Assessing the cost-effectiveness of woodlands in the abatement of carbon dioxide emissions

Final report to the Forestry Commission

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1 Executive summary

1.1 Aims and methods

The aim of this study was to estimate the cost-effectiveness (CE) of forestry as a means of delivering greenhouse gas (GHG) emissions abatement. It concentrated on the impact of additional new woodland creation and does not consider changes to the management of existing woodlands. Previous research has shown that managing neglected woodlands is much less effective for carbon abatement than investment in woodland creation[1][2].

Two main CE metrics were used. These were the cost per tCO_2e and the cost per £ value CO_2e:

- £PV[3] cost excluding carbon/tCO_2e
- £PV cost excluding carbon/ £PV CO_2e

The first ('physical' measure) was applied to the mean CO_2e retention[4] over the investment horizon. The second ('value' measure) was calculated by discounting the value of the CO_2e change that occurs in each year of the investment. In calculating the PVs the Treasury declining discount rate was applied (see 2.4.2).

Initially four time horizons were used: 2030, 2050, 2100 and 2200. Analysis revealed that woodland creation could make no useful contribution to meeting short-term policy targets. These horizons were then reduced to two: 2050 and 2200 (36 and 186 years from 2014). Carbon net retention was recorded to 2050 and 2200 but cost-effectiveness was only measured over the horizon to 2200.

The CE metrics and marginal abatement cost curve (MACC) were calculated using social costs and prices[5]. The analysis informs government of the costs and benefits to society of additional new woodland creation directed at carbon abatement. Additional public expenditure in grant aid may be required to encourage private landowners to invest in new planting but that aspect is not considered. It does not affect the (social) cost-effectiveness metric used in the study.

1.2 Forest systems

The steering group defined seven forest systems (see Table 1.1) and these were applied in up to 11 regions across GB. Planting was assumed to take place on a range of soil types depending on the region (mineral loam, mineral gley, organo-mineral loam, organo-mineral gley) and planting was assumed to be on permanent pasture in all regions except in two English regions (South-east and Eastern/East Midlands) where planting on arable land was also investigated.

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[1] ADAS (2009). Analysis of Policy Instrument for Reducing Greenhouse Gas Emission from Agriculture, Forestry and Land Management – Forestry Options. Report for The Forestry Commission.

[2] Matthews, R et al (2011). Carbon impacts of using biomass in bioenergy and other sectors: forestry. DECC project TRN 242/08/2100. Final report parts a and b. Forest Research. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/282812/DECC_carbon_impacts_final_report30th_January_2014.pdf

[3] Present Value

[4] The sum of the annual net retentions divide by the number of years.

[5] Grant aid was excluded from the analysis since it is a transfer within society.

1.3 Technical data

Yield classes were derived for each tree species in each region (see Table 3.4) based on Forestry Commission records. A total of 98 different forest system/region scenarios for each time horizon were defined. Forest Research used their CSORT model (see 3.4.1) to produce year by year data on wood output, carbon retention and emissions for the individual tree species managed as indicated in the table. They also produced emission data associated with the inputs used in forest establishment.

Table 1.1 Forest systems and specifications

Forest system	Species	Thinned?	Clearfell?
Short rotation forestry (SRF): managed for energy (15 and 25 years)	Red alder (100%)	No	Yes
Farm woodland: managed for mixed objectives	Sycamore/Common alder/ Birch (65%), Douglas fir[6] (25%)	Yes	No
Broadleaf1: managed for game/biodiversity	Sycamore/Common alder/ Birch (45%), Oak (45%)	No	No
Broadleaf2: managed for timber and carbon	Oak (45%), Birch (45%)	Yes	Yes
Upland conifer: managed for timber	Sitka spruce (90%)	No	Yes
Lowland conifer: managed for timber (England)	Douglas Fir (90%)	Yes	Yes
Lowland conifer: managed for timber (Wales, Scotland)	Sitka spruce (90%),	Yes	Yes
Continuous cover forestry (CCF); managed for mixed objectives	Sycamore/Beech (30%), Douglas Fir (60%)	Yes	No

Note: 10% of the area is open space in all options except SRF.

Forest Research provided estimates of the annual carbon fluxes from soil for the soil types assumed for the different regions. For mineral soils carbon fluxes were based on IPCC values for a moist, temperate climate. Data for organic soils were based on literature values. Values for organo-mineral soils were interpolated between the mineral and organic estimates Emissions were substantial where planting was on organo-mineral soils after pasture but negative on mineral soils after arable cropping (see Table 3.6).

The estimates for sequestration were adjusted down by a permanence buffer of 15%. This allows for the fact that permanence of the plantations will not be 100% due to risks of natural events including fire, wind and disease, and permissions to fell without re-planting. The occurrence of new diseases with significant impacts on carbon sequestration rates (such as *Phytophthora ramorum* in larch and *Chalara* dieback in ash)[7] makes the estimation of carbon sequestration particularly difficult since there is a possibility that new diseases may arise at any time.

Carbon emissions from wood products were based on IPCC (2003) Good Practice Guidelines (see 3.5.5): exponential decay functions with half-lives of 25 and 35 years were used for

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[6] Sitka Spruce was substituted for Douglas Fir as a more appropriate species in two Scottish regions (Highlands and Islands and Grampian).

[7] See http://www.forestry.gov.uk/pestsanddiseases

roundwood products/board and sawn timber products respectively. Other wood products were assumed to release stored carbon immediately after harvest.

We estimated the carbon emission reduction on combustion of woodfuel assuming a 50% split between power and heat generation. This broadly reflects the predominant current usage of woodfuel. End-of-life carbon gains on combustion (where wood is used as woodfuel at the end of its useful life) were assessed to be small and were excluded since it was not possible to satisfactorily link them to the emission profiles used in CSORT. The carbon emission reduction from substitution of wood for other materials in construction was examined and included in the sensitivity analysis. Any apparent benefits from displacement of agricultural production were excluded since output would be expected to increase through expansion or intensification in the UK or elsewhere.

1.4 Costs

The cost of land was based on opportunity costs derived from farm management data for different regions. This was preferable to the use of observed land prices which may be affected by subsidy and capitalised at market rather than Treasury discount rates. Costs for woodland establishment and management were based on current commercial rates. Total costs were substantially higher in England (especially the south) and Wales than in Scotland. This reflected differentials in opportunity costs, labour costs and the cost of materials.

1.5 Income from carbon, timber and woodfuel

DECC (2013)[8] central non-traded prices for CO_2e were used. These increase substantially over time from £61 per tCO_2e in 2014 to £341 per t in 2075.

Timber prices were based on Forestry Commission standing sale prices for conifers. Broadleaved standing sales were those used in a recent study for the Forestry Commission (CJC Consulting, 2012)[9] (see Annex 1). For SRF an equivalent standing sale price was derived by subtracting the costs of harvesting, handling, processing and transport from a delivered plant price.

Woodland creation may deliver public benefits from changes to landscape and biodiversity. These possible environmental benefits were not included in the basic analysis due to uncertainty over their magnitude and their exclusion from other studies on woodland as an abatement mechanism. However, their possible impact was assessed through sensitivity analysis.

1.6 Cost-effectiveness of the systems

The physical and financial effects of woodland creation were modelled for each of the systems and regions. The seven woodland systems produce quite different patterns of carbon retention and emission over time depending on whether the planting was permanent or subject to thinning and/or clearfell in a rotation. Changes were modelled on a year to year basis in Excel. For a given time horizon the present values of the cost and income streams were calculated together with the total and mean annual net CO_2e retention per ha.

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[8] DECC (2014). https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

[9] CJC Consulting (2012). Study to assess investment returns in woodland creation in Great Britain. Report to the Forestry Commission.

1.6.1 Carbon performance

Mean carbon retention to 2050 was determined principally by yield class, soil type and previous land use (see Annex 2 and Table 1.2). Retention was highest where broadleaves managed for carbon and timber, lowland conifers or CCF were planted on mineral soils after arable. The highest mean net retention was 210 tCO_2e per ha for lowland conifers in England (Eastern/East Midlands). A small number of forest systems on organo-mineral soils with low growth rates had negative carbon retentions to 2050.

When carbon retention was assessed to 2200 permanent broadleaves, lowland conifers and CCF performed best especially in southern and eastern England where yield classes and soils were more favourable for carbon retention. The highest mean retentions were for permanent broadleaves in South-east England (530 tCO_2e per ha) and lowland conifers in England (Eastern and East Midlands)(501 tCO_2e per ha).

Table 1.2 Range in carbon retention and cost-effectiveness of forest systems

Forest System	Country	Range for GB countries		
		Mean net Retention to 2050 (tCO_2e/ha)	**Mean net Retention to 2200 (tCO_2e/ha)**	**Cost Effectiveness to 2200 (£PV excl C /tCO_2e/ha mean)**
SRF 15 year rotation	**England**	Neg-91	68-224	188-366
	Scotland	Neg-6	7-80	229-3162
	Wales	Neg	68	337
SRF 25 year rotation	**England**	9-135	195-351	82-132
	Scotland	Neg-44	134-208	45-107
	Wales	10	201	80
Farm woodland	**England**	42-164	143-314	48-96
	Scotland	0-66	84-229	40-108
	Wales	46	143	72
Broadleaf1 (managed for biodiversity/game)	**England**	Neg-126	320-530	61-84
	Scotland	Neg-4	195-297	32-46
	Wales	Neg	320	42
Broadleaf2 (managed for timber/carbon)	**England**	6-159	106-285	140-245
	Scotland	Neg-30	77-136	101-148
	Wales	6	106	167
Upland conifer	**England**	61-98	284-337	27-33
	Scotland	37-81	244-304	26-30
	Wales	85	331	30
Lowland conifer	**England**	67-210	288-501	21-46

	Scotland	39-72	240-269	27-28
	Wales	85	331	39
Continuous cover forestry	**England**	49-196	309-452	50-88
	Scotland	Neg-60	189-288	32-56
	Wales	66	344	46

1.6.2 Cost-effectiveness ‘physical metric’ (cost per tCO2e)

Systems achieving a high rate of carbon retention to 2200 are not necessarily the most cost-effective since costs vary considerably between regions and systems. When assessed against the ‘physical’ measure of CE (cost per tCO_2e) upland and lowland conifers were the most cost-effective with costs mainly in the range £20-40 per tCO_2e. Permanent broadleaves and CCF were generally in the £40-90 per tCO_2e range. The other systems were, with some regional exceptions, much less cost-effective. When comparisons were made between countries there was a tendency for planting in Scotland to be more cost-effective than in England or Wales but with considerable regional variation. Total costs are generally lower in Scotland mainly due to lower land and labour costs which more than compensate for any lower growth rates.

1.6.3 Cost-effectiveness ‘value metric’ (cost per £PV CO_2e)

This measure of CE takes into account both the value of the CO_2e retention or emission and its timing. To be cost-effective this metric must be £<1 per £ CO_2e.

All of the systems are cost-effective for abatement with the exception of most of the SRF and Broadleaf2 (managed for carbon and timber) planting. Values in green in Annex 2 have a cost exceeding the value of the carbon retained and are therefore not cost-effective. The conifer systems are most cost-effective with costs in the range £0.2 – 0.4 per £CO_2e. CCF and permanent broadleaves are also cost-effective as are broadleaves grown for carbon and timber in Scotland but not elsewhere. Farm woodland planting is cost-effective in Scotland and Wales but less universally so in England.

1.7 Marginal abatement cost curve (MACC)

Indicative additional planting areas (per year) were developed for each region. These totalled 15,710 ha per year for the whole of GB. The 2200 MACC was derived from the ‘physical’ CE metric calculated for each forest system and region, together with the areas expected to be planted (see Table 6.4).

Lowland and upland conifers have the lowest marginal abatement cost. Lowland conifers in England achieve high rates of carbon sequestration because of their high growth rates. Upland conifers have lower rates of sequestration but this is in part compensated for by lower production costs. In total around 5,000 ha per year of conifers could be planted per year at a cost of <£30 per tCO_2e. Most of this planting is in Scotland (4,000 ha), with 525 ha in Wales and 400 ha in England. The total mean carbon retention is 1.36 $mtCO_2e$.

A further 1,500 ha could be planted at a cost of up to £40 per tCO_2e delivering a further 0.44 $mtCO_2e$ of abatement. This consisted largely of conifers with some permanent broadleaves, with planting located mainly in Scotland. Farm Woodland and CCF options enter the MACC at higher levels of abatement cost.
MacLeod et al. (2010)[10] used £100 per tCO_2e as a benchmark for assessing the potential

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[10] MacLeod et al. (2010). Review and update of UK marginal abatement cost

contribution of agriculture, land use and land use change to carbon abatement. The forestry MACC (Table 6.4) indicates that all forest systems with the exception of broadleaves (for timber and carbon) and SRF deliver abatement at <£100 per tCO_2e. The estimated quantity per year is 3.4 $MtCO_2e$ at expected planting rates.

1.8 Sensitivity to assumptions

The results were subjected to sensitivity analysis for carbon and timber prices and product substitution.

Only the ‘‘value’ CE metric is affected by the price of carbon. The ‘physical’ metric does not depend on the carbon price. Applying the DECC ‘low’ value restricted cost-effective planting (2200 horizon) to permanent broadleaves in Scotland and Wales, upland and lowland conifers in all countries and continuous cover in Scotland. Lower carbon prices tend to restrict cost-effective planting to sites where costs are low.

Increasing the timber prices by 1% per year improved CE substantially for those forest systems where harvesting takes place. Systems with a CE of <£40 per tCO2e improved in cost-effectiveness by around £6-7 per tCO2e. The most cost-effective system (lowland conifers in England, Eastern and East Midlands) improved from £21 per t to £13 per tCO2e.

Allowing for the carbon gains from 50% substitution of timber products in construction had only a small impact on CE This was based on the assumption that emission displacement would decline over time in line with the reduction in carbon emissions from power generation forecast by DECC.

1.9 Conclusions

Forestry’s contribution to additional abatement is strongest in the longer term, although significant abatement is feasible before then. Carbon emissions from soil- when planted on organo-mineral soils - and low rates of sequestration in early life limit the short-term abatement (to 2030) achieved by many forest systems. The most cost-effective forestry options in the long-term are conifers and permanent broadleaves, especially in Scotland where costs are low. Continuous cover forestry, rotational broadleaves, farm woodlands and SRF are less cost-effective, at least under the management systems applied in this study.

More information is needed on emissions from soil for which it proved difficult to obtain reliable data. More analysis is required on the social opportunity cost of land, product substitution and end-of-life timber use as woodfuel. There is also a need for a more comprehensive modelling of forest management systems to identify which planting and management regimes are most cost-effective for delivering net carbon retention. Some of the less cost-effective options in this study (e.g. farm woodlands, broadleaves for carbon and timber, SRF) may reflect the particular management regimes used. Where non-carbon social or environmental benefits from woodland creation can be identified and quantified they are likely to be positive and improve cost-effectiveness.

Limited information is available on the CE of other carbon abatement options. Various studies of options in agriculture and other sectors have produced very wide ranges in the CE of possible options. Within forestry, lowland and upland conifers are the most cost-effective options. In terms of areas likely to be planted the best opportunities are located in Scotland. When CE is measured in value terms at DECC central non-traded carbon prices, the majority of

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curves for agriculture. Final report to the Committee on Climate Change. http://www.theccc.org.uk/wp-content/uploads/2010/12/pr_supporting_research_SAC_agriculture.pdf forest systems and locations are cost-effective for abatement. Consideration should be given to forestry as an element in a portfolio approach to abatement given the distinctive risks and abatement profiles of different forest options.

2 Objectives and methodology

2.1 Background

In 2008, the European Commission published proposals for reducing the EU's greenhouse gas emissions by 20% and increasing its proportion of final energy consumption from renewable sources to 20%. Both targets are to be achieved by 2020. The Climate Change Act 2008 and the accompanying Impact Assessment provide the rationale for taking action to reduce UK greenhouse gas (GHG) emissions by at least 34% by 2020 and at least 80% by 2050.

The Read[11] report concluded that forest creation should be encouraged as a contribution to emission reduction. Following the work of the Independent Panel on Forestry in England, Defra has indicated that it wishes to see significantly more woodland creation with an average planting rate of 5,000 ha per year[12] in England to 2060. It indicates the role of woodlands in the growth of the UK forest carbon market and has concluded[13] that 'carbon markets arguably present the biggest current opportunity for PES[14] schemes in forestry'.

The net emission reduction achieved from forestry depends on a large number of factors including the amount of CO_2 sequestered in timber and other wood products, emissions or accumulation in soil carbon, and emissions from forest establishment, management, harvesting, and the utilisation of wood (including combustion).

This project focuses on the carbon consequences of woodland creation. It seeks to build a framework that includes all the relevant elements for an assessment of cost-effectiveness.

2.2 Objectives

The aim of this study is to estimate the cost-effectiveness of forestry as a means of delivering GHG emissions abatement. The emphasis is on woodland creation since previous analysis has indicated that investment in changes to woodland management is likely to be much less cost-effective than investment in creation[19].

The project examines a number of forestry options to assess their abatement potential. The objective is to calculate cost effectiveness measures for each, which are (i) comparable across forest systems, and (ii) provide the basis for comparison with alternative mitigation methods.

The specific objectives are to:

- ☐ define a set of forestry measures that best represents the contribution that forestry can make to GHG abatement;
- ☐ estimate the cost of CO_2 emissions abatement achieved through creating different

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[11] Read, D.J., Freer-Smith, P.H., Morison, J.I.L., Hanley, N., West, C.C. and Snowdon, P. (eds). (2009). *Combating climate change – a role for UK forests. An assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change*. The synthesis report. The Stationery Office, Edinburgh.

[12] Defra (2013). Government Forestry and Woodlands Policy statement. http://www.defra.gov.uk/publications/files/pb13871-forestry-policy-statement.pdf

[13] Defra (2013). Developing the potential for Payments for Ecosystem services: an action plan. www.gov.uk/defra

[14] Payments for ecosystem services

[19] ADAS (2009). Analysis of Policy Instrument for Reducing Greenhouse Gas Emission from Agriculture, Forestry and Land Management – Forestry Options. Report for The Forestry Commission.
Matthews, R et al (2011). Carbon impacts of using biomass in bioenergy and other sectors: forestry. DECC project TRN 242/08/2100. Final report parts a and b. Forest Research. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/282812/DECC_carbon_impacts_final_report30th_January_2014.pdf

types of woodland;

- assess the potential scale of such abatement including, where possible, a regional breakdown of where woodland may be planted; and,
- use the results to generate marginal abatement cost curves (MACCs) that can be used to provide comparisons with evidence compiled for other abatement technologies.

