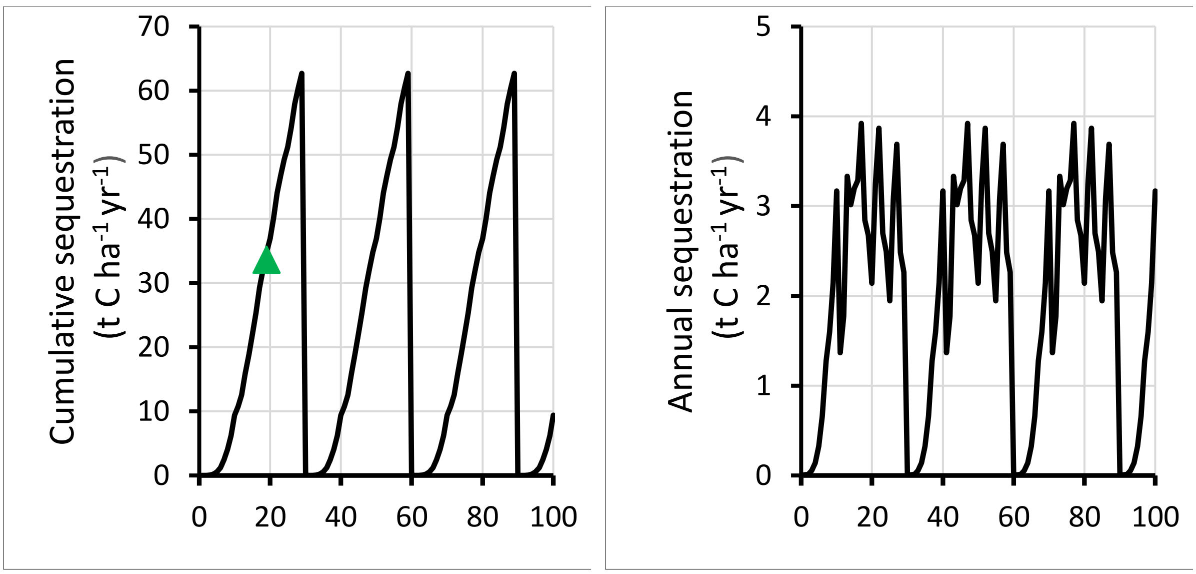

Figure 13. The predicted rate of carbon sequestration for a poplar agroforestry system (156 trees ha^{-1}) managed on a 30 year rotation using calibration data described by Upson (2014). The variation between years is due to weather variations.

One advantage of using the Yield-SAFE agroforestry model, is the capacity to also predict the effect of the system on the crop or grass yields between the tree rows. In the narrow alley system, only 80% of the total area was cropped. Over 30 years, the predicted equivalent crop yield was 26% of that of a 30-year arable control, and 45% of a combination of 12 years cropping and 18 years grass. In the first 19 years, the equivalent crop yield was 41% (Figure 14).

Figure 14. Predicted effect of 156 trees ha^{-1} at Silsoe, with 12 years arable cropping, and 18 years grass, using the Yield-SAFE model. Season to season variation is a result of assumed weather data.

4.5 Silvopasture agroforestry

A silvopasture system that has been popularised in Northern Ireland is the planting of widely spaced ash, sycamore and other broadleaf species at 400 trees per hectare (Figure 15). The reported benefits of the system include extending soil trafficability by 17 weeks, improving grass utilisation, and reducing nutrient loss to water courses (McAdam quoted by Gilliland 2020). The level of spiders, birds, and beetles in the agroforestry system are also higher than either the grassland or an ash woodland system alone.

Figure 15. Silvopasture system with ash at Loughgall in Northern Ireland (Photo by Paul Burgess)

Beckert et al. (2016) examined the carbon storage within three experimental silvopasture systems established at Glensaugh near Aberdeen in Scotland in 1988. Scots pine (*Pinus sylvestris*), hybrid larch (*Larix eurolepis*) and sycamore (*Acer pseudoplantanus*) were planted at densities of 100, 200, and 400 trees ha^{-1}. Samples were collected in the pasture and the agroforestry sites in 2012, 24 years after planting. The mean level of carbon sequestration in biomass at the agroforestry sites (400 trees ha^{-1}) over 24 years was between 1.42 and 4.00 t C ha^{-1} yr^{-1} (Table 17).

Table 17. Reported annual carbon sequestration rates of three tree species (400 tree ha^{-1}) in a silvopasture system in Eastern Scotland over 24 years (derived from Beckert et al. (2016).

	Measured 24 years		Modelled 40 years	
Agroforestry	Carbon storage (t C ha^{-1})	Net change (t C ha^{-1} yr^{-1})	Carbon storage (t C ha^{-1})	Net change (t C ha^{-1} yr^{-1})
Hybrid larch (400 trees ha^{-1})	96	4.00	195	4.90
Scots pine (400 trees ha^{-1})	90	3.75		
Sycamore (400 trees ha^{-1})	34	1.42		

Time series for biomass carbon: the results from the silvopasture experiment at Glensaugh were examined in the Yield-SAFE model using mean daily meteorological data from Glensaugh for 1996 to 1999 (Rennie et al. 2017). The model was calibrated using the height and biomass measurements for the hybrid larch plots. After calibration, the model predicted a vegetation biomass at 24 years of 164 t C ha^{-1} for the woodland plot, and 98 t C ha^{-1} for the silvopasture site, compared to measured values of 167 t C ha^{-1} and 96 t C ha^{-1} (Beckert et al. 2016) (Figure 16). After 40 years, the model predicted a yield of 195 t C ha^{-1}, equivalent to

4.90 t C ha^{-1} yr^{-1}. The Yield-SAFE model was also used to predict the grass yield, resulting in a mean yield of 6.3 t ha^{-1} over 24 years and 4.8 t ha^{-1} over 40 years compared to an initial yield of 9.3 t ha^{-1}, i.e. 68% and 52% respectively (Figure 17).

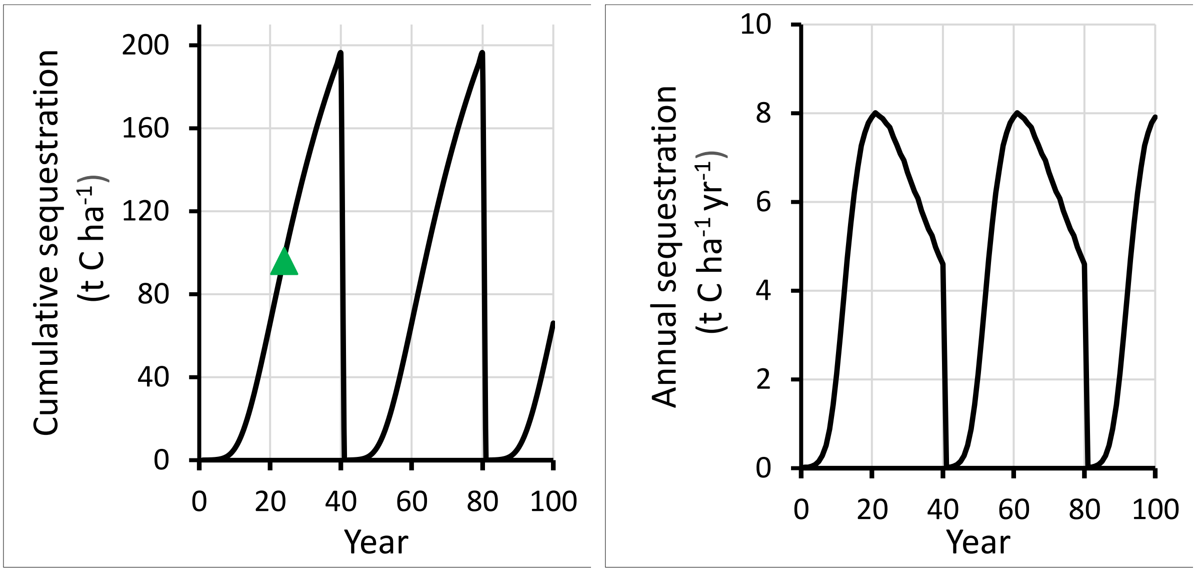

Figure 16. Predicted a) cumulative and b) annual carbon sequestration by the trees within a hybrid larch silvopasture system (400 trees ha^{-1}) managed on a 40 year rotation. Measured data at 24 years from Beckert et al. 2016 is shown.