2.3 Measuring cost-effectiveness

2.3.1 Cost-effectiveness in ‘physical’ terms

Cost-effectiveness (CE) is defined in the Treasury Green Book as an ‘analysis that compares the costs of alternative ways of producing the same or similar outputs’. In a policy context it is primarily the social cost that is relevant for the CE calculation. This accounts for all costs and benefits to society from the investment including both market and non-market costs and benefits. The cost-effectiveness measure of a forest option is essentially its Net Present Value excluding any carbon value, divided by the tonnes of CO_2 emissions avoided.

HM Treasury and DECC (2012)[21] define the CE in the non-traded emission sector as:

CE= -(NPV)/ C

CE = Cost effectiveness (£ per tCO_2e)

NPV = Net present value of the option (excluding carbon value) (£)

C = GHG emission change (tCO_2e)

In this formula the NPV is the net cost of the option and this is divided by the emission change.

2.3.2 Cost-effectiveness in ‘value’ terms

Cost-effectiveness is normally assessed in terms of the physical change resulting from intervention (as indicated in 2.3.1). This is useful for comparison with the CE of other abatement options which are usually given in terms of cost per tCO_2e.

However, this is at best a limited measure of the impact on social welfare because it fails to account for (i) the fact that the annual carbon sequestration in forests changes over time as the forest matures, and (ii) the value of the GHG impact also changes over time.

As an alternative, CE can be expressed entirely in value terms i.e.

CE= -(NPV)/ C_{PV}

CE = Cost effectiveness (£ per £CO_2e)

NPV = Net present value of the option (excluding carbon value) (£)

C_{PV} = GHG emission change (£ PV of CO_2e)

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[21] https://www.gov.uk/government/policies/using-evidence-and-analysis-to-inform-energy-and-climate-change-policies/supporting-pages/policy-appraisal

Unlike the physical approach to CE the 'value' measure is based on discounting each year's flow of CO_2e up to the end of the horizon. It has merit when comparing mechanisms that deliver different time profiles of GHG impact. But it is less useful for comparisons with alternative (non-forestry) mechanisms for reducing net carbon emissions because CE is typically measured in 'physical' terms (£ per tCO_2e)[23]. We report the CE metrics in both physical and value terms.

2.3.3 Public and private appraisal

This project is focussed on the appraisal of forestry from society's perspective. A social discount rate is appropriate as are social prices and costs. As Kesiki and Atkins (2012)[24] point out, there is no certainty that cost-effective social projects will be taken up by private investors. These investors will make their own decisions based on their cost estimates, discount rates, values attached to the carbon sequestered and their attitudes to risk. Landowners may also have specific opportunity costs and private benefits from woodlands that they incorporate into their decision making.

The cost-effectiveness analysis will not therefore indicate what investors will do. It will be up to government to intervene if it wishes to deliver a socially desirable outcome. It has typically intervened in forestry with grant aid, an intervention that incurs public expenditure costs.

2.3.4 Public expenditure costs

Where grant aid is given to support new planting the exchequer payment is treated as a transfer and has no net effect on CE. However, grant aid would involve transaction costs for both provider and recipient, and these costs would be an addition to the social cost of the investment.

Any requirement for public expenditure in order to deliver net emission reductions from forestry is likely to be a factor in the assessment of the forestry option given current pressure to contain public expenditure. This will be especially relevant when intervention is 100% exchequer funded (rather than co-funded under a European development programme (ERDP).

Whilst the public expenditure cost of intervention is likely to affect government decision making there seems little point in developing a public expenditure measure of CE such as:

$$\text{NPV (public expenditure)/ -}tCO_2e\text{ saved}$$

since this can only be used to compare with other mechanisms that require additional public expenditure.

Any public expenditure measure of effectiveness would require an estimate of the level of grant aid needed to deliver the area estimates used in the MACC. Although the supporting analysis for the Independent Panel on Forestry (IPF) gave some estimates of the elasticity for woodland creation (% change in planted area per 1% increase in grant aid) these were based on quite limited data and analysis[25]. Much would depend on the structure of the future grant aid schemes and the extent to which finance was available under the ERDP.

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[23] Caparros et al. (2010). (Environ Resource Econ 45:49-72) describe various methods of accounting for the time flows of carbon in forests. These include the Carbon Flow Method in which forest owners get a government subsidy for sequestration and are taxed when carbon is released, and the Ton Year Accounting Method in which payments for sequestration each year are based on a carbon emission price.

[24] Kesiki, F. and Ekins, P. (2012). Marginal abatement cost curves: a call for caution. Climate Policy 12, 219-236.

[25] Woodland Creation in England http://www.defra.gov.uk/forestrypanel/views/

We therefore consider that a CE based on public expenditure would be extremely difficult to derive in the absence of information on the level of grant aid needed to effect a required supply response.

2.3.5 Developing a MACC

Marginal abatement cost curves[26] (MACC) are often presented as histograms or tabular rankings and depict how the marginal cost of abatement increases as higher cost options are included. In practice a carbon-driven forest planting/management programme would be rolled out year-by-year rather than a single investment in Year 1 (2014). However, to model this would add considerably not only to computational complexity but also its interpretation. With carbon values determined by the calendar year, each year's planting would have to be modelled individually (see 4.2) and then aggregated. The final MACC would depend on assumptions about the planting velocity and the time period for the policy initiative.

Since the project is primarily to investigate alternative creation options we use a single planting date (2014) which allows the CE of the different options to be ranked and a MACC developed. It also more easily allows comparison with other policy options for reducing carbon emissions.

2.4 Methodological issues in the analysis

2.4.1 Time horizon for the analysis

The cost-effectiveness formula given by HM Treasury and DECC (2012) has no specific time horizon. In investment appraisal the time horizon for NPV analysis is (in concept) the physical life of the asset. This may be reduced in response to the risk or other preferences of the investor. For a rotational crop, where the physical horizon could be perceived as one rotation, forestry regulations in the UK typically require re-stocking which normally results in repeated rotations into the future. This transforms an initial investment into a quasi-perpetual one.

In policy analysis DECC has advised that the time horizon should be 'the period it is believed the policy would be appropriate'. We argue against adopting a perpetual model for CE estimation on several counts. First, future forest management becomes progressively less certain as the time horizon increases. For example, where clear-felling takes place re-stocking may not be with the same species or management, and the area of open space may change. Non-commercial crops typically have no well-defined rotation and uncertain future management.

Second, discounting substantially reduces the present value of distant flows such that flows beyond 100 years have little impact on NPV (and cost per tCO_2e)[27].

Third, DECC has a number of key dates that relate to policy targets. Initial investigation revealed that forestry was unable to contribute to the 2020 target because short-term net retention rates in forestry are low. The Steering Group indicated that two calendar time horizons should be used: 2050 and 2200. For planting in 2014 these represent time horizons from planting of 36 and 186 years. Neither of these horizons relate to the physical lives of trees, whether in a rotation or not.

The Treasury Green Book[28] indicates that the residual value of an investment should be included since 'even where an appraisal covers the full expected period of use of an asset, the

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[26] see FAO Using Marginal Abatement Cost Curves to Realize the Economic Appraisal of Climate Smart Agriculture Policy Options http://www.fao.org/docs/up/easypol/906/ex-act_MACC_116EN.pdf

[27] The PV of £100 in year 100 at the Treasury declining discount rate is £5.08.

[28] https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent

asset may still have some residual value in an alternative use within an organisation, in a second-hand market, or as scrap'. However, existing regulations do not permit de-forestation and hence the only option is to maintain an existing wood at the end of the planning horizon. This effectively means extending the horizon for calculation into perpetuity. However, any residual value in 2200 will be extremely small after discounting to the present, and inconsequential in the context of other components of the CE calculation. We therefore use a zero residual value at 2200 and use the 2200 horizon for the estimation of cost-effectiveness. The net carbon sequestration at 2050 is calculated in order to indicate the contribution of the forestry systems to the 2050 policy target.

2.4.2 Discount rate

A declining (quasi-hyperbolic) discount rate as indicated in the Treasury Green Book is applied (Table 2.1).

Table 2.1 Discount rates (Treasury Green Book[29])

	Period of years			
	0-30	31-75	76-125	126-200
Discount rate	3.5%	3.0%	2.5%	2.0%

2.4.3 Risk

It is important to account for the risks associated with woodland creation as an abatement strategy. There are risks from:

- ❑ Lack of control of woodland management after establishment (apart from restrictions on felling) with consequent uncertainty surrounding the level of carbon sequestration and release (and timber output). Whilst policy may be able to restrict management options through long-term contracts it is to be expected that this would increase the public expenditure cost associated with any given area of planting.
- ❑ Imprecision in estimating timber growth and sequestration rates.
- ❑ Uncertainty over wood utilization and associated carbon release.
- ❑ Uncertainty over re-stocking: changes to species, management and open space.
- ❑ The impact of unpredictable events that reduce GHG abatement and may result in faster carbon release (e.g. disease, storms, climate change).
- ❑ Strategic risks associated with the permanent transfer of agricultural land into forestry.

A precision buffer is applied under the Woodland Carbon Code to protect verified carbon credits which investors have paid for. It was considered inappropriate to apply the precision buffer in the current study because the technical models were considered to give unbiased results. However it is appropriate to use a permanence buffer to allow for establishment, climatic, disease and policy execution risks.

The estimates for sequestration were therefore adjusted down by a permanence buffer of 15%. The permanence buffer allows for the fact that permanence of the plantations will not be 100% due to risks of natural events including fire, wind and disease, and permissions to fell without re-planting. The occurrence of new diseases with significant impacts on carbon sequestration

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[29] https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent

rates (such as *Phytophthora ramorum* in larch and *Chalara* dieback in ash)[30] makes the estimation of carbon sequestration for the different forest systems particularly difficult since there is a possibility that new diseases may arise at any time. The 15% buffer is applied in the published Forestry Commission carbon sequestration data[31].

2.5 Counterfactuals

2.5.1 Forestry policy counterfactual

In order to construct the MACC it is necessary to make estimates of the area planted over the policy time frame in each region. The steering group indicated that any carbon-focussed policy should be treated as additional to existing policy measures. Expected additional planting rates were estimated in conjunction with the Steering Group and are reported in Chapter 6.

2.5.2 Land use

Since woodland creation will substitute for another land use we need to consider the effect of the substitution on carbon emissions. The main assumption is that woodland will be planted on permanent pasture/rough grazing and displace sheep or cattle production. However, in some regions we also consider planting on arable land and substitution for arable cropping/ temporary grass. The carbon impact of changes to land use are considered in section 3.4.3.

2.5.3 Product substitution

The UK imports around 89% of its wood consumption[33], and in the context of world trade UK wood output is extremely small. Any increase in UK timber output will have a minimal impact on price. We assume that the marginal increase in domestic timber production from additional woodland creation will substitute for imported timber. If the marginal increase in UK timber production reduces timber harvesting and output elsewhere there could be carbon savings from reduced emissions in production, forest management and transport. Since these changes will occur over a long time horizon it is difficult to forecast the impact of increased timber output on timber imports and substitution for non-timber materials.

A conservative assumption in the context of UK emissions[34] is to discount any emission reduction from import substitution and include the emissions associated with the production, management, harvesting and ultimate decay of additional domestic timber.

Additional timber production may substitute for other materials in construction and hence reduce the carbon emissions associated with the production of these materials. This aspect is examined in section 3.4.8.

2.6 Previous estimates of forestry cost-effectiveness

Previous research on the cost-effectiveness of forestry in reducing GHG emissions in the UK[36] is limited to four main studies: (NERA, 2007)[37], SAC (2008)[38], ADAS (2009)[39] and Nijnik et al.

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[30] See http://www.forestry.gov.uk/pestsanddiseases

[31] See http://www.forestry.gov.uk/forestry/infd-8jue9t

[33] Forestry Statistics 2012. Forestry Commission.

[34] In a global context there may be emission savings from reduced transport.

[36] Only UK cost-effectiveness studies are considered relevant to UK climate change policy because social investment outside the UK is irrelevant.

[37] NERA (2007). *Market Mechanisms for Reducing GHG Emissions from Agriculture, Forestry and Land Management.* NERA Economic Consulting. Report to Defra. http://archive.defra.gov.uk/evidence/economics/foodfarm/reports/ghgemissions/wholerep.pdf

[38] SAC (2008). UK Marginal Abatement Cost Curves for the Agriculture and Land Use, Land-Use Change and Forestry Sectors out to 2022, with Qualitative Analysis of Options to 2050 (RMP4950) 20/11/2008.

(2013)[40]. Estimated costs per tCO_2e from forest creation differed widely but this is not surprising given that there were major differences in the forestry contexts, assumptions and methodologies.

NERA estimated a carbon price that would cover the costs of establishment, the assumed loss of Single Farm Payment and loss of land value all discounted at 7%. The break-even carbon prices were £100 per tCO_2e for farmers planting lowland oak woodland, and £10-50 per tCO_2e to plant Sitka spruce on poor grassland.

The SAC estimate was only for Sitka spruce. Cost effectiveness (£ per tCO_2e) was estimated for a single 49-year spruce rotation at a constant 3.5% discount rate as:

(PV costs – PV revenue)/cumulative CO_2e abatement.

Costs included establishment costs and the opportunity cost of land. Revenue consisted of income from timber but excluded any other social benefits. Effectiveness was measured as carbon sequestration plus any additional benefits from reduced emissions resulting from substitution in other sectors. The CE for sequestration benefits alone was £-7.12 /tCO_2e derived from an NPV of £-6,405 per ha divided by a lifetime abatement of 899 tCO_2e per ha (18.35 tCO_2e per year for 49 years). The negative sign for the CE indicates that the NPV of timber revenue exceeded the NPV of costs and implies this type of forestry planting more than achieves the 3.5% social rate of return from timber output alone. The conclusion drawn was that this type of forestry investment has no social cost and it is therefore highly cost-effective as a mitigation measure. However, soil carbon emissions and emissions from timber product were excluded and timber prices were assumed to increase at 2.5% per year in real terms.

Nijnik et al. (2013) calculated the social cost effectiveness of planting Sitka spruce in different regions of the UK. The carbon sequestered was undiscounted but the financial flows were discounted at 3.5%. Estimates of CE varied from £1.8 to £20.7 (PV per tCO_2e) depending on land price and yield class. The regional comparisons indicated that the most cost-effective planting was on poor livestock land and in Scotland. However, the research is limited by not accounting for the time pattern of sequestration and emissions, and carbon changes in soil. It is also restricted to one species for which it treats yield class as independent of land quality (and price) in the UK regions. It is well established that yield class is highly dependent on climate and land quality[41].

The ADAS study is the most comprehensive to date. It derived the cost-effectiveness and CO_2e abatement potential of 14 forestry options. The options included short rotation energy forests, coniferous and broadleaved forestry and improved management of existing under-managed woodlands. In order to achieve a common basis of comparison, given widely differing rotation lengths, the NPVs over a rotation were converted to equivalent annual costs. A 100-year horizon was used and a constant discount rate of 3.5%

Short-rotation energy forestry options had a high negative CE (no net cost for the emission reduction). However, this was on the basis of high assumed yield classes (16 to 36). Of the

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Final Report to the Committee on Climate Change http://www.theccc.org.uk/pdfs/SAC-CCC%3B%20UK%20MACC%20for%20ALULUCF%3B%20Final%20Report%202008-11.pdf

[39] ADAS (2009). Analysis of Policy Instrument for Reducing Greenhouse Gas Emission from Agriculture, Forestry and Land Management – Forestry Options. Report for The Forestry Commission.

[40] Nijnik, Maria, Guillaume Pajot, Andy Moffat and Bill Slee (2013). An economic analysis of the establishment of forest plantations in the United Kingdom to mitigate climate change. Forest Policy and Economics 26, 34-42.

[41] See Macmillan, D, C. (1991). Predicting the yield class of Sitka spruce on better quality agricultural land in Scotland. Forestry 64, 359-372.

more usual species conifers were more cost effective than broad-leaved woodland. But results were sensitive to the land cost and the time horizons used.

3 Modelling woodland creation

3.1 Forest systems investigated

The steering group indicated a number of forestry systems and management specifications that were to be investigated in the study (Table 3.1). These were similar to those used in the ADAS (2009)[42] study and the Read report[43].

Table 3.1 Forest systems and specifications

	Species	Planting distance (m)	Rotation (years)	Thinned?	Clearfell?
Short rotation forestry (SRF): managed for energy	Red alder (100%)	1.5	25	No	Yes
Farm woodland: managed for mixed objectives	Sycamore/Common alder/ Birch (65%), Douglas fir[44] (25%)	2.5	Indefinite	Yes (3 thinnings)	No
Broadleaf1: managed for game/biodiversity	Sycamore/Common alder/ Birch (45%), Oak (45%)	2.5	Indefinite	No	No
Broadleaf2: managed for timber and carbon	Oak (45%), Birch (45%)	1.7	100	Yes (MT[45] thin)	Yes
Upland conifer: managed for timber	Sitka spruce (90%)	1.7	Max MAI[46]	No	Yes
Lowland conifer: managed for timber (England)	Douglas Fir (90%)	1.7	Max MAI	Yes (MT thin)	Yes
Lowland conifer: managed for timber (Wales, Scotland)	Sitka spruce (90%),	1.7	Max MAI	Yes (MT thin)	Yes
Continuous cover forestry (CCF); managed for mixed objectives	Sycamore/Beech (30%), Douglas Fir (60%)	1.7	N/A	Yes (5 year cycle)	No

Note: 10% of the area is open space in all options except SRF.

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[42] ADAS (2009). Analysis of Policy Instrument for Reducing Greenhouse Gas Emission from Agriculture, Forestry and Land Management – Forestry Options. Report for The Forestry Commission.

[43] Read, D.J., Freer-Smith, P.H., Morison, J.I.L., Hanley, N., West, C.C. and Snowdon, P. (eds). (2009). *Combating climate change – a role for UK forests. An assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change*. The synthesis report. The Stationery Office, Edinburgh.

[44] Sitka Spruce was substituted for Douglas Fir as a more appropriate species in two Scottish regions (Highlands and Islands and Grampian).

[45] MT. Based on the management tables given in Edwards, P.N. and Christie, J. M. (1981). Yield models for forest management, Forestry Commission Booklet 48, HMSO, London.

[46] Mean annual increment (MAI). This is the average annual increase in tree volume. See http://en.wikipedia.org/wiki/Optimal_rotation_age

Seven forest systems were defined and each had a prescribed rotation length defined by the Steering group in conjunction with Forest Research. Two different rotation lengths were used for the short rotation forestry (15 and 25 years) which effectively expands the woodland systems to eight.

It should be noted that the optimal rotation length for CO_2 emission reduction may differ from that for timber production or the delivery of other benefits. However, to investigate this aspect and produce ‘optimal’ rotation lengths was beyond the scope of the project. In any case rotation length is a private decision which may be influenced by the personal interests of the owner.

Table 3.1 also indicates the establishment and management details for each of the forest systems. These determine the costs of establishing and maintaining each woodland, and also influence the carbon sequestration and timber output.

The size of woods planted in recent years is not necessarily a good guide to the size of woodlands that will be planted in the future because the types of woodlands planted in the past differ somewhat from those listed in Table 3.1. Size will also be influenced by the structure of grant aid offered in support of planting. Nevertheless we give in Table 3.2 the mean and median areas planted under recent schemes. The data reflect the conditions of the grant schemes operating at the time and do not include non-grant aided planting[52]. The means and medians differ indicating that the size distributions are skewed.

Table 3.2 Areas and mean area planted under recent grant-aided planting

	Number of cases	Total area planted (ha)	Mean area of woodland (ha)	Median are of woodland (ha)	Range in area (ha)
Scotland (2009-2013)					
Central Scotland Mixed Woodland	47	902	19.19	12.42	0.51-54.5
Mixed conifer/broadleaved woodland	403	1,930	4.79	2.60	0.25-107.6
Native woodland planting	1135	19,453	17.14	2.50	0.25-433.0
Productive broadleaf woodland	32	321	10.02	5.86	2.00-71.3
Productive conifer - high cost	20	352	17.59	14.05	2.00-54.5
Productive conifer - low cost	88	4,454	50.61	22.35	1.02-402.8
Total	1,822	28,412	15.59	3.07	0.25-433.0
England Woodland Grant Scheme (2006-2013)					
Standard woodland	685	917	1.34	0.78	0.02-41.5
Small standard woodland	1394	666	0.48	0.37	0.01-2.39
Native woodland	3082	3895	1.26	0.61	0.01-25.4

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[52] A number of large woodlands are known to have been planted in recent years by such bodies as the Woodland Trust and MOD. These are not included in published statistics.

	Number of cases	Total area planted (ha)	Mean area of woodland (ha)	Median are of woodland (ha)	Range in area (ha)
Community woodland	355	544	1.53	0.61	0.01-24.5
Special broadleaved woodland	62	97	1.57	1.27	0.10-8.25
Total	5587	6120	2.00	0.55	0.01-41.5-
Wales Glastir Woodland Creation (2011-2013**)**	274	748	2.73	1.17	0.11-66.3

Against this historical background and after discussion with the Steering Group and UPM Tilhill we used planting areas for the different forest systems as given in Table 3.3. These are average areas per plantation that we anticipate being planted under a carbon-focussed policy.

Table 3.3 Woodland systems and areas per woodland

	Species	**Areas (ha)**		
		England	Wales	Scotland
Short rotation forestry (SRF): managed for energy	Red alder (100%)	2.0	2.0	5.0
Farm woodland: managed for mixed objectives	Sycamore/Common alder/ Birch (65%), Douglas fir (25%)	3.0	3.0	2.0
Broadleaf1: managed for game/biodiversity	Sycamore/Common alder/, Birch (45%), Oak (45%)	5.0	5.0	5.0
Broadleaf2: managed for timber and carbon	Oak (45%), Birch (45%)	2.0	2.0	5.0
Upland conifer: managed for timber	Sitka spruce (90%)	15.0	15.0	50.0
Lowland conifer: managed for timber (England)	Douglas Fir (90%)	10.0	10.0	25.0
Lowland conifer: managed for timber (Wales, Scotland)	Sitka spruce (90%),	10.0	10.0	25.0
Continuous cover forestry (CCF); managed for mixed objectives	Sycamore/Beech (30%), Douglas Fir (60%)	5.0	5.0	25.0

Note: 10% of the area is open space in all options except SRF.

3.2 Regions and Yield Classes

In order to cover the spatial variation in costs and outputs of woodlands in different parts of the UK 11 regions were defined by the Steering Group (Table 3.4). Wales was treated as one region whereas England and Scotland were each subdivided into five existing or historical conservancy areas or combinations of areas.

Yield class is a key measure of tree growth and also a major determinant of the rate of carbon sequestration. Yield classes for each species and regions were based on the weighted mean yield classes observed in each of the FC conservancies over the 1961-1990 period. These were rounded to the nearest yield class in the integer sequence: 2, 4, 6, 8, 12, 14, 16, 18 by Forest Research in their production of output from the CSORT model (see Section 3.4.1). Table 3.4 gives the yield classes used for each region. It is assumed that these yield classes will apply over the investment horizons examined.

Table 3.4 Mean yield classes (Forestry Commission data)

Country	**Region**	**Species**							
		Red alder	Common alder	Beech	Sycamore	Birch	Douglas Fir	Oak	Sitka spruce
England	Eastern and East Midlands	10	8	8	8	8	16	4	14
	South-east	10	8	6	8	8	12	6	12
	South-west	10	8	8	8	8	16	4	18
	West Midlands and North-west	10	8	8	6	8	16	4	14
	Yorkshire and North-east	10	8	6	8	8	12	4	14
Scotland	Central Scotland	8	6	6	4	6	8	4	14
	Grampian	8	6	4	4	6	8	2	12
	Highland and islands	8	6	4	4	6	4	2	12
	Perth and Argyll	8	6	6	6	6	10	4	14
	South Scotland	10	8	6	6	8	12	4	14
Wales	Wales	10	8	6	8	8	14	4	16

Note: Yield classes for all relevant species were increased by one class (e.g. 8 to 10) for Farm Woodlands to account for the higher quality of the planted land.

3.3 Timber and wood output

Forest Research provided year by year data on the standing volume (m3 per ha) of each species, and the volume (m^3 per ha) and mean volume (m^3 per tree) of thinnings and clearfell. This information was used to determine the standing timber values of harvested wood under the forest systems[54]. Year by year data for each forest system were also provided on the volumes of the various types of raw wood (m^3 per ha): sawn timber, saw-log off-cuts, small roundwood, branches, bark and woodfuel.

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[54] SRF output was priced using a different method.

3.4 Carbon data

3.4.1 Carbon sequestration in wood growth, litter and deadwood

Forest Research applied their CSORT model (Morison *et al*., 2012)[56] to derive most of the carbon sequestration and emission data. CSORT has been developed from the earlier CARBINE model (Thompson and Matthews, 1989[57]; Matthews, 1994[58], 1996[59]) which currently is applied for large-scale analysis of the potential impacts on GHG emissions of scenarios for forest management (Matthews and Broadmeadow, 2009)[60]. Compared to CARBINE, CSORT is a 'second generation' forest carbon accounting model applied at the per-hectare scale, capable of representing a wider range of forest systems and more complex management regimes, such as required for this project. Both models are based on long-established underpinning models of forest growth and yield relevant to UK conditions (Edwards and Christie, 1981)[61] and represent litter and soil carbon dynamics consistently with current scientific understanding of UK forest soils (Morison *et al*., 2012).

The CSORT model was used by Forest Research to provide:

- Changes in forest carbon stocks
- Levels of production of primary wood raw materials
- Carbon stock dynamics of harvested wood products including losses to atmosphere at end of life
- GHG emissions associated with forest operations (i.e. forest establishment, forest maintenance, tree harvesting and extraction of wood products to forest roadside).

Results were produced for all the species, yield classes, countries and forest management systems given in Table 3.1. No errors are attached to the model results which are treated as unbiased mean estimates. The estimates for sequestration were adjusted down by a permanence buffer of 15% (see 2.4.3).

3.4.2 Carbon emissions and retention in soils

Forest Research provided estimates of the annual carbon fluxes from soil for the regional soil types (mineral loam, mineral gley, organo-mineral loam, organo-mineral gley) under two

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[56] Morison, J., Matthews, R., Miller, G., Perks, M., Randle, T., Vanguelova, E., White, M. and Yamulki, S. (2012). Understanding the carbon and greenhouse gas balance of forests in Britain. Forestry Commission Research Report. Forestry Commission: Edinburgh.

[57] Thompson, D.A. and Matthews, R.W. (1989). The storage of carbon in trees and timber. Research Information Note 160. Forestry Commission: Edinburgh.

[58] Matthews, R.W. (1994). Towards a methodology for the evaluation of the carbon budget of forests. In Kanninen, M. (ed.) Carbon balance of the world's forested ecosystems: towards a global assessment. Proceedings of a workshop held by the Intergovernmental Panel on Climate Change AFOS, Joensuu, Finland, 11-15 May 1992, 105-114. Painatuskeskus: Helsinki.

[59] Matthews, R.W. (1996). *The influence of carbon budget methodology on assessments of the impacts of forest management on the carbon balance*. In Apps, M.J. and Price, D.T. (eds.) Forest ecosystems, forest management and the global carbon cycle. NATO ASI Series **I 40**. Springer-Verlag: Berlin, 233-243.

60 Matthews, R.W. and Broadmeadow, M.S.J. (2009). The potential of UK forestry to contribute to Government's emissions reduction commitments. In: Read, D.J., Freer-Smith, P.H., Morison, J.I.L., Hanley, N., West, C.C. and Snowdon, P. (eds.) (2010). Combating climate change – a role for UK forests. An assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change. The Stationery Office: Edinburgh, 139-161.

[61] Edwards, P.N. and Christie, J.M. (1981). *Yield models for forest management*. Forestry Commission Booklet 48. Forestry Commission: Edinburgh.

previous land uses (arable, pasture) (Table 3.5). Both arable (which includes leys) and permanent pasture were used for the South-east and Eastern/ East Midlands of England. Elsewhere permanent pasture was assumed. For mineral soils carbon fluxes were based on IPCC[65] values for a moist, temperate climate. Data for organic soils were based on literature values[66]. Values for organo-mineral soils were interpolated between the mineral and organic estimates.

Table 3.5 Soil types and previous land use[67]

Country	Region	Soil type	Previous land use
England	Eastern and East Midlands	Mineral gley	Arable and pasture
	South-east	Mineral gley	Arable and pasture
	South-west	Mineral loam	Pasture
	West Midlands and North-west	Mineral loam	Pasture
	Yorkshire and North-east	Organo-mineral gley	Pasture
Scotland	Central Scotland	Organo-mineral loam	Pasture
	Grampian	Mineral gley	Pasture
	Highland and islands	Organo-mineral gley	Pasture
	Perth and Argyll	Organo-mineral gley	Pasture
	South Scotland	Organo-mineral loam	Pasture
Wales	Wales	Organo-mineral gley	Pasture

Note: Pasture is permanent grassland and rough grazing. Arable include rotations involving temporary leys.

Table 3.6 gives the carbon fluxes per ha for each soil type and previous land use. The figures are net changes in emissions reflecting the change in land use, i.e. against a counterfactual of continued pasture or arable use. In these data no account is taken of the effect of planting method or tree species on the carbon balance. On mineral soils after pasture there is an initial emission of CO_2e followed by no change, whereas when planting after arable there is no loss on planting but small gains in soil carbon for 20 years. The organo-mineral soils show larger losses of CO_2e on planting followed by further small losses over the first 50 years.

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[65] UNFCCC/CNUCC (2011) A/R Methodological Tool.Tool for estimation of change in soil organic carbon stocks due to the implementation of A/R CDM project activities. Executive Board Report 60 http://cdm.unfccc.int/methodologies/ARmethodologies/tools/ar-am-tool-16-v1.1.0.pdf
IPCC (2006). *2006 IPCC Guidelines for National Greenhouse Gas Inventories,* prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan.
IPCC, 2003. *Good Practice Guidance for Land Use, Land-Use Change and Forestry*, prepared by the National Greenhouse Gas Inventories Programme, Jim Penman, Michael Gytarsky, Taka Hiraishi, Thelma Krug, Dina Kruger, Riitta Pipatti, Leandro Buendia, Kyoko Miwa, Todd Ngara (eds). Published: IGES, Japan.

[66] Vanguelova, E.I, Nisbet,T.R., Moffat, A.J., Broadmeadow, S. Sanders, T.G.M. and Morison, J.I.L.. (2013) A new evaluation of carbon stocks in British forest soils. *Soil Use and Management* 29; 169-181.
Batjes, N.H. (2002) Carbon and Nitrogen stocks in the soils of Central and Eastern Europe. *Soil Use and Management* 18; 324-329.

[67] The different soil types are defined in http://www.forestry.gov.uk/forestry/INFD-8J3QRL#define

Table 3.6 Carbon fluxes in different soil types and previous land uses (tC per ha, negative values are emissions).

Year	Mineral loam after pasture	Mineral gley after pasture	Organo-mineral loam after pasture	Organo-mineral gley after pasture	Mineral loam after arable	Mineral gley after arable
0	-11.5	-9.5	-12.96	-10.96	0	0
1	0	0	-0.97	-0.97	0.8	0.8
2	0	0	-0.97	-0.97	0.8	0.8
3	0	0	-0.97	-0.97	0.8	0.8
4	0	0	-0.97	-0.97	0.8	0.8
5	0	0	-0.97	-0.97	0.8	0.8
6	0	0	-0.97	-0.97	0.8	0.8
7	0	0	-0.97	-0.97	0.8	0.8
8	0	0	-0.97	-0.97	0.8	0.8
9	0	0	-0.97	-0.97	0.8	0.8
10	0	0	-0.97	-0.97	0.8	0.8
11	0	0	-0.97	-0.97	0.8	0.8
12	0	0	-0.97	-0.97	0.8	0.8
13	0	0	-0.97	-0.97	0.8	0.8
14	0	0	-0.97	-0.97	0.8	0.8
15	0	0	-0.97	-0.97	0.8	0.8
16	0	0	-0.09	-0.09	0.8	0.8
17	0	0	-0.09	-0.09	0.8	0.8
18	0	0	-0.09	-0.09	0.8	0.8
19	0	0	-0.09	-0.09	0.8	0.8
20	0	0	-0.09	-0.09	0.8	0.8
21	0	0	-0.09	-0.09	0	0
22-50	0	0	-0.09	-0.09	0	0
51+	0	0	0	0	0	0

Note: negative numbers are emissions

These estimates of soil retention and emissions whilst based on IPCC guidelines differ from those currently in use for applying the Woodland Carbon Code[68]. Soils emissions, particularly for organo-mineral soils, need to be clarified by further research.

3.4.3 Carbon emission effects of changes to land use

New planting will displace a prior land use and any output associated with that use. We assume this is livestock on permanent pasture, and arable cropping on arable land. One counterfactual is thus the emission/retention profile of continued livestock or arable farming over the time horizon of the investment (up to 186 years).

It is normally assumed that any agricultural output displaced will be produced by more intensive use of agricultural land in the UK or imported. If underutilised land is used it is reasonable to assume no net impact on agricultural emissions. If production is displaced abroad much would

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[68] http://www.forestry.gov.uk/forestry/INFD-8J3QRL

depend on the agricultural technology used to produce the marginal output. But a conservative view would be that there would be no clear saving in global emissions. On this basis, whilst there may be possible gains from reduced agricultural emissions, they are uncertain and a conservative approach would exclude them. This is the approach adopted here.

3.4.4 Emissions from inputs and operations

Based on data from the literature presented in Morrison et al. (2012)[71], Forest Research estimated the annual emissions associated with forestry operations. These largely consisted of direct emissions associated with diesel used in thinning, harvesting, extraction, road construction and maintenance, and herbicide application. Where possible, up stream emissions associated with fencing wire and posts, herbicide and plant production were included.

These emissions had a minimal impact on the net sequestration. Hence the outcomes are not sensitive to the particular assumptions made.

3.4.5 Emissions from timber and wood

We include annual carbon emissions from harvested wood product (thinnings and clearfell). Emission estimates are based on the Forestry LULUCF which are based on equation 12.1 of the 2006 IPCC Guidelines for National Greenhouse Gas Inventories[72]. Carbon is stored (temporarily) in wood product, with emissions assumed to be represented by an exponential decay function. The half-lives were as indicated in the 2003 IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry[73]. Decay functions with half-lives of 25 and 35 years were used for roundwood products/board and sawn timber products respectively.

3.4.6 Emissions from biomass for combustion

The Forest Research carbon models assume that 50% of the final crop harvest of tops and branches plus all off-cuts from saw-logs and small roundwood are used as woodfuel. Where woodfuel substitutes for alternative energy sources the net CO_2e impact of the substitution needs to be calculated since there will not be precise carbon neutrality.

Woodlfuel is used for both heat and power generation but there are no precise data on the current utilisation volumes for different types of plant. Discussion with Forestry Commission staff and others suggested that 40% by volume is used in power generation, 25% in combined heat and power plants (CHP) and 35% for heating. We assume that utilisation in the future will be 50% power generation and 50% heat for the UK as a whole.

DECC[75] recommend using the grid long-run marginal generation based emission (LMGE) factors[76] for small changes in power generation. The emission factor for 2014 is 0.320 kg CO_2e per KWh but this declines over time to 0.032 kg CO_2e per kWh in 2049 after which it is constant. This is a reflection of expected technical and regulatory change that will progressively reduce carbon emissions. For heat generation we assume that the main substitution will be for oil. DECC[77] recommend that we apply a carbon emission factor of 0.2885 kg CO_2e per kWh at 93% efficiency.

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[71] Morison, J, Matthews, R., Miller, G., Perks, M., Randle, T., Vanguelova, E., White, M. and Yamulki, S. (2012). *Understanding the carbon and greenhouse gas balance of forests in Britain*. Forestry Commission Research Report. Forestry Commission: Edinburgh.

[72] http://unfccc.int/resource/docs/2011/cmp7/eng/10a01.pdf

[73] http://www.ipcc-nggip.iges.or.jp/public/gpglulucf/gpglulucf.html

[75] Jennifer McVey personal communication.

[76] https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

[77] DECC personal communication.

The direct (biogenic) emissions are accounted for in the CSORT models by equating emissions to prior sequestration. Hence it is only the indirect emissions from woodfuel that need to be included.

The thermal efficiency of power production from woodfuel depends on plant characteristics and the moisture content of the fuel (Matthews et al., 2011)[84]. A survey of reported efficiencies suggests an indicative figure of 35% for wood chips in power generation and 70% for heat generation. Table 3.7 shows the calculation for power generation where the net carbon saving is 414 $kgCO_2$ per t wood chips combusted in 2014. The corresponding figure for heat production is 743 $kgCO_2$ per t wood chips.

Table 3.7 Calculation of emission change when substituting woodfuel in power generation in 2014

	Indirect emission (kg CO2e per kWh)	LMGE emission factor (kg CO2e per kWh)	Net calorific value[85] of wood (kWh per kg)	Reduction in emissions (kg CO2e per t wood) at 35% thermal efficiency
Chips (30% moisture)	0.01579	0.320	3.89	414
Pellets (10% moisture)	0.03895	0.320	4.72	464

Source: Defra/DECC (2012) and Defra Ricardo-AEA[86]

3.4.7 End-of-life combustion

At the end of its life a proportion of wood will be recovered and combusted, mainly for power generation. A major expansion in biomass fuelled power stations is in progress[87] in part reflecting the restrictions to be imposed under the EU Landfill Directive. Combusted material will reduce emissions in so far as the biogenic emissions are already accounted for in CSORT. This uses an IPCC-based exponential function for the release of CO_2e following harvest as wood product decays.