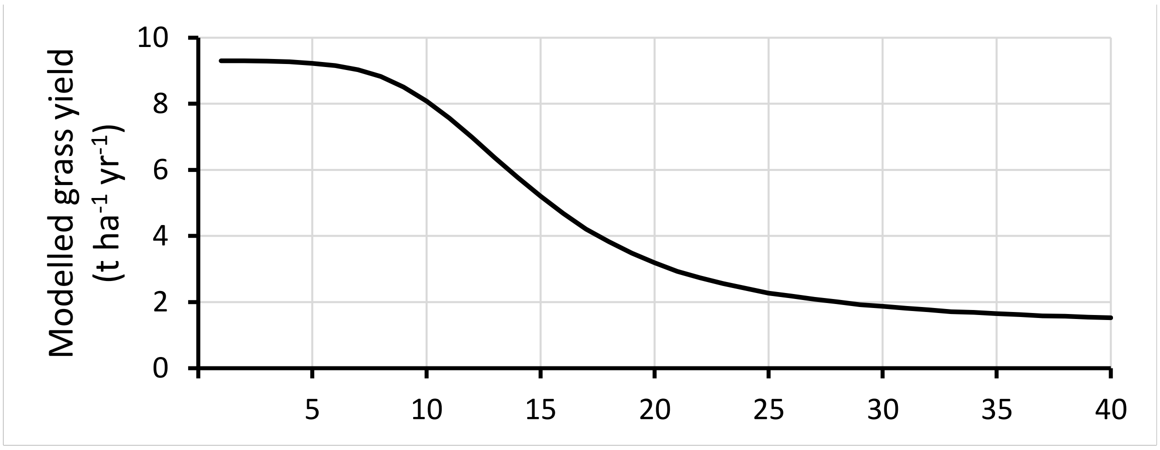

Figure 17. Predicted effect of 400 trees ha^{-1} at Glensaugh on the grass yield over 40 years, using the Yield-SAFE model

There are also some limited measurements for the ash silvopasture system planted at Loughgall in Northern Ireland in 1989, with three treatments: 100, 400, and 2500 stems ha^{-1}. Eight trees were harvested within the 400 stems ha^{-1} plot in 2011, with a mean diameter at breast height (Dbh) of 27.6 cm and a mean height of 14.9 m (Rodrigo Olave, personal communication 2022). Using weather data from Loughgall, the Yield-SAFE model predicted a mean Dbh of 26.9 cm and a mean height of 13.4 m at 22 years (Figure 18) and a cumulative sequestration of 81 t C ha^{-1}, similar to the values obtained at Glensaugh. This would imply a biomass sequestration rate of 3.68 t C ha^{-1} yr^{-1}, which is higher than the value of 2.4 t C ha^{-1} yr^{-1} quoted by Gilliland (2020) for the system.

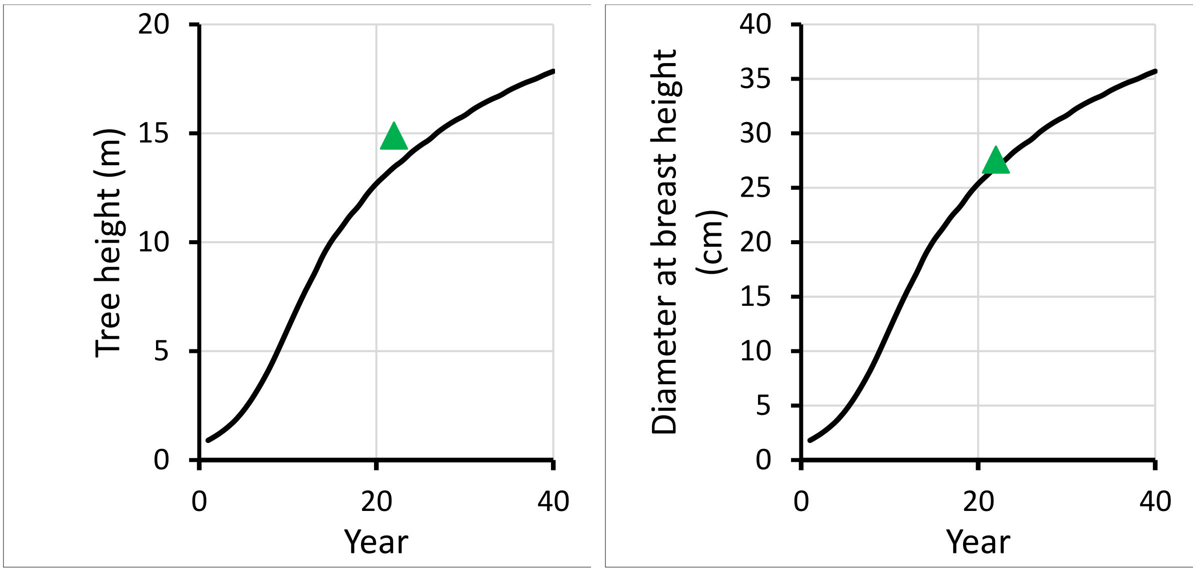

Figure 18. Predicted a) height and b) diameter at breast height of the ash trees at Loughgall using the Yield-SAFE model. Measured data at 22 years from Olave 2022 is shown.

In Bedfordshire, Upson et al. (2016) reported a mean rate of vegetation carbon of 35.9 t C ha^{-1} for a 14 year old woodland, equivalent to 2.56 t C ha^{-1} yr^{-1} (Table 18). A parkland agroforestry system with 4% tree coverage achieved about 11% of this value.

Table 18. Measured tree biomass carbon of a 14-year old woodland and a parkland silvopasture system (Upson et al. 2016)

	Total tree carbon storage (t C ha^{-1})	Time period	Net change (t C ha^{-1} yr^{-1})
Agroforestry 4% coverage; 64 trees ha^{-1}	4.0	14	0.28
Mixed broadleaf 1600 trees ha^{-1}	35.9	14	2.56

The assumed value of **4.90 t C ha^{-1} yr^{-1}** over 40 years, based on the results at Glensaugh, is higher than the value reported for the silvoarable system of 2.10 t C ha^{-1} yr^{-1} over 30 years (Table 16). The reasons for the greater increase include the higher tree density (400 v 156 trees ha^{-1}) and the longer time period so that the trees are sequestering carbon for longer (40 v 30 years). The mean value for the parkland silvopasture system (4% coverage) over 14 years was 0.27 t C ha^{-1} yr^{-1}. If the number of trees was increased to 400 trees ha^{-1}, this value could increase to 1.60 t ha^{-1} yr^{-1}. The lower value for the parkland site may be a result of the shorter time period, as tree growth is generally greatest beyond 10 years after planting. The values reported are within the range of 0.58 to 4.68 t C ha^{-1} yr^{-1} reported across eight silvopasture systems reported in the Appendix (Table 26).

4.6 Summary

- Agroforestry systems can be divided between boundary planting systems and within field systems. The effect of high tree densities in field-systems on food production and livelihoods need to be considered.

5 Scaling up

The preceding three sections have focused on i) the rate of greenhouse gas emissions of the baseline agricultural enterprise, ii) the level of soil carbon emissions and sequestration, and iii) the carbon sequestration in tree biomass. In this section we bring the results together and examine the implications at a national scale. The results are expressed in terms of CO_2e.

5.1 Potential greenhouse gas abatement from agroforestry

The effect of six interventions on greenhouse gas sequestration were examined (Table 19). The interventions on cropland were relatively consistent ranging from 7.0 to 8.3 t CO_2e ha^{-1} yr^{-1}, which relative to a typical emission on cropland of 1.9 t CO_2e ha^{-1} yr^{-1}, results in a benefit of 8.9 to 10.2 t CO_2e ha^{-1} yr^{-1}. These values are about half of that reported as the mean carbon sequestration of unharvested conifers over 100 years of about 19 t CO_2 ha^{-1} yr^{-1} reported by Forester et al. (2021).

The mean carbon sequestration rates with the shelterbelt and hedgerow systems on grassland over 40 years of 6.1-6.3 t CO_2e ha^{-1} yr^{-1} was lower than the cropland systems (7.9-8.1 t CO_2e ha^{-1} yr^{-1}) because of the lack of a soil carbon benefit. The greatest carbon sequestration benefit was predicted for the 400-tree ha^{-1} silvopasture system equivalent to a mean sequestration of 15.9 t CO_2e ha^{-1} yr^{-1} over 40 years (Table 19).

Table 19. Predicted greenhouse gas emissions (negative values) or carbon sequestration (positive values) of shelterbelt, hedgerow, silvoarable and silvopasture systems on either cropland or grassland

Baseline (t CO_2e ha^{-1} yr^{-1})	Intervention (width in brackets)	Time (yr)	Sequestration (t C ha^{-1} yr^{-1})		Greenhouse gas sequestration (t CO_2e ha^{-1} yr^{-1})			
			Soil	Tree	Crop & livestock	Soil	Tree	Total
Cropland	Shelterbelt (6 m)	40	0.50	1.72	0.00	1.83	6.31	8.14
-1.87	Hedgerow (2 m)	40	0.50	1.66	0.00	1.83	6.09	7.92
	Silvoarable	19	0.46	1.65	-0.77[b]	1.69	6.05	6.97
	Silvoarable	30	0.29	2.10	-0.49[b]	1.06	7.70	8.28
Grassland	Shelterbelt (6 m)	40	0.00	1.72	0.00	0.00	6.31	6.31
-3.94[a]	Hedgerow (2 m)	40	0.00	1.66	0.00	0.00	6.09	6.09
	Silvopasture	24	0.00	4.08	-2.64[c]	0.00	14.97	12.33
	Silvopasture	40	0.00	4.90	-2.05[c]	0.00	17.97	15.92

[a]: note that in this example, the grassland baseline was assumed to be 3.94 t COe ha^{-1} yr^{-1}, which is 0.61 t CO_2e ha^{-1} yr^{-1} higher than the counterfactual calculated in Table 6.

[b]: the silvoarable crop-related emissions were assumed to be directly related to a mean crop yield that was 41% of the baseline value during years 1-19, and 26% during years 1-30.