The decay function is conceptual and is not linked to actual products and their expected lifespan, and the CSORT output did not give this linkage to actual product life. We cannot therefore develop a clear linkage to the implied end of life assumed in CSORT. However, we can calculate the likely magnitude of the effect. There will only be end-of-life combustion gains from those forest systems that have harvested material. We take SS YC12 (Highland and Islands) as an example. The first clearfell occurs in year 54 (2068) producing 115 odt[88] timber per ha. Taking a 35 year mean life would give a date for combustion of 2103. Assuming utilisation for power production, the LMGE is constant from 2049 at 0.032 kg CO_2e per kWh (see 3.4.6). There will be transport and processing emissions to be deducted and we assume these are similar to those for chips (Table 3.7). The net gain is thus 0.016 kg CO_2e per kWh.

The calorific value of dry wood is 5.3 kWh per kg[89] and we assume a thermal efficiency for

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[84] Matthews, R et al (2011). Carbon impacts of using biomass in bioenergy and other sectors: forestry. DECC project TRN 242/08/2100. Final report parts a and b. Forest Research.
[85] http://en.wikipedia.org/wiki/Heat_of_combustion
[86] http://www.ukconversionfactorscarbonsmart.co.uk/
[87] UK biomass power stations. Biomass Energy Centre, Forestry Commission.
[88] Oven dry tonnes.
[89] http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,20041&_dad=portal&_schema=PORTAL

power generation of 35%[90]. At 25% utilisation of harvested wood the CO_2e emission reduction is 0.85 tCO_2e per ha. With three harvests the total would be 2.6 tCO_2e per ha. This is a small gain in the context of 112 tCO_2e abatement from this forest system over three rotations.

The end-of-life combustion effect is uncertain because it is difficult to predict the proportion of timber product that will be combusted. Even at a 50% recovery rate the carbon gains appear to be small when used for power generation. Since it was not possible to link end-of-life use with the carbon decay functions used in CSORT and given considerably uncertainty over the level of recovery that will occur we exclude this element from the analysis. The example calculation suggests that it will not materially affect the conclusions but more detailed work is needed to clarify this aspect.

3.4.8 Emission savings from product substitution

Incremental additions to UK wood output will most obviously substitute for imported wood because this is the closest substitute. We assume that when increased domestic production substitutes for imported wood the carbon implications from differences in transport and handling are sufficiently small to be ignored. However, there are other substitution possibilities. SAC (2008)[91] identified the two main substitution routes with potential for carbon abatement:

- ❑ Fossil fuels in the energy generation sector; and
- ❑ Concrete or steel in the construction sector.

In both cases the potential for substitution will only occur with forest systems that produce thinnings and/or clearfell. Unthinned permanent plantations (e.g. permanent broadleaves) can confer no substitution gains – in these cases the potential social gain modelled in this study is only from sequestration (with adjustments for soil carbon and inputs/operations). In contrast, systems that are thinned and/or felled can potentially deliver both sequestration and substitution benefits.

Substitution of woodfuel and residual wood for other fuels in power and heat generation has been considered above (section 3.4.6). SAC (2008) allow for product substitution in their cost-effectiveness estimates but do not indicate what assumptions were made.

Examination of trade in wood offers no unambiguous information on product substitution. UK wood production has shown a trend increase of 0.218m m3 (c. 2.5%) per year over the last decade (Figure 3.1). Apparent wood consumption increased to 2007 but then declined, with an overall trend of -1.24m m3 per year[92] over the decade. The decline post- 2007 almost certainly reflects, at least in part, a decrease in UK economic activity. The recent changes are consistent with the view that increased production has substituted for imported timber, its most obvious substitute.

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[90] http://www.power-technology.com/projects/tilbury-power-station/

[91] SAC (2008). UK Marginal Abatement Cost Curves for the Agriculture and Land Use, Land-Use Change and Forestry Sectors out to 2022, with Qualitative Analysis of Options to 2050 (RMP4950) 20/11/2008. Final Report to the Committee on Climate Change http://www.theccc.org.uk/pdfs/SAC-CCC%3B%20UK%20MACC%20for%20ALULUCF%3B%20Final%20Report%202008-11.pdf

[92] Estimated by linear regression from the data in Figure 3.1.

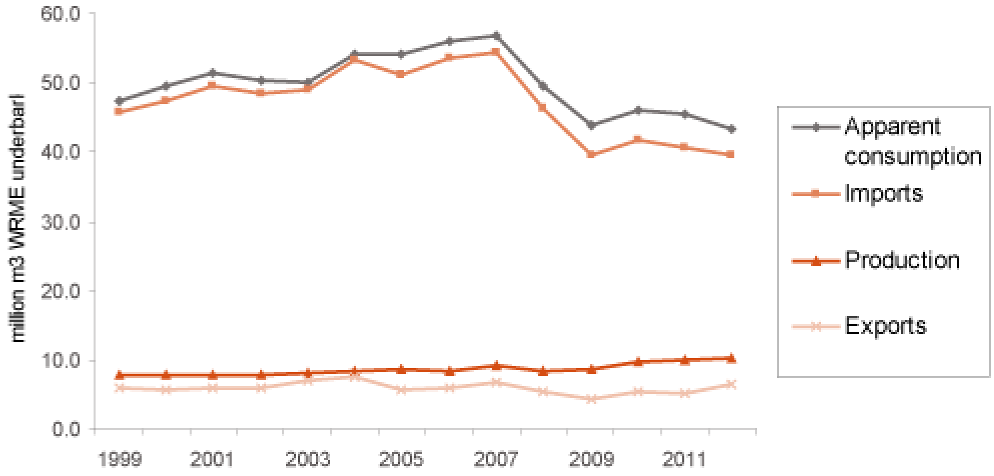

Figure 3.1 Apparent consumption of wood in the UK, 1999-2012[93]

Wood is widely used in the construction of low-rise buildings, including residential and light commercial structures. However, timber may be limited as compared to steel, aluminium, bricks or concrete by its stability and structural strength. This restricts its substitution potential unless engineered to enhance the structural properties. Cross laminated timber (CLT) has improved structural properties because cross-grain movement is controlled by lamination. It normally forms the structural floor and wall element of buildings, and has been used successfully to build up to nine storeys in the UK[94]. Whilst there are no official data on the growth of the market for CLT its use is increasing and there is clearly considerable potential for substitution in certain types of buildings[95].

Sathre and Gustavsson (2009)[96] made an extensive review of studies that measured the potential for carbon substitution in domestic and industrial buildings. They found that the mean gain from a medium level of displacement was 2.0 tC emission reduction per tC of additional wood products used. The mean gain for a low level of displacement was 0.7tC per tC whereas a high level displaced 4.4tC per tC.

The potential for carbon abatement through product substitution would thus appear to be high. Nevertheless at present there are no CLT plants in the UK. The short-term substitution potential for UK timber is thus quite limited. In the longer term this may change. Even so, much of the emission associated with the production of construction materials ultimately reflects the power usage in manufacture[97]. The emissions from marginal electricity consumption are expected to decline substantially over time[98], with post-2049 carbon emissions predicted by

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[93] Source: Forestry Statistics 2013. Forestry Commission.

[94] See http://www.bre.co.uk/filelibrary/pdf/projects/low_impact_materials/IP17_11.pdf

[95] See http://www.building.co.uk/the-rise-of-cross-laminated-timber/5069291.article

[96] Roger Sathre and Leif Gustavsson (2009). A state-of-the-art review of energy and climate effects of wood product substitution. http://lnu.se/polopoly_fs/1.42303!Energy%20and%20climate%20effects%20Report%202.pdf

[97] For example steel production is extremely energy intensive and electricity usage is the main source of carbon emissions in production. See http://www.iea-coal.org.uk/documents/82861/8363/CO2-abatement-in-the-iron-and-steel-industry,-CCC/193

[98] https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

DECC[99] to be at very low levels. Clearfell of the conifer systems used in this study will not occur until after 2049. In practice, substitution will be driven by the technical specifications of UK-produced substitute materials, relative product costs and any restrictions imposed by building regulations. Codes such as that for sustainable homes[100] will impact on construction practice although there may be no requirement to increase the use of UK produced timber. It would seem unwise to assume that laminated board with superior structural properties will necessarily be produced in the UK although there is certainly evidence for the potential of CLT as a structural material.

There are thus some major uncertainties about future levels of wood substitution. However, to illustrate the potential for carbon abatement through product substitution we take the example of an additional 20% substitution (20% of all conifer sawn timber output substituted for other construction materials) from the upland conifer SS YC12 system in the Highland and Islands. The carbon content of the sawn timber output at year 54 is 18.9 tC (69.4 tCO_2e) per ha. We apply the Sathre medium displacement factor of 2.0 tC emission reduction per tC of additional wood output. However, the emission reduction will depend on changes in the emissions from manufacture of the material for which substitution takes place. As indicated above, we use the DECC forecast of reducing carbon emissions from power generation to adjust the Sathre saving. In this case it is reduced to 0.188% emission reduction per tC[101]. The carbon saving from 20% substitution is 2.6 tCO_2e per ha. Over 186 years there will be three clearfells to give a carbon saving in total of 8 tCO_2e per ha. This only increases the mean CO_2e net retention by 1.6% increase. Under the assumption that power is the main carbon emission in the material for which timber substitutes, the impact on net carbon retention from substitution is small.

In the analysis we do not assume any product substitution from the marginal increase in timber output. Much will depend on whether structurally improved timber-based materials are manufactured in the UK in future and the extent to which carbon emissions are progressively reduced in the manufacture of more traditional materials. Matthews et al. (2011)[102] assess net carbon retention in forestry against a range of non-wood counterfactuals. However, no quantitative information is given on the technical assumptions relevant to product substitution. They do not appear to factor in the progressive reduction in carbon emissions from power generation predicted by DECC. More detailed research is needed on these aspects and our conclusions should be treated as preliminary only.

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[99] https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

[100] https://www.gov.uk/government/policies/improving-the-energy-efficiency-of-buildings-and-using-planning-to-protect-the-environment/supporting-pages/code-for-sustainable-homes

[101] DECC (2014) give the long run marginal carbon emissions from electricity generation declining from 0.32 kg CO2e per kWh in 2014 to 0.03 kg CO2e per kWh after 2049. The emissions from the substitute are assumed to decline correspondingly. https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

[102] Matthews, R et al (2011). Carbon impacts of using biomass in bioenergy and other sectors: forestry. DECC project TRN 242/08/2100. Final report parts a and b. Forest Research. https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/282812/DECC_carbon_impacts_final_report30th_January_2014.pdf

4 Costs and benefits of the forest systems

4.1 Benefits

In principle, a social analysis should include all the costs and benefits to society from an investment. In the context of new forest planting this includes the value of the net retained carbon, the value of wood and timber produced, and any other public benefits (e.g. from biodiversity change). Private benefits to landowners should in principle also be included. These may be derived, for example, from enhanced shooting, shelter, wildlife or amenity. However, we excluded any private benefits, there being no information on which these could be reliably estimated.

4.2 Carbon value

DECC indicates carbon values that should be used in government policy analysis. DECC distinguishes between the traded and non-traded sectors. The traded sector comprises businesses covered by the EU Emissions Trading System (EU ETS). The system uses a cap and trade approach to limit emissions of CO_2 from power plants, a wider range of energy intensive industries and commercial airlines. The non-traded sector comprises all other carbon emissions.

Where wood is used for domestic heating, small heat-generation boilers, combined heat and power (CHP) plants or small-scale generators outside the EU Emissions Trading System (EU ETS), the normal formula for CE estimation is used in which no account is taken of the value of the carbon. However, in both cases the impact of burning wood on CO_2e emissions is included as a deduction from the CO_2e saved (the denominator).

Some wood may be used in installations within the EU ETS (large scale power. heat and combustion plants) as co-firing in electricity generation. This is a sector subject to cap and trade where the DECC carbon values differ from those in the non-traded sector.

CO_2e values were taken from the DECC (2014)[104] schedule of traded and non-traded carbon values from 2014 until 2100. The central values are used. Most of the wood output from new woodland creation will be in the non-traded sector for which carbon prices are predicted to increase to 2075 (£341 per tCO_2e) and then fall. Traded values equal non-trade values after 2030 and since there is no wood output from any forest system until 2029[106], we simplified the pricing of carbon emissions by using non-traded prices throughout. In the absence of any other information we assume the 2100 value of £297 per tCO_2e applies beyond 2100.

4.3 Timber and wood

4.3.1 Timber prices

Real GB coniferous standing sale prices fell from 1987 to 2003 (Figure 4.1)[107] but have recovered slightly in the last decade. The average GB nominal price in the year to March 2013 was £13.29 per cu m.

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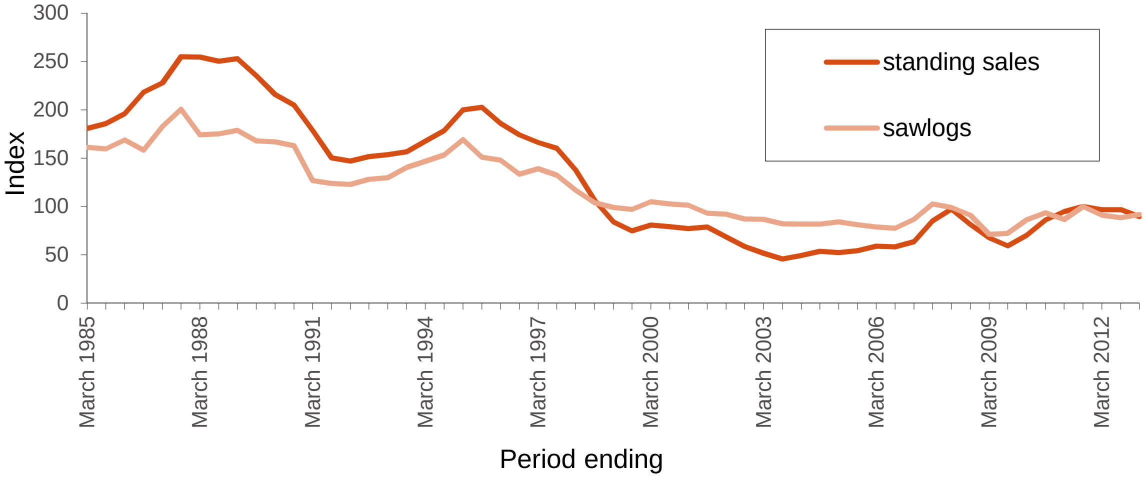
[104] DECC (2014). https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

[106] The 15 year SRF system planted in 2014 is harvested in 2029.

[107] http://www.forestry.gov.uk/pdf/SSSSeptember2013rev.pdf/$FILE/SSSSeptember2013rev.pdf

Figure 4.1 **Coniferous standing sales and sawlog price indices[1] in real terms[2], 1985-2013**



Source: Timber Price Indices: data to March 2013

Forecasting future timber prices is not straightforward. The EU-27 and in particular the eurozone members Sweden, France, Germany and Finland are major suppliers of wood products to the UK[108]. UK timber prices are largely dependent on import prices which will change depending principally on market supply and demand within Europe and the GBP/euro exchange rate[109]. The growing demand for wood as an energy source has raised prices for thinnings and low volume material in locations near sources of demand. This change in demand has modified the price/size curve at least in England.

We were unable to locate any long-term forecasts for exchange rate movements or future timber prices. Timber revenue forecasts were therefore based on estimated price size curves. They are however subjected to sensitivity analysis to identify how critical the assumed timber prices were to the estimates of CE.

4.3.2 Estimation of price-size curves

Price-size curves for conifers were estimated from FC standing sales price data. Linear and logarithmic regressions were fitted to the mean FC standing conifer price series for each of the GB countries from 1 April 2011 to 31st March 2013[110][111]. The best fitting regression as judged by R^2 was used to give a set of smoothed prices in relation to tree volume (Annex 1 Table 8.1). Prices broadly increase with increasing tree volume but there are substantial price differences between the three countries, with prices in England higher than those in Scotland or Wales. In the absence of any published data on regional prices we applied these prices to all regions within a country.

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[108] http://www.forestry.gov.uk/website/forstats2012.nsf/0/D7DD6DF6687BC57880257A32004E1A4F

[109] Over the last 30 years the average rate of decline in sterling against the euro has been 1.3% per year.

[110] http://www.forestry.gov.uk/pdf/SSSSeptember2013rev.pdf/$FILE/SSSSeptember2013rev.pdf

[111] England price=21.45+3.452*LN (tree volume) (R^2=077); Scotland price=16.38+4.845*LN (tree volume) (R^2=0.79); Wales price=3.01+12.055*(tree volume) (R^2=0.54)..

We asked relevant FC staff and UPM/Tilhill to comment on the prices estimated in Annex 1 Table 8.1. A number of factors were indicated as possibly explaining the differences between countries. Higher harvesting costs and different markets for smaller volume material (which typically also has a lower yield per ha) result in lower prices for smaller trees. Proximity to markets is clearly important because it affects transport costs. In England the presence of hardwoods in conifer plantations and a distinctive system of reserve pricing was thought to account for some of the relatively higher prices. Since none of the factors could be quantified and were mostly thought to be small we used the conifer prices as in Table 8.1. It should be noted that timber prices are irrelevant for some of the forest systems used in this study because there is no harvesting.

There are no equivalent FC standing sale data for timber from broadleaves, and information from individual sales indicates considerable variation in price depending on size, quality and species. In the absence of an FC price size curve for broadleaves we use a GB price-size curve developed from commercial sources for the Forestry Commission investment model[112] (Annex 1 Table 8.2). This gives similar prices to the England conifer curve at low tree volumes, rising to £24 per cu m at a tree volume of 1.00m^3 and £30 per cu m above 1.6m^3.

4.3.3 Short rotation forestry

The short rotation forestry system differs from the others in rotation length. Its output is specifically woodfuel. The standing timber price size curves were not appropriate for this crop. Instead we estimated current costs and returns as the basis for revenue.

A typical delivered price for chips (at 30% moisture) is £110 per t. We assume mechanical harvesting[113] and extraction, haulage to a conditioning plant where the chips are produced and stored for a year, and then haulage to end user. The total cost will vary with haulage distances but where production is near a processing plant the minimum would be £60 per t at 30% moisture.

The maximum net revenue to the producer is thus in the order of £50 per t at 30% moisture. This is higher than a typical price for hardwood or softwood woodchip grade material at roadside (up to £30-50 per t). Nevertheless we use the £50 per t standing crop as an indicative figure to assess the net return from creating short rotation forestry.

4.4 Other public benefits

Considerable research has been undertaken to value the public benefits from woodlands[114]. New woodlands may deliver a wide range of ecosystem services including benefits to biodiversity, landscape, recreation, flood alleviation, air pollution and water quality. These

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[112] CJC Consulting (2012). Study to assess investment returns in woodland creation in Great Britain. Report to the Forestry Commission.

[113] Many alternatives exist including non-mechanical harvesting and conditioning on site rather than at a specialised plant.

[114] See recent reviews:
http://www.defra.gov.uk/forestrypanel/files/IPF_Woodland_Economy_Creation_Management.pdf
Willis, K. G., Garrod, G. Scarpa, R., Powe, N., Lovett, A., Bateman, I. J., Hanley, N. and Macmillan, D. C. (2003). The Social and Environmental Benefits of Forests in Great Britain. Report to Forestry Commission, Edinburgh. Centre for Environmental Appraisal and Management, University of Newcastle upon Tyne [online] available at:
http://www.forestry.gov.uk/pdf/sebreport0703.pdf/$FILE/sebreport0703.pdf
Eftec (2010). The Economic Contribution of the Public Forest Estate in England, for Forestry Commission England [online] available at: http://www.forestry.gov.uk/pdf/eng-pfe-econmicresearch-final.pdf/$FILE/eng-pfe-econmicresearch-final.pdf

benefits are highly site and woodland specific and depend in part on the extent of woodland visibility and accessibility by the public.

Eftec (2010)[115] has reviewed the evidence in their valuation of the public estate in England and concluded that the highest benefits are provided by urban and peri-urban woodlands, high priority biodiversity sites and accessible woods with developed facilities. The non-use biodiversity and cultural benefits (i.e. excluding regulating services, timber and carbon) were estimated to average £300 per ha per year for priority sites. Benefits from non-priority sites were around £30 per ha per year. Aesthetic benefits were considered to average £40 per ha per year but £10 where woodlands were managed primarily for timber. This suggests a combined benefit of £10 per ha per year for conifers, and £70 per ha per year for other systems in England. But these are broad and uncertain estimates. The recreational value of accessible rural sites with few or no facilities was valued by Eftec at £180 per ha per year in England. But they point out that the value is highly variable depending on accessibility and location.

Willis et al. (2003) found that recreation, biodiversity and landscape benefits from existing forestry were much lower in Scotland and Wales than in England. This reflects in part the lower populations and more limited opportunities to view or visit.

Given the uncertainty over the magnitude of these social benefits it was considered inappropriate to include biodiversity and aesthetic benefits in the calculation of CE. Other studies on the topic also excluded such benefits[116]. This approach was considered preferable to one that included estimates of the monetary value of benefits that were difficult to justify and open to dispute. Much would depend on how policy was defined and the extent to which planting was directed at the delivery of other non-market benefits in addition to carbon.

4.5 Costs associated with new planting

4.5.1 Land

The cost of moving land from another use into forestry is the social opportunity cost of the land. For agricultural land this would be the net social benefit of the agricultural net output foregone. Valatin (2012)[117] has argued that land values or opportunity costs should allow for the loss of option value to society which may not be adequately expressed in current (private) land values. In principle the social opportunity cost would be estimated annually over the investment horizon for each region and forestry system. In comparisons with other government mechanisms for emissions reduction it would be important to note any food security or environmental implications of expanding planting on farmland.

Private opportunity costs may be a good proxy for social costs assuming that they contain no subsidy element. Land prices reflect market expectations of private income but this may be discounted at a rate that exceeds the social discount rate. We might therefore expect observed land prices to somewhat underestimate equivalent social valuations of land. However, since private discount rates are unobservable it is difficult to adjust for this effect.

We assess land prices and private opportunity costs as possible bases for social opportunity cost.

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[115] Eftec (2010). The Economic Contribution of the Public Forest Estate in England, for Forestry Commission England [online] available at: http://www.forestry.gov.uk/pdf/eng-pfe-econmicresearch-final.pdf/$FILE/eng-pfe-econmicresearch-final.pdf

[116] ADAS (2009) and SAC (2008) also excluded public benefits other than timber and carbon in their estimation of cost-effectiveness.

[117] Valatin, Gregory (2012). Marginal Abatement Cost curves for Forestry. Forest Research. *www.forestry.gov.uk/pdf/FCRP019.pdf/$FILE/FCRP019.pdf*

4.5.2 Land prices

The main sources of land price statistics (Valuation Office Agency (VOA)[118], Savills[119] and RICS[120]) all show major increases in the nominal price of all types of farmland in recent years. The VOA data records valuers' estimates of prices for typical arable, dairy and mixed farms. This classification fails to separate out poor quality livestock farms and would not be a guide for prices of land moving into forestry.

The RICS land prices publish land prices for GB which are averages irrespective of land quality and are not regionalised. But the data do reveal the substantial increases that have occurred in recent years in land prices throughout GB. The RICS land price index for England and Wales was 401 in 2012 compared with a base of 100 in 1995, a nominal increase of over 400% in slightly less than 20 years. Since 2009, prices have increased by around 35% driven by low interest rates coupled with a tight land supply and improved commodity prices especially for arable crops.

Savills' land sales data (Figure 4.1) also show substantial increases in the nominal prices of all categories of land in recent years (when the rate of inflation has been low).

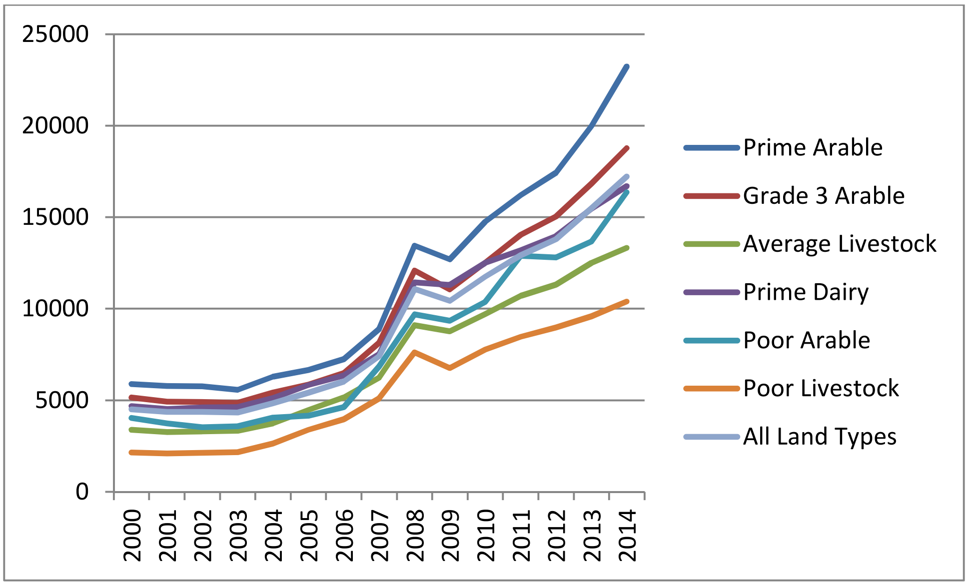

Figure 4.1 Great Britain average land values (£ per ha)

Table 4.3 shows 2014 average prices for Grade 3 arable and poor grassland (weighted by area sold). Prices for Grade 3 arable are higher in the East, East Midlands an South-east than elsewhere in GB. Poor grassland prices are much lower in Scotland than England or Wales. These prices are exclusive of any Single Farm Payment (SFP) which is normally retained or sold by separate negotiation.

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[118] Valuation Office Agency (2011) Property Market Report 2011 [online] available at: http://www.voa.gov.uk/dvs/_downloads/pmr_2011.pdf

[119] Savills (2012) Market Survey Agricultural Land. 2012 [online] available at: http://www.savills.co.uk/research/rural-research.aspx

[120] RICS (2014) Rural Land Market Survey H1 2014. http://www.rics.org/uk/

Table 4.3 Regional prices for land (June 2014, £ per ha) (Savills).

	England						Scotland	Wales
Region	**North**	**East**	**East Midlands**	**West Midlands**	**South-west**	**South-east**	**All**	**All**
Grade 3 arable	16,230	23,600	20,445	17,340	16,360	19,060	14,315	14,885
Poor grassland	8,985	6,210	12,360	12,160	11,945	14,870	3,880	10,650

We also obtained indicative prices from UPM/Tilhill for land purchased or suitable for planting (Table 4.4). These prices are ex-Single Farm Payment (SFP) and contain no capitalised element of this payment. Where few or no land sales for forestry have taken place (as is the case in parts of England) the prices are more speculative. The UPM/Tilhill prices tended to lie between the Grade 3 arable and poor grassland prices given in Table 4.3.

Table 4.4 Regional land prices (£ per ha) (UPM/Tilhill)

		Woodland system						
Country	**Region**	**SRF**	**Farm woodland**	**BL managed for biodiversity**	**BL managed for timber**	**Upland conifer**	**Lowland conifer**	**CCF**
England	**South-east**	12,400	12,400	12,400	12,400	N/A	12,400	12,400
	South-west	12,400	12,400	12,400	12,400	N/A	12,400	12,400
	Eastern and East Midlands	11,100	11,100	11,100	11,100	N/A	11,100	11,100
	West Midlands and North-west	11,100	11,100	11,100	11,100	3,800	11,100	11,100
	Yorkshire and North-east	11,100	11,100	11,100	11,100	3,800	7,500	11,100
Scotland	**Highlands and Islands**	3,500	3,500	3,500	3,500	2,500	N/A	3,500
	Grampian	3,500	3,500	3,500	3,500	2,500	7,500	3,500
	Central Scotland	3,500	3,500	3,500	3,500	2,500	3,800	3,500
	Perth and Argyll	3,500	3,500	3,500	3,500	2,500	3,800	3,500
	South Scotland	**3,500**	**3,500**	**3,500**	**3,500**	**2,500**	**3,800**	**3,500**
Wales	**All**	11,100	11,100	11,100	11,100	7,500	7,500	11,100

Of the various sources of land price information the UPM/Tilhill estimates of market prices are preferred since they reflect observed regional prices for planting land or expectations of prices where no recent sales exist. However, there may be concerns that land prices still reflect some element of subsidy. They are also likely to underestimate the social value of land since market valuations might be expected to be made at a higher market interest rate than the Treasury rate discount rate. Any such effect would enhance the cost-effectiveness of forestry for carbon abatement.

4.5.3 Opportunity cost of land

The opportunity cost of the land (net income foregone) avoids the issues associated with using observed land prices. With decoupling of agricultural support the opportunity cost of land should not reflect any subsidy element. However, estimating the marginal opportunity cost of planting land to society is not straightforward. This may be affected by food security and environmental issues. However, with no information on which to incorporate these aspects we base social opportunity costs on evidence from farm incomes.

SAC (2008)[121] used an opportunity cost approach to land valuation in their assessment of forestry as a MACC component. They assumed that woodlands would displace uncultivated land with a low agricultural potential, i.e. rough grazing. Opportunity cost was based on the next best land use and a constant (real) cost of £141/ha for sheep grazing was used, based on published farm management data[122]. It is not clear whether this was a gross or net margin per ha. For small areas converted to woodland the gross margin is generally preferred since fixed costs savings are likely to be small or zero[123]. Converting the £141 per ha to a present value (PV) at 3.5% in perpetuity gives a present cost of £4,028 per ha.

SAC Consulting (2010)[124] in a study for Forestry Commission Scotland (FCS) of the impact of planting on farm profitability used different income foregone figures depending on farm type and the extent of any cost saving (Table 4.5). What is clear from these figures is that the opportunity cost can differ substantially depending on land quality and the extent of any cost saving.

Table 4.5 Agricultural income foregone from woodland planting in Scotland (£ per ha)

Farm type	No cost saving	Less operations	Less operations and farm labour
Arable	631	270	155
Improved grass	321	139	26
Unimproved grass	43	11	-13

Note: based on mean of 2006/07 and 2007/08 farm accounts data.

Current published farm management data are available for specific farm enterprises but direct evidence on what enterprises are being displaced is minimal. For upland grassland SAC Consulting (2013/14)[125] give a mean crossbred ewe gross margin of £330 per ha at 12.5 ha per 100 ewes and 150% lambs reared. For improved hill breeds the gross margin is £189 per ha. For spring calving upland suckler cows the mean gross margin is £243 per ha.

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[121] SAC (2008). UK Marginal Abatement Cost Curves for the Agriculture and Land Use, Land-Use Change and Forestry Sectors out to 2022, with Qualitative Analysis of Options to 2050 (RMP4950) 20/11/2008. Final Report to the Committee on Climate Change.

[122] The Farm Management Handbook (2007/08). SAC Consulting, Edinburgh.

[123] When larger areas of a farm are planted some fixed cost savings would be expected.

[124] SAC Consulting (2010). Impact of woodland creation on farm profitability. Study for David Henderson Howat, Forestry Commission Scotland. http://www.forestry.gov.uk/pdf/SACfarmforestrymodelsreport.pdf/$file/SACfarmforestrymodelsreport.pdf

[125] The Farm Management Handbook (2013/14). SAC Consulting, Edinburgh.

In a lowland context the gross margins can be much higher, depending on output. The opportunity cost of arable land is also highly dependent on output (yield). The average spring barley (feed) gross margin is £601 per ha and spring oilseed rape, £503 per ha[126]).

Nix (2014)[127] gives lower mean gross margins for spring lambing flocks of £123 per ha (upland) and £260 per ha (lowland) in England. The gross margins for winter and spring oilseed rape are £462 and £237 per ha respectively.

It is to be expected that woodlands will be planted on land with relatively low net opportunity cost either because it is unproductive or because there are compensating private gains to the owner (e.g. from shooting or wildlife). But much will depend on the scale of new planting (since at the margin, opportunity cost per ha will increase with aggregate area planted) which itself will be determined by the grant aid on offer.

4.5.4 Land cost: conclusion

An opportunity cost approach was preferred to the use of market prices for land. We used opportunity costs (per year) of £350[128] per ha in south-east and south west England, £220 per ha elsewhere in England and Wales, £100 per ha in the Highlands and Islands and £120 elsewhere in Scotland. These allow for some cost saving on the gross margins foregone and reflect the expectation that less productive land would be planted.

We used a zero residual land value at the end of the 2200 investment horizon for the reasons given in 2.4.1.

4.5.5 Planting and management costs

Typical costs of site preparation, planting and post-planting management were derived from consultation with industry sources. In some cases (e.g. ground preparation, drainage and roading) costs are highly site dependent and average costs were used. No costs for environmental assessment were included but these may be significant for larger plantations or those in environmentally sensitive locations. Land agent's fees were included for all forest systems except SRF and Farm woodland. In the latter systems planting would generally take place on land within a farm holding and without a land sale.

Costs were specified for each year of the investment horizon and were specific to each forest system and region. It is not therefore possible to present all the cost data in tabular form in this report. Instead we give three examples of how the costs were constructed (Table 4.6).

Table 4.6 Cost structure for example forest systems

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[126] These reduce to £344 and 293 per ha at the lower quoted yields.

[127] Farm Management Pocketbook 45th edition (2014). www.the pocketbook.co.uk

[128] There is no subsidy element in these opportunity costs since support is now decoupled into the Single Farm Payment (which is transferred separately in a land sale).

Activity	Unit	Year	Farm woodland (Wales)	Broadleaf1: managed for game/biodiversity (England south-west)	Upland conifer: managed for timber (South Scotland)
Legal /agent fees	(£ per ha)	-1	N/A	500	95
Land opportunity cost	(£ per ha)	Annually	220	350	120
Plan preparation	(£)	0	500	500	750
Drainage	(£ per ha)	0	20	21	163
Ground preparation	(£ per ha)	0	159	167	644
Marking out	(£ per ha)	0	16	36	N/A
Fencing	(£ per ha)	0	1,350	2,060	0
Trees - conifers	(£ per tree)	0	0.34	N/A	0.25
Trees -broadleaves	(£ per tree)	0	0.25	0.25	N/A
Tubes	(£ per tree)	0	N/A	0.66	N/A
Stakes	(£ per tree)	0	N/A	0.34	N/A
Spiral guards	(£ per tree)	0	0.33	N/A	N/A
Planting labour	(£ per ha)	0	423	1,530	417
Weeding	(£ per ha)	1	215	240	208
Weeding	(£ per ha)	2	129	240	0
Weeding	(£ per ha)	3	108	130	0
Weeding	(£ per ha)	4	0	60	0
Beating up	(£ per ha)	1	147	276	608
Beating up	(£ per ha)	2	74	184	304
Maintenance	(£ per ha)	1	142	648	0
Maintenance	(£ per ha)	2	71	648	0
Maintenance	(£ per ha)	3	71	248	0
General maintenance	(£ per ha)	4 and annually	71	475	100
Insurance	(£ per ha)	1 and annually	6	6	5
Roading	(£ per ha)	30	0	0	5,000
Present value over 186 years	(£ per ha)		12,611	31,326	9,023

Of the three examples, upland conifers in Scotland have the lowest costs (£9,023 per ha), a reflection of low land, labour and establishment costs, although £5,000 per ha is allowed for roading. The cost of Broadleaf1 in south-west England is much higher, a reflection of higher land and labour costs and the higher cost of establishing and maintaining broadleaves. Farm woodland planting in Wales is intermediate in cost terms.

When the complete list of all the forest systems and regions was examined it was apparent that costs were highest in England (SEE, SWE, EE and EM) in part due to high land and establishment costs. For precisely the opposite reasons costs were lowest in Scotland and especially in the Highlands and Islands. Upland conifers had the lowest costs and short rotation forestry the highest[129].

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[129] Forest Research modelled short rotation forestry with replanting at the end of the first rotation. Costs would be lower without re-planting.

5 Performance of the forest systems

5.1 Forest systems

Seven basic forest systems were modelled (Table 5.1) with SRF modelled with two rotation lengths. With planting in three countries and up to 11 regions coupled with two previous land uses in two of the England regions, the total number of combinations modelled was 98. With two time horizons (36 and 186 years) the total number of runs was 196.

Table 5.1 Numbers of models developed for each forest system and country

Forest system	England	Scotland	Wales
	Number of regions/soil types included	Number of regions/soil types included	Number of regions/soil types included
Short rotation forestry (SRF): managed for energy (15 and 25 year rotations)	7	5	1
Farm woodland: managed for mixed objectives	7	5	1
Broadleaf1: managed for game/biodiversity	7	5	1
Broadleaf2: managed for timber and carbon	7	5	1
Upland conifer: managed for timber	2	5	1
Lowland conifer: managed for timber	7	4	1
Continuous cover forestry (CCF): managed for mixed objectives	7	5	1

There were too many alternative scenarios to be presented in detail individually. We initially therefore take examples of each forest system in selected regions to demonstrate the time-related carbon characteristics of each forest system.

5.2 Short rotation forestry, 25 year rotation, England: Eastern and east Midlands

This is a red alder plantation on arable land (mineral gley) (see Table 3.1). It is restocked every 25 years, with wood output used as woodfuel. Figure 5.1 shows the cyclical pattern of retentions and emissions from a single planting in 2014. Note that the left hand scale refers to annual changes and the right hand scale to the cumulative net retention of carbon. Each bar in the chart represents one year. The detailed carbon changes together with the cost-effectiveness (CE) measures are given for this and the other example systems in Annex 2.