[c]: the silvopastoral livestock-related emissions were assumed to be directly related to a mean grass yield that was 67% of the baseline value during years 1-24, and 52% during years 1-40.

The expansion of shelterbelts and hedgerows on crop land and pasture land by 10,000 ha in year 1, would result in a mean saving of 98-102 kt CO_2e yr^{-1} over the subsequent 40 years (Table 20). The lack of an assumed SOC benefit with trees on pasture was balanced by the assumed reduction in livestock emissions.

Table 20. Predicted annual saving of greenhouse gases over 40 years assuming 10,000 ha planted to the system in year 1

Land Cover	Area (million ha)	Intervention	Time Period	Addition	Increased area (ha)	Net benefit (kt CO_2e yr^{-1})
Cropland	4.84	Shelterbelt (6 m)	40	23.64%	10000	100
	4.84	Managed hedgerow (2 m)	40	23.64%	10000	98
	4.84	Silvoarable (41% crop)	19	0.21%	10000	88
	4.84	Silvoarable (26% crop)	30	0.21%	10000	101
Grassland	11.18	Shelterbelt (6 m)	40	10.24%	10000	102
	11.18	Managed hedgerow (2 m)	40	10.24%	10000	100
	11.18	Silvopasture (67% stock)	24	0.09%	10000	163
	11.18	Silvopasture (52% stock)	40	0.09%	10000	199

The expansion of silvoarable systems to 0.21% of the cropland area, equivalent to 10,000 ha, would result in a reduction in emissions by a mean of 101 kt CO_2e yr^{-1} over 30 years. Such an increase would represent a substantial increase in the area of silvoarable systems. Den Herder et al. (2017) estimated an area of 2,000 ha of silvoarable agroforestry in the UK using the LUCAS land cover and land use dataset derived from sample points at intervals of 4 km x 4 km in 2012.

The planting of silvopasture systems (400 trees ha^{-1}) was predicted to result in a mean annual carbon abatement of 15.9 t CO_2e ha^{-1} yr^{-1} over 40 years. Expanding the area of silvopasture agroforestry by 10,000 ha, i.e. 0.09% of the grassland area, was predicted to result in a mean saving of 199 kt CO_2e yr^{-1} over 40 years (Table 20).

5.2 Sequencing of planting

The above values assume that all of 10,000 ha of planting occurs in year 1. In practice the planting of 10,000 ha may occur from planting 1000 ha per year in years 1-10, 500 ha per year in years 1-20, or 250 ha per year in years 1-40. The total carbon sequestration will eventually be the same, but the timing of the annual carbon sequestration across the 10,000 ha will vary substantially (Figure 19). The effect of planting 1,000 ha each year in years 1-10, rather 10,000 ha in year 1 was to move the peak in greenhouse gas abatement by 5 years, and to reduce the peak by 4%, and to reduce the emission reduction within the next 40 years by 12%. Planting 500 ha each year in years 1-20, delayed the peak by another 8 years, reduced the peak by 8%, and the emissions reduction in the next 40 years by 29%. Planting 250 ha over 40 years, reduced the emissions reduction in the next 40 years by 60%.

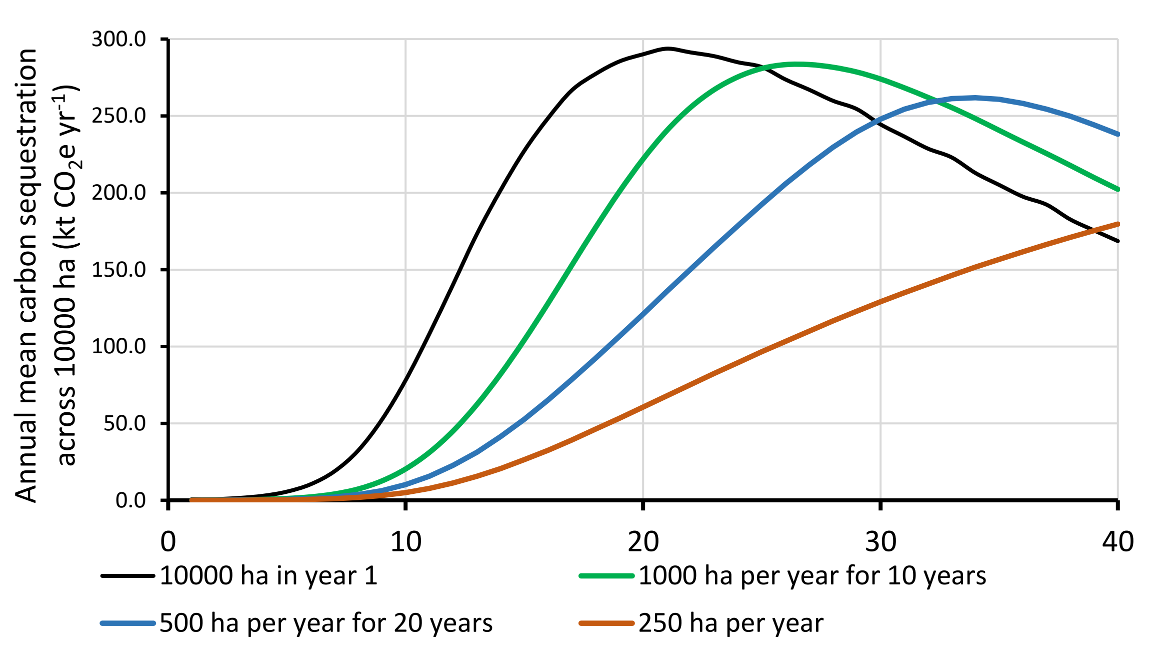

Figure 19. Different planting rates based on the silvopasture examine. For example of 10,000 ha, will affect the temporal distribution of the reduction in greenhouse gases. Planting all 10,000 ha at one time, will result in peak sequestration at about 20 years.

The phasing of the silvoarable and shelterbelt systems were also examined. From the analysis, it is apparent that the predicted carbon sequestration using the Yield-Class model for the agroforestry systems (Figure 19, Figure 20), results in earlier sequestration than that predicted from the Forest Research Woodland Code model (Figure 21). The reason for this difference has still to be established.

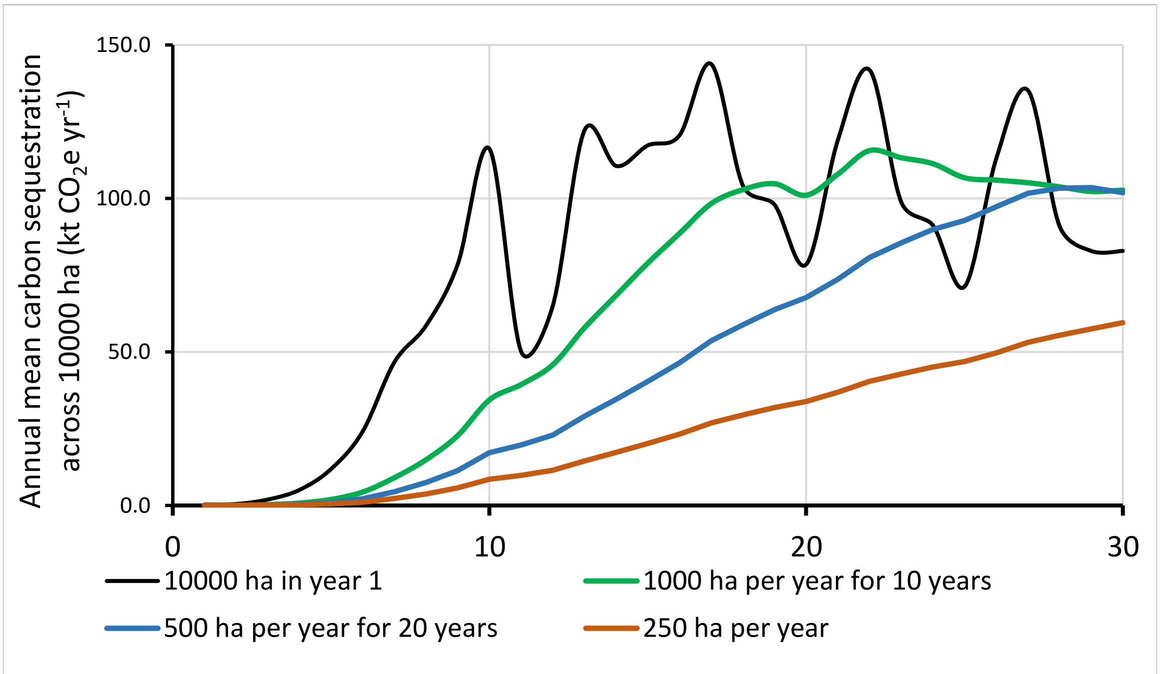

Figure 20. Planting rates of the silvoarable system (156 trees ha^{-1}) affects the predicted temporal distribution of the carbon sequestration. Planting all 10,000 ha at one time, will result in peak sequestration at about 15 years. Substantial variation in the carbon sequestration when the systems were all planted in year 1 is due to the assumed weather.