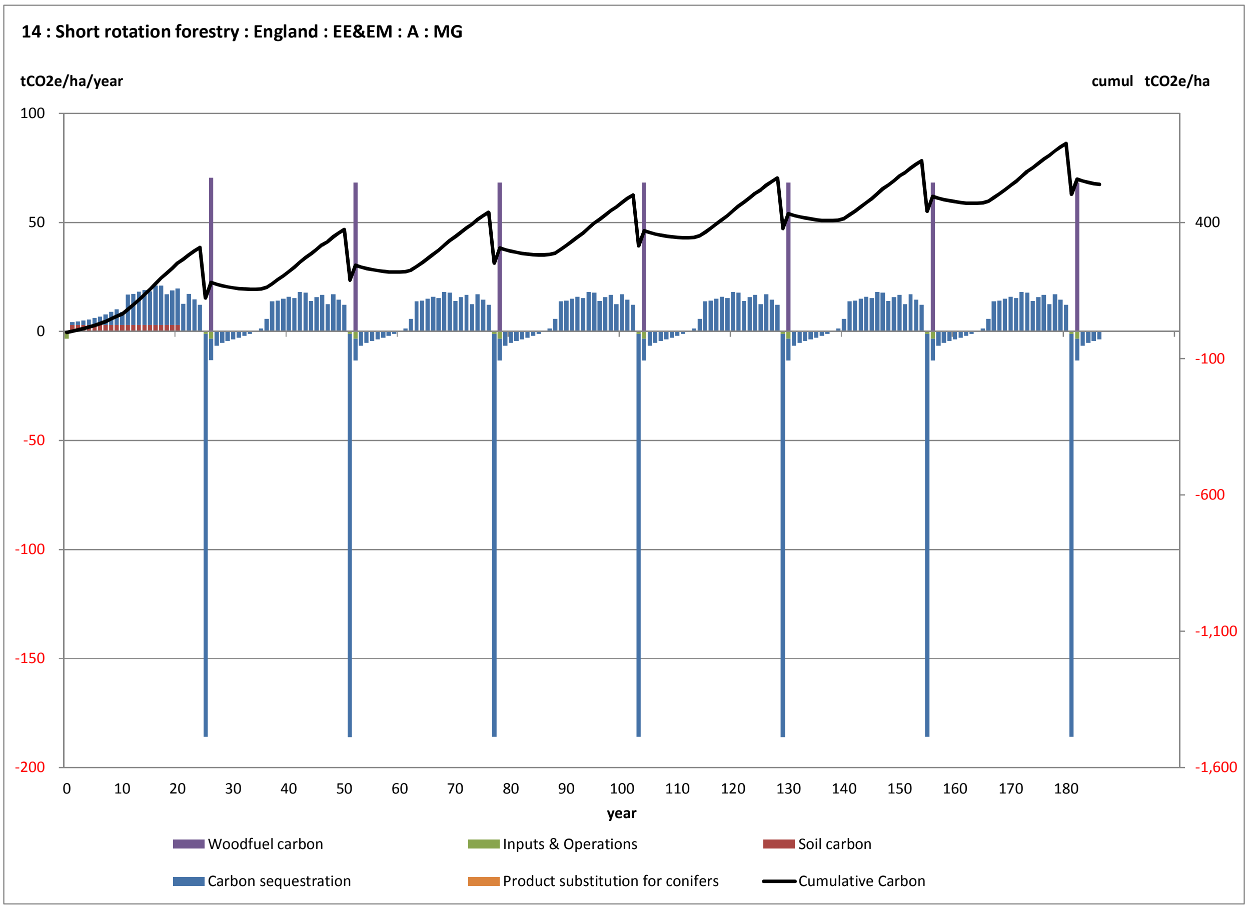

Figure 5.1 Short rotation forestry: carbon changes following planting

This SRF system has a 25 year cycle with gradually increasing carbon retention over time. With this system and location there are gains in soil carbon and growth at or shortly after planting but losses from inputs and operations. At harvest there are emissions from material not used as woodfuel but gains from woodfuel substitution. The mean net retention[130] is 351 tCO_2e to 2200. This largely reflects the gains from woodfuel substitution plus a small contribution from retention in soil. The carbon sequestered in growth is released on combustion.

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[130] Calculated as the sum of the annual retentions divided by the number of years.

5.3 Farm woodland (South Scotland)

In this system the species mixture is sycamore, common alder, birch and Douglas Fir (see Table 3.1). The plantation is thinned but not clearfelled. The soil is organo-mineral loam after pasture.

Figure 5.2 shows the cumulative carbon retention per ha with the farm woodland system. Total cumulative CO_2e initially falls due to the release from soil, and emissions associated with inputs at planting. It then increases to year 30 when the first thinning takes place. Cumulative carbon peaks at year 45 but then declines due to emissions following thinning. By year 186 (2200) the mean retention is relatively low at 129 tCO_2e per ha.

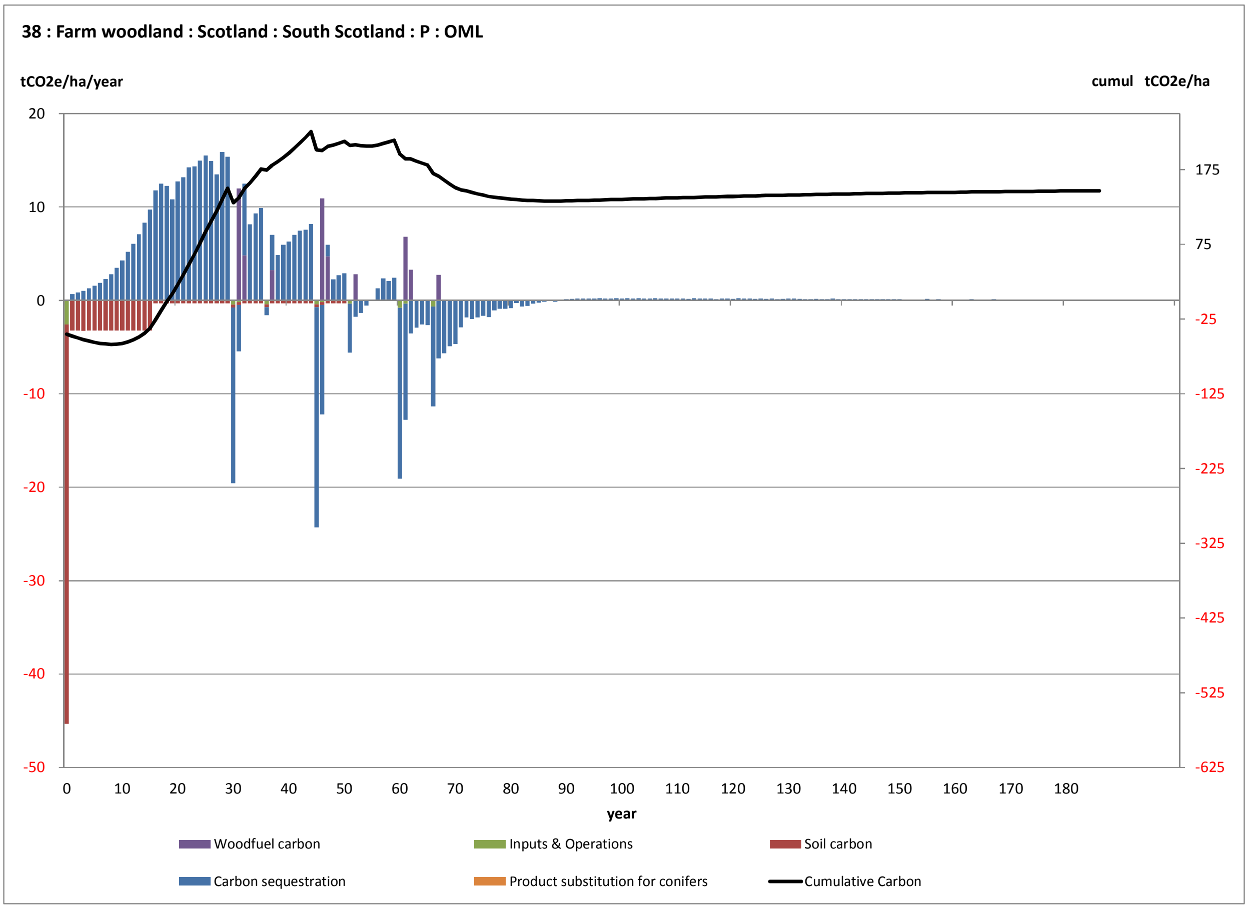

Figure 5.2 Farm woodland: carbon changes following planting

5.4 Broadleaf1 (managed for biodiversity/game) (south-west England)

This is a permanent broadleaved mixture of sycamore, common alder, birch and oak unthinned and unharvested (see Table 3.1). The planting is on mineral loam after pasture.

Figure 5.3 shows the cumulative build-up of carbon. By year 18 sequestration associated with growth has replaced the emissions from soil and inputs, and net carbon retention becomes positive. From then on the carbon balance increases to give a cumulative net retention of 553 tCO_2e by 2200, and a mean retention of 373 t. There is no harvesting and therefore no associated carbon gain or loss.

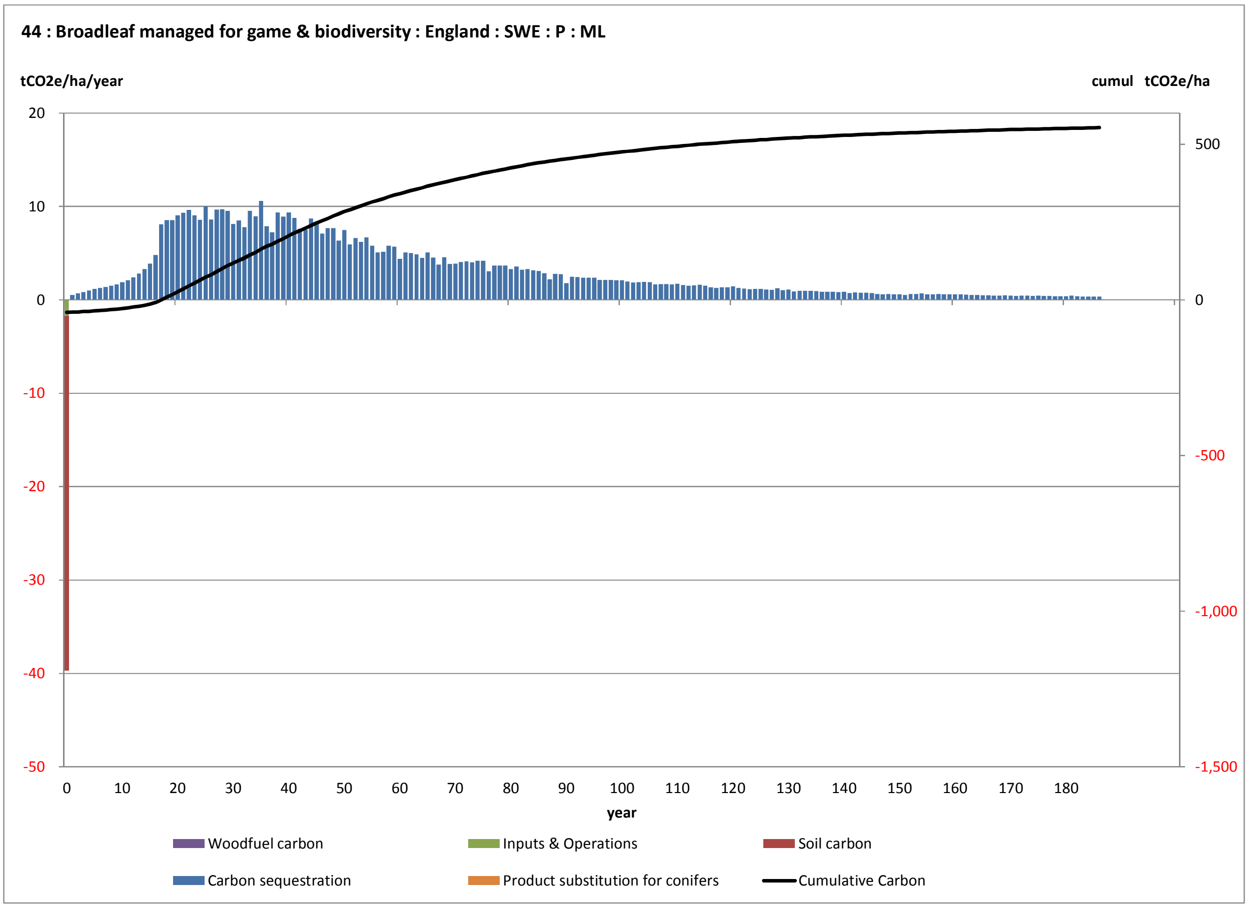

Figure 5.3 Broadleaf1 (managed for biodiversity/game): carbon changes following planting

5.5 Broadleaf2 (managed for timber/carbon) (West Midlands and North-west England)

This is an oak/birch mixture in a 100 year rotation with thinning. The soil is a mineral loam after pasture. Figure 5.4 shows the pattern of carbon retention and release with a gradual build-up of carbon retained over the 100 year cycle followed by release following harvest. After 186 years the cumulative retention of CO_2e is 244 t per ha (a mean net retention of 158t per ha). This reflects the low yield classes of the oak and birch, and the carbon release after thinning and clearfell.

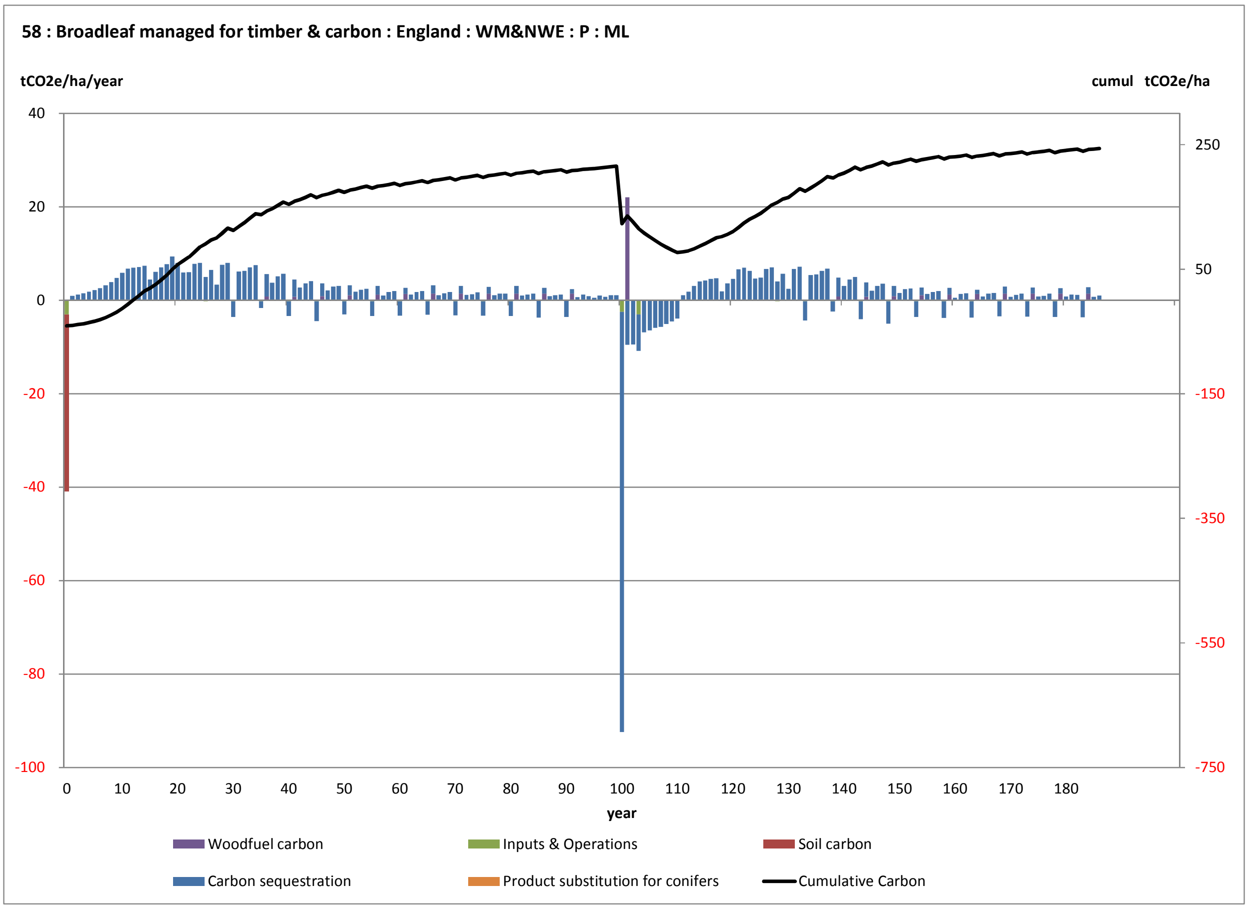

Figure 5.4 Broadleaf2 (managed for timber/carbon): carbon changes following planting

5.6 Upland conifer managed for timber (Scotland: Highlands and Islands)

Planting is Sitka spruce on an organo-mineral gley after pasture. The plantation is thinned and clearfelled after 54 years and then replanted. Figure 5.5 shows the cyclical pattern of carbon changes to 2200 with initial losses from soil and input emissions followed by accumulation of carbon and ultimate release after clearfell. There are substantial gains from woodfuel substitution and over 186 years the mean net retention is 244 tCO_2e.

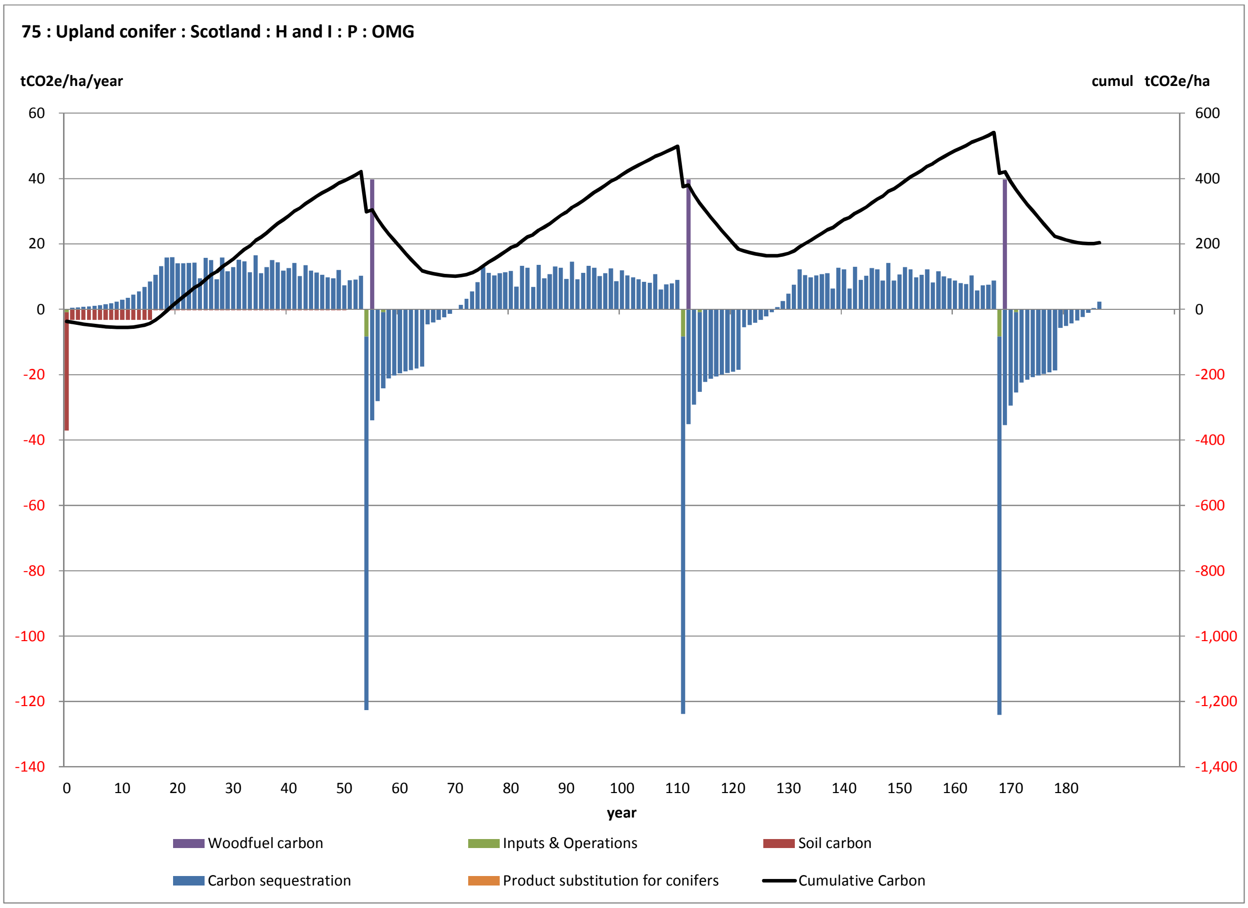

Figure 5.5 Upland conifer: carbon changes following planting

5.7 Lowland conifer managed for timber (England: Yorkshire and North-east)

This is a pure Douglas Fir stand, thinned and in rotation. Thinning is every five years with clearfell at 58 years. The soil is organo-mineral gley.

Figure 5.6 shows the rotational cycle of carbon retention and emission. In the 186 year time period there are three complete rotations of the Douglas Fir. The mean net retention is 288 tCO_2e over 186 years with a significant contribution from woodfuel substitution.

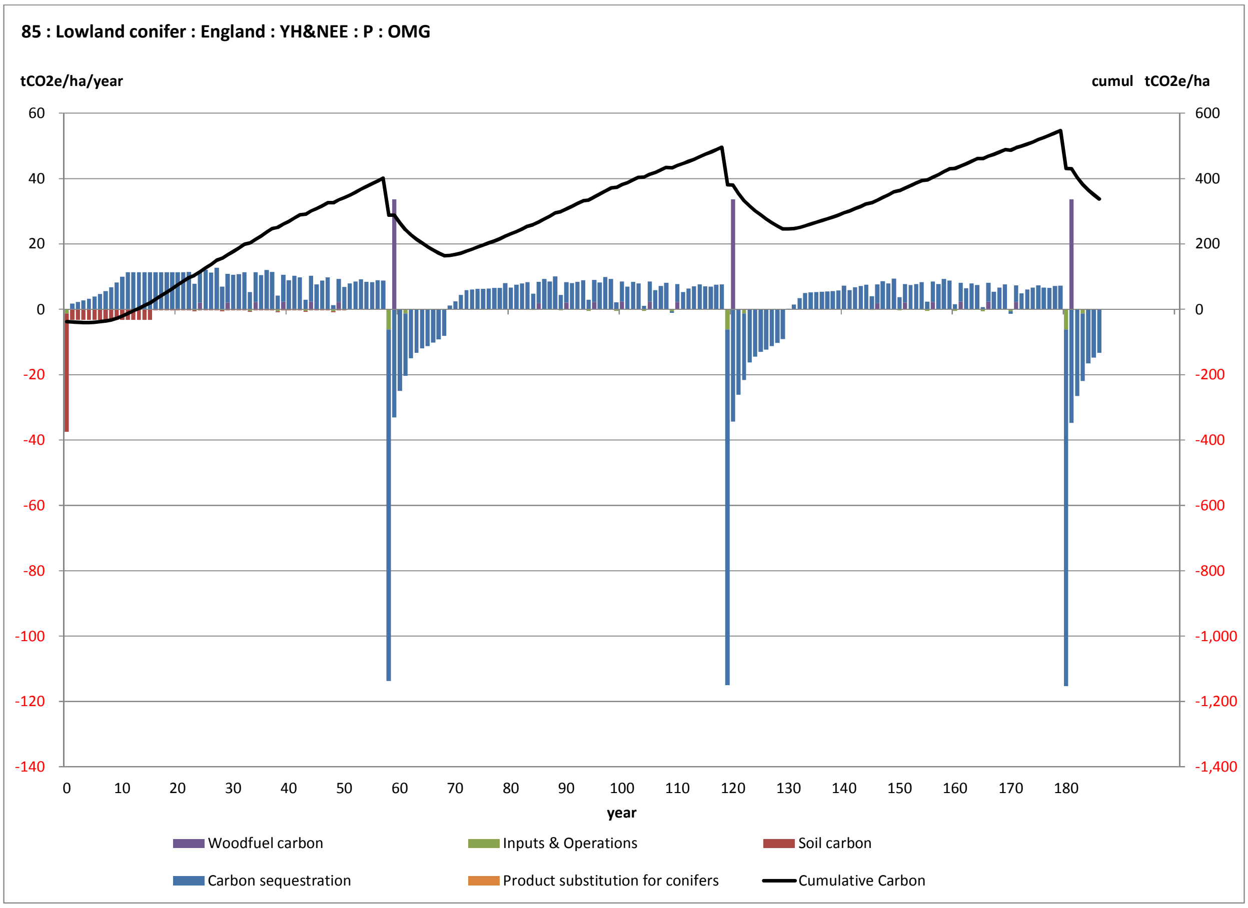

Figure 5.6 Lowland conifer: carbon changes following planting

5.8 Continuous cover forestry (Wales)

This is a sycamore, beech and Douglas Fir mixture planted on organo-mineral gley soil. The stand is selectively thinned every five years with heavy thinning of Douglas Fir and Sycamore at 100 years. There is thus a changing species mix over time without any clearfell.

Figure 5.7 shows the resulting carbon changes with an initial loss due to soil emissions, followed by carbon retention to a peak at 100 years after which the cumulative net retention increases very little. The system gives a mean net retention of 344 tCO_2e to 2200.

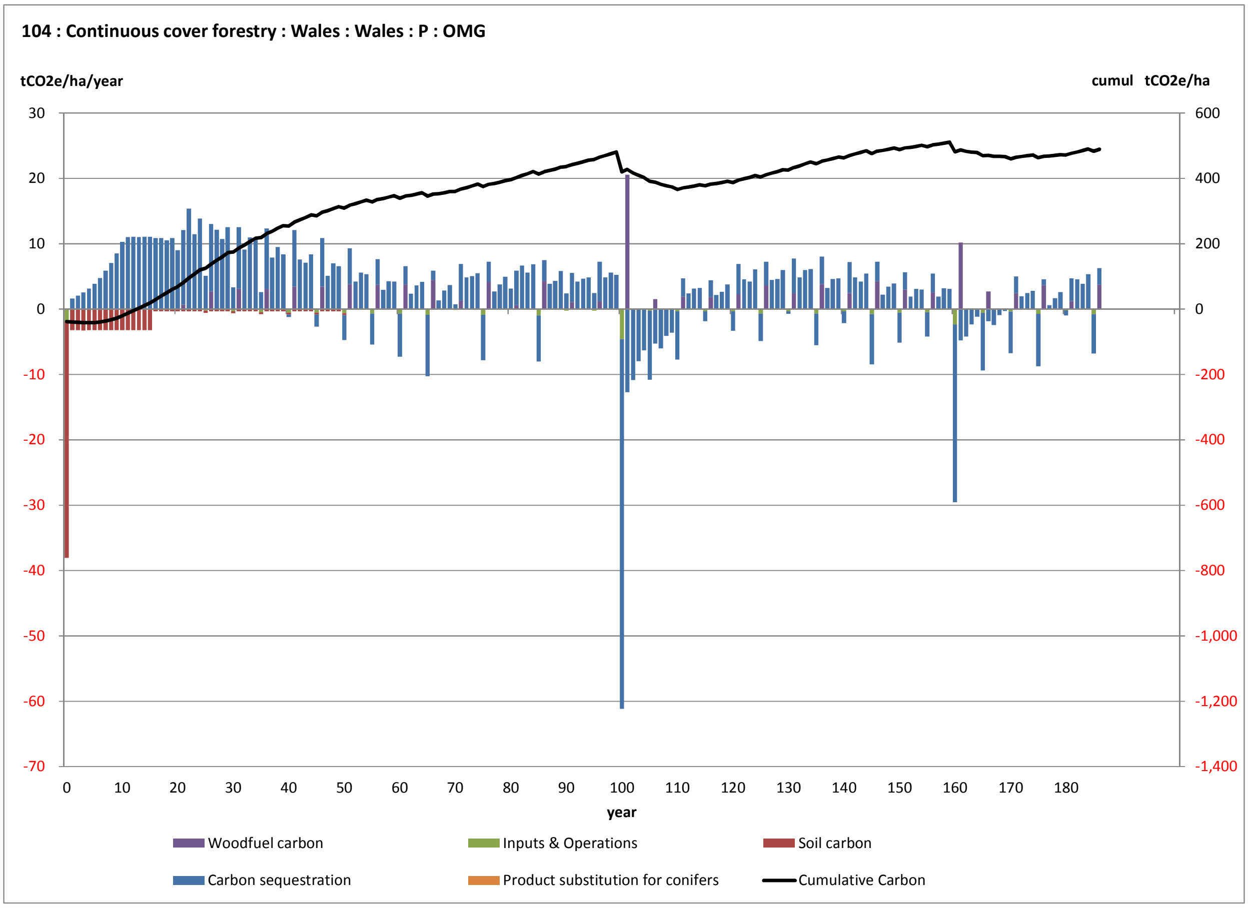

Figure 5.7 Continuous cover forestry: carbon changes following planting

5.9 Comparison of the example systems

The graphs given above demonstrate major differences between forest systems in the time profile of carbon retention and release. Because forest systems differ so markedly in their net retention profiles it is not possible to generalise about forestry as an abatement option without clearly defining the type of forestry and its management.

Comparisons between the example forest types have to be made with some care since region and forest system are confounded. However, as regards the mean net retention of carbon over 186 years, of the seven options examined, Broadleaf 1 (managed for biodiversity and game) is the most effective, delivering a retention of 373 tCO_2e per ha. This is almost entirely a result of sequestration, there being no harvest-related emissions and low emissions from soil and inputs. Both SRF and CCF exhibit similar retentions at 351 and 344 tCO$_2$e per ha respectively. Woodfuel substitution is central to the retention achieved by SRF and also contributes significantly to the performance of CCF.

Both the Farm woodland and Broadleaf2 (managed for timber and carbon) show low mean retentions of carbon (129 and 158 tCO$_2$e per ha). The location of planting affects the Farm Woodland system. This is planted on an organo-mineral loam characterised by relatively high emissions after planting (see Table 3.6). The Broadleaf2 has a low rate of growth and loses carbon from emissions after harvesting. The conifer systems are intermediate between these extremes in net retention. In both cases woodfuel substitution makes an important contribution to net retention.

5.10 Results for all scenarios

5.10.1 Carbon performance

The complete results for the 196 combinations of system, region and time horizon are given in Annex 2. Table 5.2 provides a summary. A comparison of the net retentions to 2050 and 2200 shows that mean retention of most systems is much poorer over the 36 year horizon. With some notable exceptions, the forest systems delivered limited retention to 2050 and many were characterised by negative emissions. The highest short-term retentions occurred where growth rates were high and soil emissions low – e.g. lowland conifers and continuous cover forestry in some English regions.

Table 5.2 Range in carbon retention and cost-effectiveness of forest systems

Forest System	Country	Range for GB countries		
		Mean net Retention to 2050 (tCO$_2$e/ha)	Mean net Retention to 2200 (tCO$_2$e/ha)	Cost Effectiveness to 2200 (£PV excl C /tCO$_2$e/ha mean)
SRF 15 year rotation	England	Neg-91	68-224	188-366
	Scotland	Neg-6	7-80	229-3162
	Wales	Neg	68	337
SRF 25 year rotation	England	9-135	195-351	82-132
	Scotland	Neg-44	134-208	45-107
	Wales	10	201	80
Farm woodland	England	42-164	143-314	48-96
	Scotland	0-66	84-229	40-108
	Wales	46	143	72
Broadleaf1 (managed for biodiversity/game)	England	Neg-126	320-530	61-84
	Scotland	Neg-4	195-297	32-46
	Wales	Neg	320	42
Broadleaf2	England	6-159	106-285	140-245

(managed for timber/carbon)	**Scotland**	**Neg-30**	**77-136**	**101-148**
	Wales	**6**	**106**	**167**
Upland conifer	**England**	**61-98**	**284-337**	**27-33**
	Scotland	**37-81**	**244-304**	**26-30**
	Wales	**85**	**331**	**30**
Lowland conifer	**England**	**67-210**	**288-501**	**21-46**
	Scotland	**39-72**	**240-269**	**27-28**
	Wales	**85**	**331**	**39**
Continuous cover forestry	**England**	**49-196**	**309-452**	**50-88**
	Scotland	**Neg-60**	**189-288**	**32-56**
	Wales	**66**	**344**	**46**

When comparing systems over the long term (to 2200), Broadleaf1 (managed for biodiversity and game) performed well in terms of net carbon retention because the absence of any clearfell minimised carbon release. Conifer systems and continuous cover also achieved high rates of retention despite harvesting because growth rates are higher than for broadleaved systems. Carbon retention is generally higher in England than Wales or Scotland– principally a reflection of higher growth and sequestration rates.

5.10.2 Cost-effectiveness

Systems achieving a high rate of carbon retention are not necessarily the most cost-effective since costs vary considerably between regions and systems. Cost effectiveness was only assessed over the 186 year horizon (Table 5.2). When assessed against the 'physical' measure (cost per tCO_2e) of CE upland and lowland conifers were the most cost-effective with costs mainly in the range £20-40 per tCO_2e. Broadleaf1 and CCF were generally in the £40-90 per tCO_2e range (see Annex 2). The other systems were, with some regional exceptions, much less cost-effective, with Broadleaf2 (managed for carbon and timber) and SRF characterised by high costs per unit abatement. Values in red[132] indicate situations where the mean retention of carbon is negative.

When comparisons were made between countries there was a tendency for planting in Scotland to be more cost-effective then in England or Wales but with considerable regional variation. Total costs are generally lower in Scotland mainly due to lower land and labour costs which more than compensate for any lower growth rates.

The 'value' measure of cost-effectiveness (£PV cost excluding CO_2e/£PV CO_2e) takes into account both the value of the CO_2e retention or emission and its timing. These 'value' measures of CE are given in Annex 2. Values in blue are those with a CE of less than or equal to 1.0 (£PV cost excluding CO_2e/£PV CO_2e), These have a net cost of delivering the carbon retention less than the value of the carbon retained[133] and are therefore cost-effective. Values in green indicate options that are not cost-effective.

All of the systems are cost-effective for abatement with the exception of most of the SRF and

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[132] The colour coding of results in Table 9.1 (Annex 2) is explained as a footnote at the end of the table.

[133] Note this does not take into account transaction costs in policy delivery. It may also not fully account for the execution risks.

Broadleaf2 planting. The conifer systems and some permanent broadleaved and CCF options are cost-effective, with costs in the range £0.2–0.4 per £CO_2e. CCF options in Scotland Wales also have CEs in the range £0.2-0.3 per £CO_2e. Farm woodlands are less cost-effective, with costs mainly in the range £0.3-0.5 per £CO_2e. There is considerable variation between regions but planting in Scotland and Wales is generally more cost-effective than planting in England.

6 Marginal abatement cost curve

6.1 Introduction

A marginal abatement cost curve (MACC) can be constructed by ordering options in terms of their cost-effectiveness either in physical (£ per tCO_2e) or value terms (£ per $£CO_2e$). We use the physical measure because this is the common basis for producing a MACC and hence one that allows comparisons to be made with other abatement options. Whilst a value-based MACC may be preferred because it takes account of changes in the value of carbon retained in each year of the horizon it is not a metric in common use and does not conform to the Treasury/DECC formulae for cost-effectiveness (see 2.3.1).

6.2 Total area planted per year

For any given set of assumptions there are 98 possible options in terms of forest system and region combinations across the three countries. To estimate the carbon abatement from each requires an estimate of the volume of planting of each option.

Typical prices paid for carbon sequestered by trees planted under the Woodland Carbon Code are far less than the DECC values and insufficient to stimulate planting without grant aid. Hence the additional areas planted in each region will depend on the detail of policy and in particular the extent of grant aid paid for each of the forest systems. Grant aid will be limited under EU rules in relation to the ‘standard costs’ for planting which are calculated by the Forestry Commission. Although one might expect grant aid for a GHG-orientated policy to be focussed on the most cost-effective systems for CO_2e abatement, other environmental, social and agricultural considerations may affect the grant aid structure and hence the area planted. Different expenditure priorities within the devolved elements of GB are also likely to affect the rate of forest creation.

Without a clear policy framework it is not possible to predict with any precision the annual planting rates for each forest system and region. The steering group proposed the difference between aspirational planting rates in the three countries and recent planting rates as the expected additional planting rate under a carbon-orientated policy measure (Table 6.1). Without any grant aid framework these rates are merely indicative. Since the modelling was fixed at a 2014 policy start date we use the ‘until 2019’ rates of planting for the MACC. Changing rates of planting over time will not affect the cost-effectiveness of any particular forest option.

Table 6.1 Expected planting rates under a carbon-orientated policy measure (ha per year)

	Until 2019	2020-30	2031-39	2040+
England	3,600	6000	6,000	4,900
Wales	2,110	3110	2,600	2,600
Scotland	10,000	10,000	10,000	10,000

Table 6.2 gives the expected regional split within each country based on the advice of the steering group and consultation with forest officers. The total planting area is 15,710 ha.