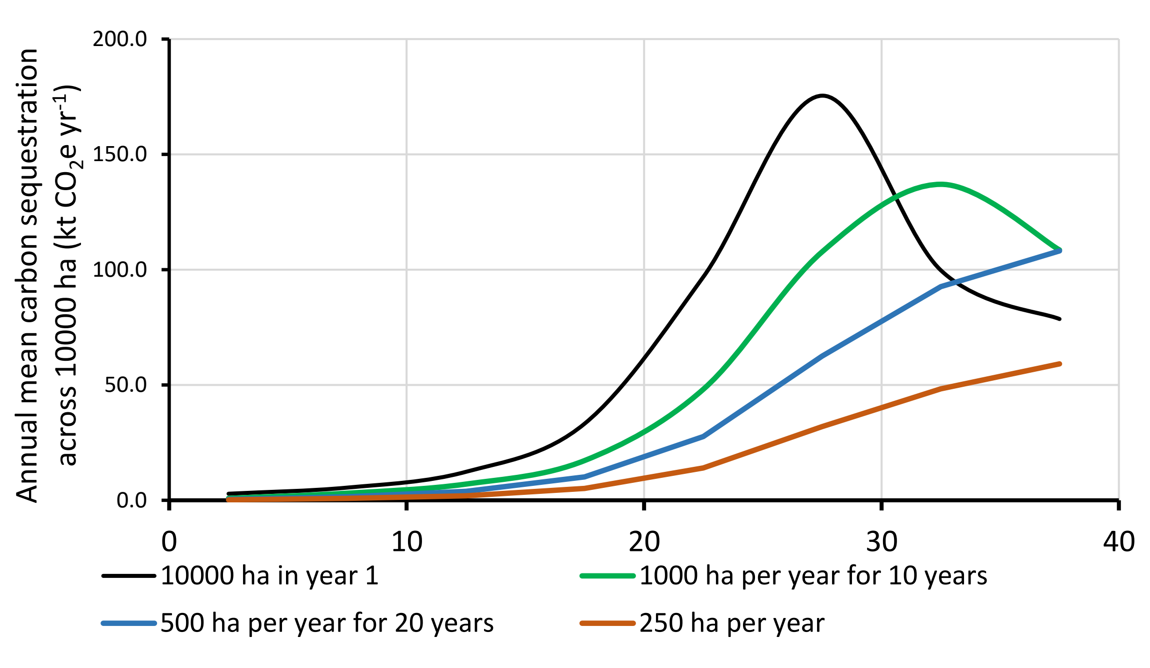

Figure 21. Planting rates of the shelterbelt, based on Woodland Code values, affects the temporal distribution of the reduction in greenhouse gases. Planting all 10,000 ha at one time, will result in peak sequestration at about 25 years.

5.3 Scaling the silvoarable results to all UK arable land

It was assumed that the baseline arable land in the UK was 4.84 million ha (Table 7), with a mean level of greenhouse gas emission of 1.87 t CO_2e ha^{-1} yr^{-1} (Table 6). Into this area, it was assumed that agroforestry systems would be planted over 10, 20, 30 and 50% of the arable land area. It was assumed that a constant area would be planted each year starting in 2022 and achieving the total area over 30 years by 2052. Thereafter it was assumed that no additional land was planted, but trees reaching 30 years would be harvested and the area replanted. It was assumed that the harvested wood would be used in ways that would maintain the permanence of carbon storage.

The silvoarable intercrop was assumed to cover 80% of the silvoarable system for the first eight years of the rotation, after which, it was assumed that the intercrop would no longer be cultivated due to declining yields and profitability. To simplify the analysis, it was assumed that the yield of the silvoarable crop yield over the first eight years would be 80% of the arable yield, which is equivalent to a mean crop yield of 21% of the arable crop control over a 30 year rotation.

Four scenarios were considered: planting 10, 20, 30 and 50% of the arable area meaning a total final area of 484,000, 968,000, 1,452,000, or 2,420,000 ha of silvoarable agroforestry (Figure 22). To achieve this over 30 years, required the planting of 16,133, 32,267, 48,400, and 80,667 ha per year respectively.

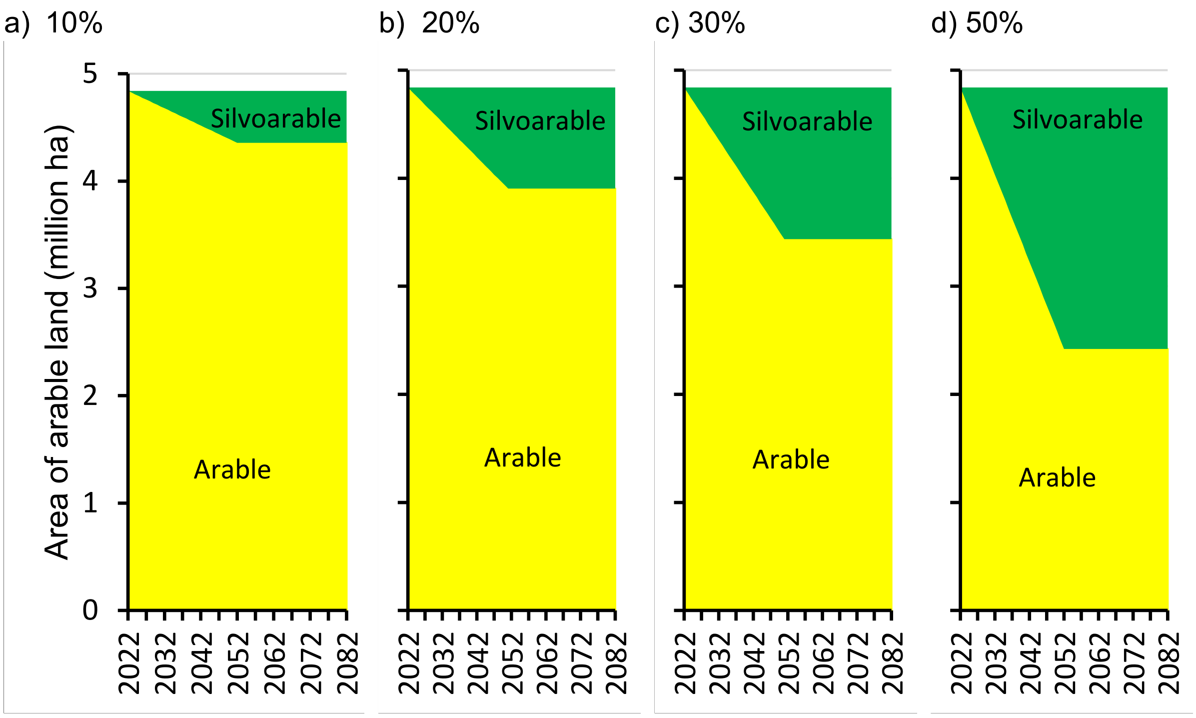

Figure 22. The assumed area of UK arable land and conversion to silvoarable agroforestry over 30 years to achieve a final area in 2052 of a) 10%, b) 20%, c) 30%, and d) 50% silvoarable.

The baseline arable system was calculated to emit 9.05 Mt CO_2e each year (Table 21), equivalent to a cumulative total of 534 Mt CO_2e between 2022 and 2080. Planting 10% of the arable area to the selected silvoarable system reduced emissions but was unable to achieve net zero. By contrast, planting 20% of the arable area was sufficient to achieve net zero greenhouse gas emissions by 2048, 26 years after the first planting in 2022. The level of steady state emissions was calculated to be 1.43 Mt CO_2e per year (Table 21). Planting 17% of UK arable land was predicted to result in emissions being in exact balance with sequestration after 30 years.

Table 21. Predicted levels of GHG emissions from allocating 10%, 20%, 30%, and 50% of UK arable land to the selected silvoarable system over 30 years

Proportion converted to silvoarable	Area of UK arable land or total converted to silvoarable (million ha)	Annual conversion (ha yr^{-1})	Steady state GHG balance after year 30 (Mt CO_2e yr^{-1})	Relative arable production at steady state (%)	Year in which net zero achieved	2022-2080 balance (Mt CO_2e)
Baseline (0%)	4.840		-9.05*	100*	-	-534
10%	0.484	16,133	-3.81**	92**	Na	-317
20%	0.968	32,267	1.43**	84**	2048	-100
30%	1.452	48,400	6.66**	76**	2042	117
50%	2.420	80,667	14.14**	61**	2037	550

Notes: Na: not achievable. *The steady state for the baseline is constant between 2022 and 2080. **The steady state for the scenario is achieved from 2051 – 2080 when the total area of land to be converted to silvoarable.

Planting 30% of the arable area was calculated to result in net zero emissions from arable land by 2042, and planting 50% would achieve net zero by 2037. After year 30, the net greenhouse gas balance was assumed to be 6.66 and 14.14 Mt CO_2 yr^{-1} for the 30% and 50% scenario respectively.

The use of the model also allowed calculation of the level of arable crop production relative to the control of no tree planting. The relative level of arable crop production for the 10%, 20%, 30%, and 50% scenarios were 92%, 84%, 76%, and 61% respectively (Table 21).

5.4 Scaling the silvopastoral results to all UK grassland

As described in Table 7, the combined area of temporary and permanent grassland in the UK is 11.18 million ha. The effect of planting the modelled larch silvopastoral system on 10, 20, 30, and 50% of the grassland area on carbon sequestration was modelled relative to an assumed baseline emission of 3.94 t CO_2e ha^{-1} yr^{-1}. For the scaling-up activity, it was assumed that the total area would be achieved by an equal annual planting rate over 40 years, so that wood production and the harvested yield each year would eventually reach a steady state. Assuming that the planting would start in 2022, this meant that the final planting of new land would be in 2062, for trees with a 40-year rotation. After this point, it was assumed that new planting would stop. In each scenario, it was assumed that the harvested wood would be used in ways that would ensure the permanence of carbon storage. It was assumed that the areas harvested after 40 years would then be replanted. As described in Figure 17, grass yields were initially high close to tree planting and decreased as the trees grew. However, for simplicity, the silvopasture carrying capacity was assumed to be 52% of the livestock system for each year of the whole tree rotation.

For the 10, 20, 30 and 50% scenario, the total land area that would need to be converted to silvopasture was 1,118,000, 2,236,000, 3,354,000, and 5,590,000 ha (Figure 23). To achieve this over 40 years, required the planting of 27,268, 54,537, 81,805, and 136,341 ha per year respectively.

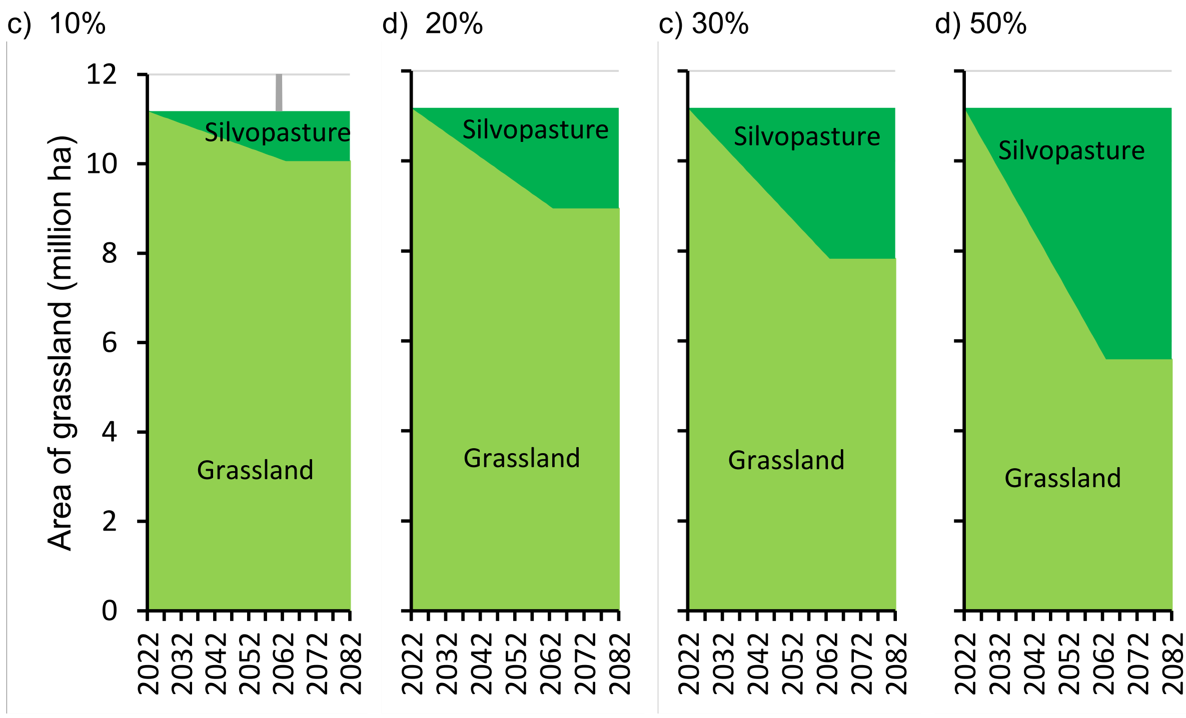

Figure 23. The assumed area of UK grassland and conversion to silvopasture over 40 years to achieve a final area in 2062 of a) 10%, b) 20%, c) 30%, and d) 50% silvopasture.

The baseline UK grassland area was calculated to emit 44.05 Mt CO_2e each year, with a cumulative total of 2,599 Mt CO_2e by the year 2080 (Table 22). Assuming that 10% of grassland was converted to silvopastoral, whilst sequestration by the trees approximately halved the emissions, it was not possible to reach net zero. Assuming that 20% of grassland was converted, by year 40 the assumed emissions from the grassland systems was still marginally greater than the sequestration by the silvopastoral system in 2062. By contrast, assuming that 30% of the grassland was planted to silvopastoral agroforestry, it was possible to achieve net zero greenhouse emissions across the combined grassland and silvopastoral area by 2051. When the 30% system reached a “steady state” in 2062, the mean annual rate of sequestration was calculated to be 21.08 Mt CO_2e yr^{-1}. Planting just over 20% of UK grassland was predicted to result in emissions being in exact balance with sequestration after 40 years.

Table 22. Predicted levels of GHG emissions from allocating 10%, 20%, 30%, and 50% of UK grassland to the selected silvopastoral system

Proportion converted to silvopasture	Area of UK grassland or total converted to silvopasture (million ha)	Annual conversion (ha yr^{-1})	Steady state GHG balance after year 40 (Mt CO_2e yr^{-1})	Relative livestock production at steady state (%)	Year in which net zero achieved	2022-2080 balance (Mt CO_2e)
Baseline (0%)	11.180		-44.05*	100*	-	-2,599
10%	1.118	27,268	-22.34**	95**	Na	-1,847
20%	2.236	54,537	-0.64**	90**	Na	-1,095
30%	3.354	81,805	21.07**	86**	2051	-343
50%	5.590	136,341	64.48**	76**	2044	1,160

Notes: Na: not achievable. *The steady state for the baseline is constant between 2022 and 2080. **The steady state for the scenario is achieved from 2062 – 2080 when the total area of land to be converted to silvopasture is achieved.

Using the model, it was also possible to calculate the assumed relative level of livestock production in each scenario (Table 22). Compared to 100% livestock production in the baseline scenario, livestock output in the 10, 20, 30 and 50% scenarios were calculated to be 95%, 90%, 86%, and 76% at steady state respectively.

5.5 Comparison with published values

The Committee on Climate Change (2020b page 67) produced some pathways to reduce net emissions from land use, land use change, and forestry agriculture from current emissions of 6-10 Mt CO_2e yr^{-1} to a net zero value by about 2035, and to become a net sink of greenhouse gases equivalent to 19 Mt CO_2e yr^{-1} by 2050. That proposal suggested that agroforestry could account for about 3 Mt CO_2e yr^{-1} of abatement in 2050 compared to about 10 Mt CO_2e yr^{-1} from afforestation (Figure 24).

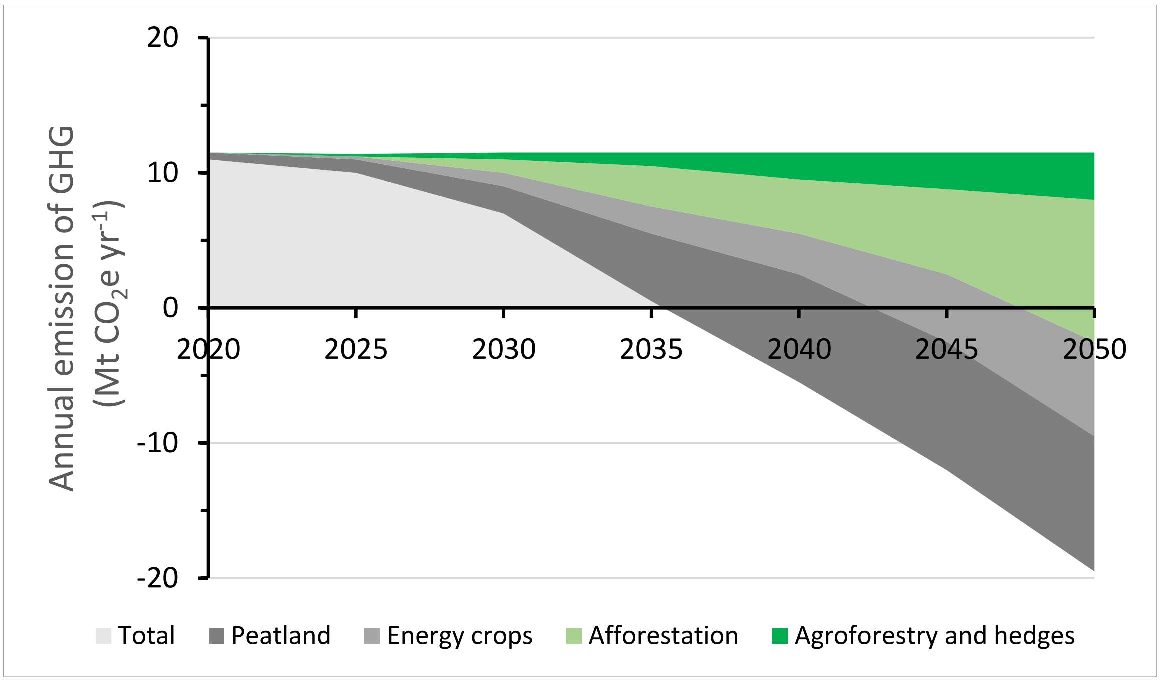

Figure 24. Schematic demonstration of abatement in the land use and land use change and forestry sector in the Balanced Net Zero Pathway (after CCC 2020b, page 171)

The Committee on Climate Change (2020b page 170) reports that annual carbon removals of 1 Mt CO_2e by 2035 and nearly 3 Mt CO_2e by 2050 could be achieved by "the integration of trees on 10% of farmland and extending the length of hedgerows by 40% by 2050" together "with better woodland and hedge management". By contrast UK Government (2020) report an estimate of 5.9 Mt CO_2e per year sequestered by agroforestry by 2050.

The analysis of expansion of either shelterbelts and hedgerows on crop land and pasture land by 10,000 ha in year 1, would result in a mean saving of 80-99 kt CO_2e yr^{-1} over the subsequent 40 years. Assuming a mean width of 2 m, the length of hedgerows and lines of trees in Great Britain would be 140,000 ha, which is similar to the estimate of 120,000 ha quoted by the Committee on Climate Change (2018). Taking a value of a 40% increase implies an increase of 56,000 ha, is predicted to result in a mean reduction in greenhouse gas emissions of about 0.56 Mt CO_2e yr^{-1} over 40 years, which is similar to the value of 0.5 Mt CO_2e yr^{-1} reported by NFU (2019) for hedgerow expansion.

The balanced land use pathway reported by the Committee on Climate Change (2020b page 76) suggests an increase in the area of agroforestry and hedgerows from about 0.9% in 2019 (220,000 ha) to 1.8% in 2050 (440,000 ha) of the UK. Subtracting the increase in hedgerows of 56,000 ha, implies an increase in agroforestry of 164,000 ha. If all of this was planted to silvopasture, say in 2023, then the mean carbon abatement of the next 40 years could be 3.3 Mt CO_2e yr^{-1}. Integrating silvopasture systems on 1% of pasture land in the UK, i.e. 111,800 ha, all in 2020, would imply a reduction of emissions of 2.22 Mt CO_2e over the subsequent 40 years. To achieve an abatement of 5.9 Mt CO_2e yr^{-1}, would require 290,000 ha, or 2.6% of the grassland area.

The current level of greenhouse gas emissions from UK agriculture is 46 Mt CO_2e yr^{-1}. In order to balance these emissions, on average, over the next 40 years, could be achieved by the **immediate** planting of 2,230,000 ha of silvopasture agroforestry, equivalent to 21% of the UK grassland area. This estimate is lower than the CCC's estimate (2020a, page 8) that agroforestry, presumably on 10% of agricultural land (~1,600,000 ha), whilst maintaining its primary use, would only provide a benefit of 6 Mt CO_2e yr^{-1} by 2050. Over the next 40 years, assuming that the planting took place equally across all grassland, the anticipated reduction in the available grass crop in that period would be about 10%.

5.6 Importance of the use of harvested wood

Eventually in a tree rotation, there is the opportunity to harvest the wood sequestered in a hedgerow or agroforestry system. In most cases, a hedgerow will not produce marketable timber, although analyses of the costs and benefits of using hedgerows to produce coppiced wood have been investigated (Smith et al. 2021). The use of wood to store carbon in harvested wood products and through the displacement of mineral construction materials is a key consideration in ensuring long-term greenhouse gas benefits. In the future, there is the hope that wood may form part of a carbon capture and storage system, but commercial systems still have to be developed.

5.7 Socio-economic considerations

At COP26 in Glasgow, it was agreed that the transition to a global net zero economy should occur "at the lowest possible economic cost" (Hibberd 2021). In a detailed study of the economic costs of abatement options in France, agroforestry was seen to have a cost, but it was competitive with other abatement options (Pellerin et al. 2017). Although the Committee of Climate Change (2020c, page 239) assumes that the cost of agroforestry per abated tonne of greenhouse gas is higher than the planting of broadleaf and coniferous woodland, in the policy report the private cost of agroforestry is assumed to be substantially lower (Committee of Climate Change 2020c, page 152).

In addition to the economic calculations, means of carbon sequestration need to be socially acceptable. The Committee on Climate Change (2020b, page 50), reported that 99% of the participants in The Climate Assembly supported tree planting. The Committee on Climate Change (2020c, page 153) also outlines the knowledge-intensive nature of climate smart farming and the need for trusted advisors, colleges and universities to develop projects to demonstrate the benefit of agroforestry.

6 Recommendations

Determining the capacity of land management practices, such as agroforestry, to reduce net greenhouse emissions is not easy, and the science and regulation of the area is developing. However, a number of recommendations can be established.

6.1 A systems perspective with multiple objectives

Farmers and landowners need to continue producing food and securing a livelihood at the same time as contributing to net zero greenhouse emissions and enhanced biodiversity. It is easy to reduce greenhouse gas emissions by reducing food production, but the UK still needs to produce food. Defra Minister of State, Victoria Prentice, at the 2022 Oxford Real Farming Conference indicated that the net level of food imports should not exceed 40% of total food consumption. This report does not specifically consider biodiversity, but any tree planting plan should consider the effects of biodiversity. For example, the Committee on Climate Change (2020b) proposed that policies to promote tree planting must also “account for the challenges of the changing climate and reflect wider environmental priorities, including for biodiversity, to harness potential synergies and avoid unnecessary trade-offs”.

6.2 Importance of baselines

A key feature in any carbon sequestration scheme is the establishment of the baseline. As indicated in Section 2, this report highlights the benefits of farming businesses in establishing a carbon inventory and current levels of greenhouse gas emissions. National greenhouse emission values suggest that mean baseline emissions from cropland may be about 2 t CO_2e ha^{-1} yr^{-1}, and those from livestock farms may be about 4 t CO_2e ha^{-1} yr^{-1}. In addition to being importance for management, baselines are important for establishing carbon credits or demonstrating net zero emissions.

6.3 Agroforestry is part of the portfolio to reduce farm-level emissions

No single intervention will allow the UK to achieve net zero, and a portfolio of approaches is needed. Dietary changes, such as reduced human consumption of animal-derived products, and reduced waste along the food supply chain are important. Methods to reduce methane and nitrous oxide emissions whilst maintaining food production should be sought. However even with these changes, there is a need to promote land use and land use change practices that sequester carbon. As 70% of the land in the UK is farmed, integration of trees on farms will be critical for the UK to meet its tree planting targets. Agroforestry, the integration of trees, on farms is therefore important, and the scenarios produced by the Committee on Climate Change suggest that the contribution of agroforestry may be about a third of that of afforestation.

6.4 Species selection

In determining the effect of agroforestry on carbon sequestration, the choice of tree species is important. This is exemplified by the results at Glensaugh where the biomass accumulation by hybrid larch and Scots pine was 164-182% higher than for sycamore. The online ecological site classification tool provided by Forest Research (2021) can be particularly helpful. For example, it indicates that sycamore is not a suitable species for Glensaugh in Scotland.

6.5 Temporal nature of agroforestry on greenhouse gas emissions

The carbon benefits of incorporating trees on farm cannot continue indefinitely unless a way is found to harvest and permanently store the wood elsewhere. Eventually, if the trees are not harvested the carbon absorption and emissions from trees reach an equilibrium. For example, it is considered that existing forests in Europe are close to a carbon balance (Naudts et al. 2016).

An interesting technical feature that has arisen from the analysis is that the rate of carbon sequestration seems to be quicker with the agroforestry systems, using the Yield-SAFE model, than using the forestry models associated with the Woodland Code. The reason for this difference and identifying which is correct is worth further study.

6.6 Agroforestry is likely to contribute to farm greenhouse gas budgets rather than tradeable carbon credits

The creation, sale, and regulation of carbon credits, such as through the Woodland Code, is a rigorous process, and the costs of administering and verifying the code can swamp the benefits. To be accredited, the system needs to demonstrate both additionality and permanence. Additionality refers to the situation where the change would not occur without a carbon market (Harrison 2021). Permanence refers to the permanence of the removal, and the Task and Finish Group (2021) suggest that if one tonne of CO_2 is only retained for century, it should only be worth, at most, 39% of a credit. In addition, prior to the start of a project, there can be a need to record the condition of the vegetation and soil before planting, and assumptions regarding carbon stocks need to be validated (Task and Finish Group 2021).

Changing agricultural land to woodland involves changes in the status of the land, and reverting forest land to agricultural land is very difficult. By contrast, there can be greater flexibility in establishing agroforestry, particularly if the trees species planted are fruit or nut trees. In general, despite their importance, in some countries, such as Ireland, the carbon storage of hedgerows is not included within the national greenhouse gas inventory (Duffy et al, 2020). Agroforestry therefore offers flexibility and can be useful in contributing to net zero farm budgets, but most agroforestry systems (because of their variability) are unlikely to result in tradeable carbon credits.

6.7 Skills and supply chains for agroforestry

The Committee on Climate Change (2020a) set out detailed recommendations on policy for land and agriculture in January 2020. Their priorities were to “strengthen regulatory baselines to ensure low-regret measures, incentive schemes such as auctioned contracts to drive afforestation; and enabling measures to address issues such as skills, supply chains to reduce barriers for tenant farmers”.

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8 Appendix

8.1 Sequestration by woodland

Describing the carbon sequestration of different forms of woodland is not easy. One of the key issues is that the rate of sequestration changes with time from planting. This is demonstrated clearly in existing models of woodland sequestration. So that the work in this report fits alongside woodland carbon sequestration model, the key features of woodland carbon sequestration are outlined below.

In the UK National Greenhouse Gas Inventory, the carbon uptake by forests is calculated using the CARBINE carbon accounting model managed by Forest Research. The key inputs for the model are the areas of new forest planted in each year, the stem wood growth rate, and the management and harvesting pattern. The CARBINE model is based on Yield-Class tables. The carbon estimates in the lookup tables for the Forestry Commission's Woodland Carbon Code are based on the output from another model called CSORT, which is based on CARBINE (Randle and Jenkins 2011).

Broadleaf woodland: Thomson et al. (2008) assumed that all broadleaf forests had the characteristics of beech (*Fagus sylvatica* L.) of yield class 6, with an initial planting density of 1.2 m x 1.2 m. One way of describing tree growth is to divide the growth into four periods: establishment (0-10 years), initial (10-40 years), full vigour (40-100 years), and mature (100-200 years) (Table 3.3). The sigmoidal growth pattern of woodland growth results in low sequestration of carbon for the first 10 years followed by high rates of sequestration at 10-40 years, and then a decline in carbon sequestration (Figure 25). Examples of the carbon sequestration of newly established woodland can be derived using the Woodland Carbon Code model (Woodland Carbon Code 2020). The calculated carbon sequestration includes roots, stem, branches, and foliage (West 2018). Assuming a thinned woodland over 100 years, a mean sequestration rate is about 2.6 t C ha^{-1} yr^{-1} (Table 23).

Coniferous woodland: Thomson et al. (2008) in describing the UK Greenhouse Gas Inventory reported that it was assumed that all conifers in Great Britain followed the growth pattern of Sitka spruce with a yield class of 12 m^3 ha^{-1} yr^{-1} (initial spacing = 2 m) (Figure 26). Assuming a thinned woodland over 100 years, a mean sequestration rate is about 2.4 t C ha^{-1} yr^{-1} (Table 23).

Table 23. Total carbon sequestration in vegetation (including roots and debris) of full stands of unthinned and thinned beech and Sitka spruce divided into four growth stages as derived from the Woodland Carbon calculator (Woodland Carbon Code 2020)

	Establishment period	Initial	Full vigour		Mature
Age (years)	0-10	10-40	40-100	0-100	100-200
Annual rate (t C ha^{-1} yr^{-1})					
Beech, yield class 6 unthinned	0.2	4.5	2.1	2.7	0.9
Beech, yield class thinned	0.2	4.0	2.3	2.6	1.0
Sitka spruce, yield class 12 unthinned	0.4	4.7	2.2	2.9	0.2
Sitka spruce, yield class 12 thinned	0.4	4.3	2.6	2.4	0.4
Age (years)	10	40	100		200
Cumulative totals (t C ha^{-1})					
Beech, yield class 6 unthinned	2	137	266		355
Beech yield class 6 thinned	2	89	163		188
Sitka spruce, yield class 12 unthinned	4	146	289		314
Sitka spruce, yield class 12 thinned	4	87	172		195

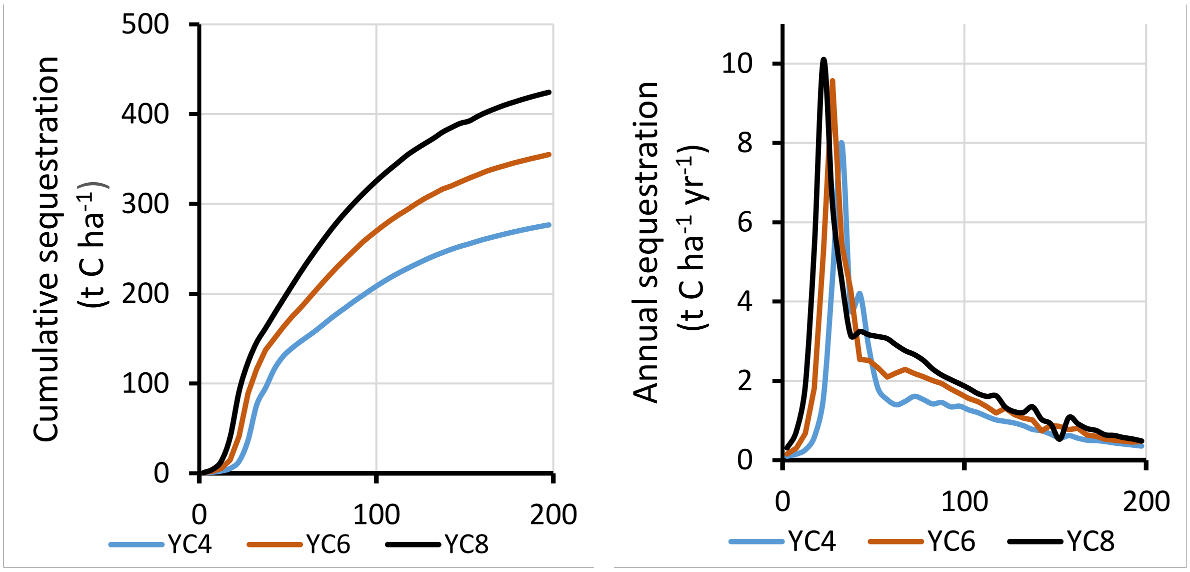

Figure 25. Predicted rate of carbon sequestration for beech (standing trees and debris) (unthinned, Yield Class = 4, 6, and 8, initial spacing = 2.5 m) (after Woodland Carbon Code 2020)

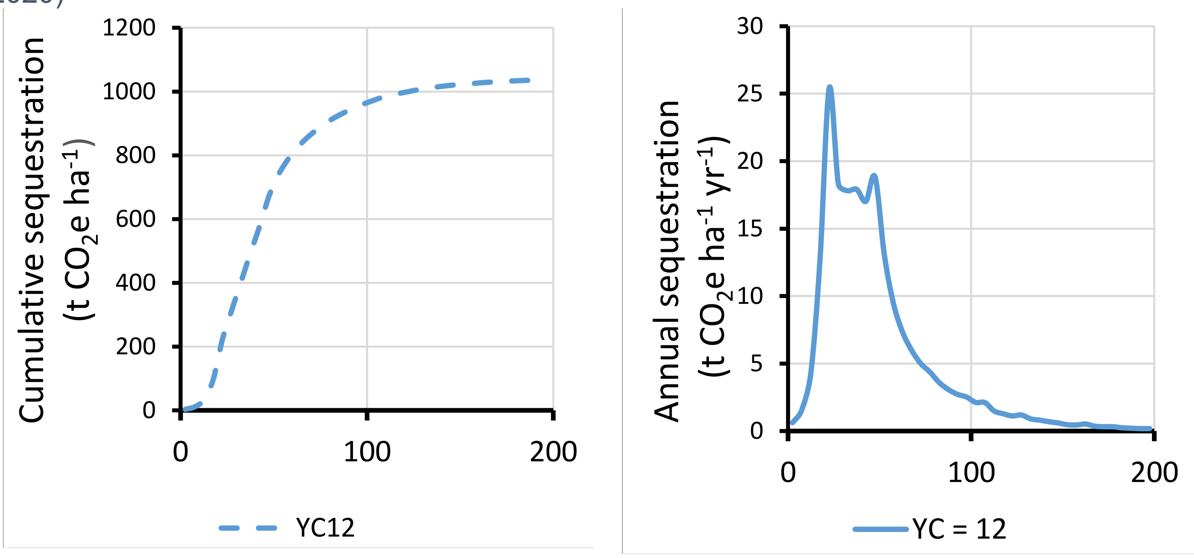

Figure 26. Predicted rate of carbon sequestration for Sitka spruce (unthinned, Yield Class = 12, initial spacing = 2 m) (after Woodland Carbon Code 2020)

8.2 Hedgerow systems in Atlantic climates

Table 24. Estimate of the carbon stored in hedgerow systems in the “Atlantic” agroclimatic zone of Europe (Kay et al., 2019). The carbon storage potential is based on a carbon content of 50% based on Aalde et al. (2006) – assuming 50% of tree biomass to be carbon.

Atlantic hedgerow system	Tree and hedgerow species	Trees (ha^{-1}) or tree cover (%)	System	Crop rotation	Tree products	Year of tree harvest	Tree and root carbon sequestration (t C ha^{-1} a^{-1})	
2 Coppice	SRC agroforestry for ruminants willow (Salix spp), alder (*Alnus glutinosa*)	0.25 /0.7 m x 24m (34%)	Lines	Grazing, hay, silage	Fodder-trees, woodchips	5-8	0.51 - 1.48	(Bärwolff et al., 2012)
3 Coppice	Fodder and energy trees willow (*Salix viminalis*), poplar (*Populus* sp.), hazel (*Corylus avellana*), alder (*Alnus glutinosa*)	1175 ha^{-1} (0.7-1.0 m within rows, 24 m within twin rows, (34%)	Lines (twin lines)	Grazing, hay, silage	Fodder-trees, woodchips	15	0.51 - 1.48	(Bärwolff et al., 2012)
4 Coppice for ruminants in France	Pear (*Pyrus* spp), honey locust (*Gleditsia triacanthos*), service tree (*Sorbus domestica*), white mulberry (*Morus alba*), Italian alder (*Alnus cordata*), goat willow (*Salix caprea*), field elm (*Ulmus minor*), black locust (*Robinia pseudoacacia*), grey alder (*Alnus incana*)	(single -2 m, double -6 m triple -10 m), 4 m trees, 1.3m coppices x 20m, (11%)	Lines: (single, double, triple)	Grazing, hay, silage	Fodder-trees, woodchips	5-8	0.16 - 0.48	(Bärwolff et al., 2012)
5 Silvopasture coppice	SRC, fodder trees Pedunculate oak (*Quercus robur*), sycamore (*Platanus occidentalis*), cherry (*Prunus avium*)	6 x 1.5 m (1056 ha^{-1} (64%) or 8 x 1.5 m (726 ha^{-1} (44%)	Lines	Grazing, hay, silage	Woodchips	5-8	0.66 - 2.80	(Lawson et al., 2016); (Bärwolff et al., 2012)
6 Silvopasture single trees	High stem timber trees poplar (*Populus* spp)	25 trees ha^{-1} (5%)	Boundary	Grazing, hay, silage	Timber	25	0.46 - 1.03	(Graves et al., 2010; Unseld, 2017)
17 Silvoarable, coppice	SRC hornbeam (*Carpinus betulus*), common ash (*Fraxinus excelsior*), alder (*Alnus cordata*)	572 ha^{-1} (11%)	Lines	Multiple crops	woodchips	4 - 6	0.16 - 0.48	(Bärwolff et al., 2012)

18 Silvoarable, coppice	SRC poplar (*Populus* spp), willow (*Salix viminalis*)	18%	Lines (48 m cropping)	Incl. cereals	woodchips	5 -8	0.27-0.78	(Bärwolff et al., 2012)
19 Silvoarable, coppice	SRC willow (*Salix viminalis*), hazel (*Corylus avellana*)	1000-1300 ha^{-1} (24%)	Twin rows with 10-15 m wide crop alley	Incl. cereals, potatoes, and grass ley	woodchips	every 2 (willow) or 5 (hazel) years	0.36-1.05	(Bärwolff et al., 2012)

8.3 High stem silvoarable systems in Atlantic climates

Table 25. Estimate of the carbon stored in silvoarable systems in the "Atlantic" agroclimatic zone of Europe (Kay et al., 2019). The carbon storage potential is based on indicated literature or – if unknown (Aalde et al., 2006) – assuming 50% of tree biomass to be carbon.

Atlantic silvoarable system	Tree and hedgerow species	Trees (ha^{-1}) or tree cover (%)	Planting and management system	Crop rotation	Tree products	Year of tree harvesting	Tree and root biomass, references ($t\ ha^{-1}\ a^{-1}$)	Carbon storage, references ($t\ C\ ha^{-1}\ a^{-1}$)
20 Silvoarable, high stem walnut	Walnut (*Juglans intermedia*)	48 -50 ha^{-1} (5%)	Lines	Crop rotation	timber	60	0.97 - 2.08 (Sereke et al., 2015); (Cardinael et al., 2017)	0.58 - 1.25 (Cardinael et al., 2017)
21 High stem timber trees. lines	Walnut (*Juglans regia*), maples (*Acer* spp), wild cherry (*Prunus avium*), checker tree, (*Sorbus torminalis*), service tree (*Sorbus domestica*), apple (*Malus domestica*), pear (*Pyrus* spp)	28-110 ha^{-1}	Lines (26-50 m between rows)		Timber	60	walnut: 0.54 - 4.58, cherry: 0.35 - 2.61 German forest tables, (Sereke et al., 2015); (Cardinael et al., 2017)	walnut: 0.32 - 2.75, cherry: 0.19 - 1.4 (Cardinael et al., 2017)
22 Atlantic arable silvoarable, single trees	Mixed hardwood: lime (*Tilia cordata*), hornbeam (*Carpinus betulus*), cherry (*Prunus avium*), alder (*Alnus cordata*), common ash (*Fraxinus excelsior*), maple (*Acer pseudoplatanus*), sessile oak (*Quercus petraea*)	150 ha^{-1}	Twin rows with 10-15 m wide crop	Rotation incl. cereals, potatoes, and grass leys	timber, woodchips	25-100 years Selected pollarding every 5-10 years	0.32 - 1.93 British forest tables	0.16 - 0.51 (Aalde et al., 2006)
23 Silvoarable, single trees	Fruit trees: apple (*Malus domestica*), pear (*Pyrus* spp), plum (*Prunus domestica*)	85-100 ha^{-1}	Single rows with 24 m wide crop	Rotation incl. cereals and grass leys	fruits (timber)	Fruit harvested annually	Apple: 2.47-2.91 (Schnitzler et al., 2014) apple:	Apple: 1.31-1.54 (Johnson and Gerhold, 2001)

8.4 High stem silvopasture systems in Atlantic climates

Table 26. Estimate of the carbon stored in silvopasture systems in the "Atlantic" agroclimatic zone of Europe (Kay et al., 2019). The carbon storage potential is based on indicated literature or – if unknown (Aalde et al., 2006) – assuming 50% of tree biomass to be carbon.

Atlantic silvopasture system	Tree and hedgerow species	Trees (ha^{-1}) or tree cover (%)	Planting and manageme nt system	Crop rotation	Tree products	Year of tree harvest	Tree and root biomass, references (t ha^{-1} a^{-1})	Carbon storage, references (t C ha^{-1} a^{-1})
7 Silvopasture, single trees	High stem timber trees poplar (*Populus* spp)	400 ha^{-1} , after 15-20 years: 120-150 ha^{-1}	Lines	Grazing , hay, silage	Timber	First cut: 15-20 harvest: 25-30	5.41 - 12.38 (Lawson et al., 2016; Graves et al., 2010)	2.78-6.35 (Fang et al., 2010)
8 silvopasture, single trees	High stem forest trees common ash (*Fraxinus excelsior*), Pedunculate oak (*Quercus robur*)	5 x 5 m (400 trees ha^{-1})	single tree scattered	Grazing , hay, silage	Timber	15	1.38 - 2.63 (Lawson et al., 2016); British, German forest tables	0.69-1.31 (Aalde et al., 2006)
9 Silvopasture, single trees	Fruit and fodder trees: walnut (*Juglans regia*), Pedunculate oak (*Quercus robur*) (including edible acorns – Acer campestre), sweet chestnut (*Castanea sativa*), cider apple trees (*Malus domestica*)	400 and 1,000 trees ha^{-1}	Lines	Grazing , hay, silage	Fruits, fodder trees, woodchips, Timber	15	walnut: 4.87-7.79, oak: 0.86-2.14 (Lawson et al., 2016); British, German forest tables	walnut: 2.92 - 4.68, oak: 0.43-1.07 (Cardinael et al., 2017; Aalde et al., 2006)
10 Atlantic grassland silvopasture, single trees	High stem timber trees paulownia (*Paulownia tomentosa*), dutch elm (*Ulmus × hollandica*)	8 x 1.5 m (726 ha^{-1} (44%)	Lines	Grazing , hay, silage	Timber	15	1.17 - 3.85 (Woods, 2008; Durán Zuazo et al., 2013; García-Morote et al., 2014; Lawson et al., 2016)	0.58 - 1.93 (Aalde et al., 2006)
11 Silvopasture, single trees	Traditional orchard fruit trees (apple – *Malus domcestica*, pear – *Pyrus* spp, plum – *Prunus domestica*)	80 ha^{-1}	Lines	Grazing , hay, silage	Fruits (woodchips)	60	2.33 (Schnitzler et al., 2014;	1.23 (Johnson and Gerhold, 2001)

							Lawson et al., 2016)	
12 Silvopasture, single trees	Fruit trees apples (*Malus domestica*), pears (*Pyrus communis*), plums (*Prunus domestica*), cherries (*Prunus avium*) and other fruit and nuts	650-750 ha^{-1} (3.5-4.5 m x 2-2.5 m)	Lines	Grazing	Fruits, nuts, woodchips	12-15	10.6 (Winzer et al., 2017)	5.3 (Aalde et al., 2006)
13 Silvopasture, single trees	High stem fodder trees common ash (*Fraxinus excelsior*)	400 ha^{-1} (two thinnings then 120-150 ha^{-1} , 5 x 5m	Lines	Grazing: ryegrass	Fodder-trees, woodchips	first cut: 15-20, harvest: 25-30	1.03-1.97 British, German forest tables	0.51-0.98 (Aalde et al., 2006)
14 Silvopasture, single trees	Fodder trees broadleaf species, e.g. Pedunculate oak (*Quercus robur*), sycamore (*Platanus occidentalis*), cherry (*Prunus avium*), beech (*Fagus sylvatica*)	200-400 ha^{-1}	Initial density must be maintained	Grazing	Fodder-trees, woodchips	Land must stay in for grazing for 20 years	1.03-1.97 British, German forest tables	0.51-0.98 (Aalde et al.

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