Table 6.2 Proportion of forestry planting by system in each country

	England	Wales	Scotland
	%	%	%
Short rotation forestry (SRF): managed for energy	5	5	5
Farm woodland: managed for mixed objectives	25	15	15
Broadleaf1: managed for game/biodiversity	30	15	20
Broadleaf2: managed for timber and carbon	15	15	15
Upland conifer: managed for timber	15	25	25
Lowland conifer: managed for timber (England)	5	N/A	N/A
Lowland conifer: managed for timber (Wales, Scotland)	N/A	10	15
Continuous cover forestry (CCF); managed for mixed objectives	5	15	5
Total area (ha per year)	3,600	2,110	10,000

6.3 Regional planting rates

The national planting rates need to be allocated to regions in order to link with the forest system models which are regionally specified. Recent regional planting rates provide one indicator of where planting may take place in that they reflect the cost and expected profitability from recent (grant-aided) planting. However they also reflect policy measures in place at the time and changes to policy to encourage carbon abatement may affect the regional distribution of planting. Even so, we broadly base the regional planting rates on the regional distribution of woodland creation under the most recent policy measures (Table 6.3).

Table 6.3 Regional planting rates

	Region	% of national planting	Planting area (ha per year)
England	Eastern and East Midlands	25	900
	South-east	10	360
	South-west	15	540
	West Midlands and North-west	30	1,080
	Yorkshire and North-east	20	720
Scotland	Central Scotland	10	1,000
	Grampian	10	1,000
	Highland and islands	40	4,000
	Perth and Argyll	20	2,000
	South Scotland	20	2,000
Wales	Wales	100	2,100

6.4 MACC

The longer horizon (2200) MACC was derived from the ‘physical’ cost-effectiveness calculated for each forest system and region, together with the areas expected to be planted (see Annex 2 and Tables 6.1-6.3). Because of the number of options it is difficult to present the MACC graphically and a table is used. Table 6.4 shows the options in order of cost-effectiveness (right hand column).

Lowland and upland conifers have the lowest marginal abatement cost. Lowland conifers in England achieve high rates of carbon sequestration because of their high growth rates. Upland conifers have lower rates of sequestration but this is in part compensated for by lower production costs. In total around 5,000 ha per year of conifers are expected to be planted per year at a cost of up to £30 per tCO_2e. Of these, 4,000 ha are in Scotland, 525 ha in Wales and 400 ha in England. The total mean carbon retention is 1.36 $mtCO_2e$.

Systems costing up to £40 per tCO_2e consist very largely of conifers with some Broadleaf1 (managed for biodiversity and game), Farm Woodland and CCF, all of the non-conifers being located in Scottish regions. Around 6,500 ha per year could be planted at a cost of up to £40 per tCO_2e producing 1.8 $mtCO_2e$ of abatement. Of this 5,050 ha per year was in Scotland.

Farm Woodland and CCF options enter the MACC at higher levels of cost. A planting rate of around 12,750 ha per year is expected with options costing up to £100 per tCO_2e to give an abatement of 3.3 $mtCO_2e$.

The forest systems with costs exceeding £100 per tCO_2e are primarily Broadleaf2 (managed for carbon and timber) and SRF. The Broadleaf 2 options are limited by low growth rates, high soil emissions (mainly organo-mineral soils after pasture) and relatively high costs. The carbon performance of the SRF 15 and 25 year rotations was poor despite the substantial retention from woodfuel substitution. Forest Research modelled SRF as a rotational crop with new establishment after each harvest. The costs of establishment every 15 or 25 years are considerable and this together with high opportunity costs of suitable land has a major impact on cost-effectiveness. Further research is needed on SRF to determine the performance of crops under different management systems.

Table 6.4 MACC for 2200 horizon

Forest System	Country	Region	Soil / Prev Land use	Total Area (ha)	Cumulative area (ha)	Net C (tCO2e/ha mean)	Cumulative Net C ('000 tCO2e)	Cost Effectiveness (PV excl C /tCO2e/ha mean)
Lowland conifer	England	EE&EM	MG/A	23	23	501	11	+21
Lowland conifer	England	EE&EM	MG/P	23	45	419	21	+25
Lowland conifer	England	WM&NWE	ML/P	54	99	413	43	+25
Upland conifer	Scotland	Grampian	MG/P	250	349	304	119	+26
Upland conifer	Scotland	Perth and Argyll	OMG/P	500	849	285	261	+26
Upland conifer	Scotland	South Scotland	OML/P	500	1,349	278	400	+27
Upland conifer	Scotland	Central Scotland	OML/P	250	1,599	278	470	+27
Lowland conifer	Scotland	Grampian	MG/P	300	1,899	269	550	+27
Upland conifer	England	WM&NWE	ML/P	297	2,196	337	650	+27
Lowland conifer	Scotland	Perth and Argyll	OMG/P	450	2,646	246	761	+27
Lowland conifer	Scotland	South Scotland	OML/P	450	3,096	240	869	+28
Lowland conifer	Scotland	Central Scotland	OML/P	300	3,396	240	941	+28
Upland conifer	Scotland	H and I	OMG/P	1,000	4,396	244	1,186	+30
Upland conifer	Wales	Wales	OMG/P	525	4,921	331	1,359	+30
Broadleaf1 managed for game & biodiversity	Scotland	South Scotland	OML/P	400	5,321	297	1,478	+32
Continuous cover forestry	Scotland	South Scotland	OML/P	100	5,421	288	1,507	+32
Upland conifer	England	YH&NEE	OMG/P	243	5,664	284	1,576	+33
Lowland conifer	England	SWE	ML/P	27	5,691	413	1,587	+35
Lowland conifer	England	SEE	MG/A	9	5,700	428	1,591	+37
Broadleaf1 managed for game & biodiversity	Scotland	Perth and Argyll	OMG/P	400	6,100	272	1,700	+38
Lowland conifer	Wales	Wales	OMG/P	210	6,310	331	1,770	+39
Lowland conifer	England	YH&NEE	OMG/P	36	6,346	288	1,780	+39
Farm woodland	Scotland	Grampian	MG/P	150	6,496	229	1,814	+40

Forest System	Country	Region	Soil / Prev Land use	Total Area (ha)	Cumulative area (ha)	Net C (tCO2e/ha mean)	Cumulative Net C ('000 tCO2e)	Cost Effectiveness (PV excl C /tCO2e/ha mean)
Continuous cover forestry	Scotland	Grampian	MG/P	50	6,546	260	1,827	+40
Broadleaf1 managed for game & biodiversity	Scotland	Grampian	MG/P	200	6,746	254	1,878	+41
Broadleaf1 managed for game & biodiversity	England	YH&NEE	OMG/P	216	6,962	320	1,947	+41
Broadleaf1 managed for game & biodiversity	Wales	Wales	OMG/P	315	7,277	320	2,048	+42
Continuous cover forestry	Scotland	Perth and Argyll	OMG/P	100	7,377	238	2,072	+43
Continuous cover forestry	Scotland	H and I	OMG/P	200	7,577	200	2,112	+45
Short rotation forestry	Scotland	South Scotland	OML/P	100	7,677	193	2,131	+45
Broadleaf1 managed for game & biodiversity	Scotland	H and I	OMG/P	800	8,477	195	2,287	+46
Broadleaf1 managed for game & biodiversity	Scotland	Central Scotland	OML/P	200	8,677	209	2,329	+46
Lowland conifer	England	SEE	MG/P	9	8,686	347	2,332	+46
Continuous cover forestry	Wales	Wales	OMG/P	315	9,001	344	2,441	+46
Farm woodland	Scotland	H and I	OMG/P	600	9,601	170	2,542	+47
Farm woodland	England	EE&EM	MG/A	113	9,714	314	2,578	+48
Continuous cover forestry	England	YH&NEE	OMG/P	36	9,750	309	2,589	+50
Continuous cover forestry	Scotland	Central Scotland	OML/P	50	9,800	189	2,598	+56
Continuous cover forestry	England	EE&EM	MG/A	23	9,822	452	2,609	+60
Broadleaf1 managed for game & biodiversity	England	SEE	MG/A	54	9,876	530	2,637	+61
Broadleaf1 managed for game & biodiversity	England	EE&EM	MG/A	135	10,011	461	2,699	+61
Farm woodland	Scotland	South Scotland	OML/P	300	10,311	129	2,738	+63
Farm woodland	England	EE&EM	MG/P	113	10,424	233	2,764	+65
Farm woodland	England	WM&NWE	ML/P	270	10,694	220	2,823	+66

Forest System	Country	Region	Soil / Prev Land use	Total Area (ha)	Cumulative area (ha)	Net C (tCO2e/ha mean)	Cumulative Net C ('000 tCO2e)	Cost Effectiveness (PV excl C /tCO2e/ha mean)
Farm woodland	England	SEE	MG/A	45	10,739	283	2,836	+69
Broadleaf1 managed for game & biodiversity	England	SEE	MG/P	54	10,793	449	2,860	+72
Short rotation forestry	Scotland	H and I	OMG/P	200	10,993	142	2,889	+72
Farm woodland	Wales	Wales	OMG/P	105	11,098	160	2,906	+72
Short rotation forestry	Scotland	Grampian	MG/P	50	11,148	208	2,916	+72
Continuous cover forestry	England	SEE	MG/A	9	11,157	449	2,920	+72
Continuous cover forestry	England	EE&EM	MG/P	23	11,179	371	2,928	+74
Broadleaf1 managed for game & biodiversity	England	EE&EM	MG/P	135	11,314	379	2,980	+74
Farm woodland	Scotland	Perth and Argyll	OMG/P	300	11,614	118	3,015	+76
Broadleaf1 managed for game & biodiversity	England	WM&NWE	ML/P	324	11,938	356	3,131	+77
Continuous cover forestry	England	WM&NWE	ML/P	54	11,992	352	3,150	+78
Farm woodland	England	YH&NEE	OMG/P	180	12,172	143	3,175	+79
Short rotation forestry	Wales	Wales	OMG/P	105	12,277	201	3,196	+80
Farm woodland	England	SWE	ML/P	135	12,412	227	3,227	+81
Short rotation forestry	England	YH&NEE	OMG/P	36	12,448	195	3,234	+82
Short rotation forestry	England	EE&EM	MG/A	45	12,493	351	3,250	+84
Broadleaf1 managed for game & biodiversity	England	SWE	ML/P	162	12,655	373	3,310	+84
Continuous cover forestry	England	SWE	ML/P	27	12,682	364	3,320	+86
Continuous cover forestry	England	SEE	MG/P	9	12,691	368	3,323	+88
Short rotation forestry	England	SEE	MG/A	18	12,709	351	3,330	+96
Farm woodland	England	SEE	MG/P	45	12,754	202	3,339	+96
Broadleaf managed for timber & carbon	Scotland	Grampian	MG/P	150	12,904	136	3,359	+101

Forest System	Country	Region	Soil / Prev Land use	Total Area (ha)	Cumulative area (ha)	Net C (tCO2e/ha mean)	Cumulative Net C ('000 tCO2e)	Cost Effectiveness (PV excl C /tCO2e/ha mean)
Short rotation forestry	Scotland	Perth and Argyll	OMG/P	100	13,004	142	3,373	+101
Broadleaf managed for timber & carbon	Scotland	Central Scotland	OML/P	150	13,154	114	3,390	+104
Short rotation forestry	Scotland	Central Scotland	OML/P	50	13,204	134	3,397	+107
Farm woodland	Scotland	Central Scotland	OML/P	150	13,354	84	3,410	+108
Broadleaf managed for timber & carbon	Scotland	Perth and Argyll	OMG/P	300	13,654	120	3,446	+113
Short rotation forestry	England	WM&NWE	ML/P	54	13,708	253	3,459	+116
Broadleaf managed for timber & carbon	Scotland	South Scotland	OML/P	300	14,008	93	3,487	+125
Broadleaf managed for timber & carbon	England	SEE	MG/A	27	14,035	285	3,495	+128
Short rotation forestry	England	SWE	ML/P	27	14,062	253	3,502	+132
Broadleaf managed for timber & carbon	England	EE&EM	MG/A	68	14,130	246	3,519	+140
Broadleaf managed for timber & carbon	Scotland	H and I	OMG/P	600	14,730	77	3,564	+148
Broadleaf managed for timber & carbon	England	YH&NEE	OMG/P	108	14,838	106	3,576	+151
Broadleaf managed for timber & carbon	Wales	Wales	OMG/P	315	15,153	106	3,609	+167
Broadleaf managed for timber & carbon	England	SEE	MG/P	27	15,180	203	3,615	+179
Short rotation forestry	England	EE&EM	MG/A	0	15,180	224	3,615	+188
Short rotation forestry	England	SEE	MG/A	0	15,180	224	3,615	+207
Broadleaf managed for timber & carbon	England	EE&EM	MG/P	68	15,247	165	3,626	+210
Broadleaf managed for timber & carbon	England	WM&NWE	ML/P	162	15,409	158	3,651	+218
Short rotation forestry	Scotland	South Scotland	OML/P	0	15,409	60	3,651	+229
Broadleaf managed for timber & carbon	England	SWE	ML/P	81	15,490	158	3,664	+245

6.5 Sensitivity analysis

Three aspects were examined: sensitivity to DECC carbon prices, the impact of product substitution and increasing timber prices.

6.5.1 Carbon pricing

DECC[134] give low, central and high non-traded carbon prices, and the previous analysis was done using the central estimates. The central estimate increases from £61 per tCO_2e in 2014 to £341 per t in 2075, declining to £297 after 2100. The low estimate increases from £30 per t in 2014 to £136 per t in 2065, declining to £74 per t in 2065. The high estimate increases from £91 per t in 2014 to £561 per t in 2085, declining to £520 per t in 2081.

Changing the carbon price has no impact on the net retention of carbon or the physical CE measure of cost per tCO_2e retained (£ PV cost excluding CO_2e/ tCO_2e). It therefore has no effect on the MACC which uses 'physical' CE information. The only metric it affects is the 'value' CE measure (£PV cost excluding CO_2e/£PV CO_2e). To be cost-effective an option must have a CE ratio <1.

At the low carbon price 46 out of 98 systems were cost-effective (to 2200). This contrasts with 70 when the central price was used. Those scenarios that remained cost-effective at the lower price were primarily those with an original CE <0.5 in Annex 2. These are primarily permanent broadleaves in Scotland and Wales, upland and lowland conifers in all countries and CCF in Scotland. In broad terms, low carbon prices tend to push cost-effective planting to sites where costs are low, although coniferous planting remains cost-effective in all regions. At the high carbon price all systems with the exception of 15 year SRF were cost-effective.

We can conclude that the most resilient systems to lower than anticipated carbon prices are permanent broadleaves, upland and lowland conifers and continuous cover forests, principally in Scotland and Wales.

6.5.2 Product substitution

This aspect was discussed in Section 3.4.8. It was argued there the gains from substitution may be small from marginal increases in UK timber output. Not only is cross laminated timber not manufactured in the UK but DECC forecast a major reduction in the long-run marginal emissions from power generation. This will reduce the gains from substitution.

To assess this aspect further we examined the impact of taking 50% of the sawn wood output as substituting for other structural material. The Sathre medium displacement factor of 2.0 tC emission reduction per tC of additional wood output was used, adjusted for changes in the expected emissions from power generation. For many of the forest systems there is no sawn timber output and therefore no impact. Only with upland conifers, lowland conifers and continuous cover are there possible gains from substitution. In these systems the carbon gain from 50% substitution was, at its highest, 49 tCO_2e at 2200. The CE of upland and lowland conifers was improved by around £3 per tCO_2e.

6.5.3 Timber prices

SAC (2008)[135] assumed an annual timber price increase of 2.5% in their assessment of the cost-effectiveness of Sitka spruce for carbon abatement. We do not regard a 2.5% per year price increase as remotely realistic since it implies a 2200 price in real terms almost 100 times

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[134] https://www.gov.uk/government/publications/valuation-of-energy-use-and-greenhouse-gas-emissions-for-appraisal

[135] SAC (2008). UK Marginal Abatement Cost Curves for the Agriculture and Land Use, Land-Use Change and Forestry Sectors out to 2022, with Qualitative Analysis of Options to 2050 (RMP4950) 20/11/2008. Final Report to the Committee on Climate Change http://www.theccc.org.uk/pdfs/SAC-CCC%3B%20UK%20MACC%20for%20ALULUCF%3B%20Final%20Report%202008-11.pdf

that in 2014. Given the history of standing timber prices over the last 20 years (see Figure 4.1) this appears optimistic. The timber price assumption used by SAC offers at least a part explanation for the negative cost per tCO_2e they reported for upland conifers.

Nevertheless, to test the sensitivity to timber price we applied a 1% per year price rise to those options producing timber from thinnings or clearfell, using the 186 year horizon. Systems with a CE of <£40 per tCO2e improved in cost-effectiveness by around £6-7 per tCO2e. The most cost-effective system (lowland conifers in England, Eastern and East Midlands) improved from £21 per t to £13 per tCO2e.

6.6 MACC: conclusions

The marginal abatement cost of new forestry planting is lowest for rotational conifers (both upland and lowland) at £21-£40 per tCO_2e. Some broadleaves (unharvested and managed for biodiversity and game), Farm Woodland and CCF options also have a CE <£40 per tCO_2e. Other forest systems were less cost-effective.

Around 6,500 ha per year could be planted at a cost of up to £40 per tCO_2e producing 1.8 $mtCO_2e$ of abatement. This planting was mainly in Scotland (5,050 ha per year), with 711 ha in England and 735 ha in Wales.

These results cannot readily be compared with other studies of forestry cost-effectiveness because of differences in assumptions and methodology which were discussed in Section 2.6. Placing forestry in the wider context of options for carbon abatement was problematic because DECC do not provide comparators. SAC (2008) examined agricultural options for carbon mitigation for which the range in CE was £-3,602 per tCO_2e to +£14,280. ADAS (2011)[136] examined a range of agricultural options for Defra and estimated CEs between £-14 and £+297 per tCO_2e. Moxey[137] (Chart 1 below) examined a range of mitigation measures in a range of sectors including forestry for which data were based on Read et al. (2009[138]). The CE of afforestation was in the £0-41 per tCO_2e range.

MacLeod et al. (2010)[139] used £100 per tCO_2e as a benchmark for assessing the potential contribution of agriculture, land use and land use change to carbon abatement. The forestry MACC (Table 6.4) indicates that all forest systems with the exception of broadleaves (for timber and carbon) and SRF deliver abatement at <£100 per tCO_2e. The estimated quantity per year is 3.4 $MtCO_2e$ at expected planting rates.

These studies indicate the wide range in CE ratios for different options. ADAS point out that most of the low cost (negative CE) agricultural options face implementation barriers. From our analysis it is upland and lowland conifers that offer the most cost-effective possibilities. Using the ‘value’ measure of CE, which incorporates DECC-estimated future carbon values, most forestry options are cost-effective.

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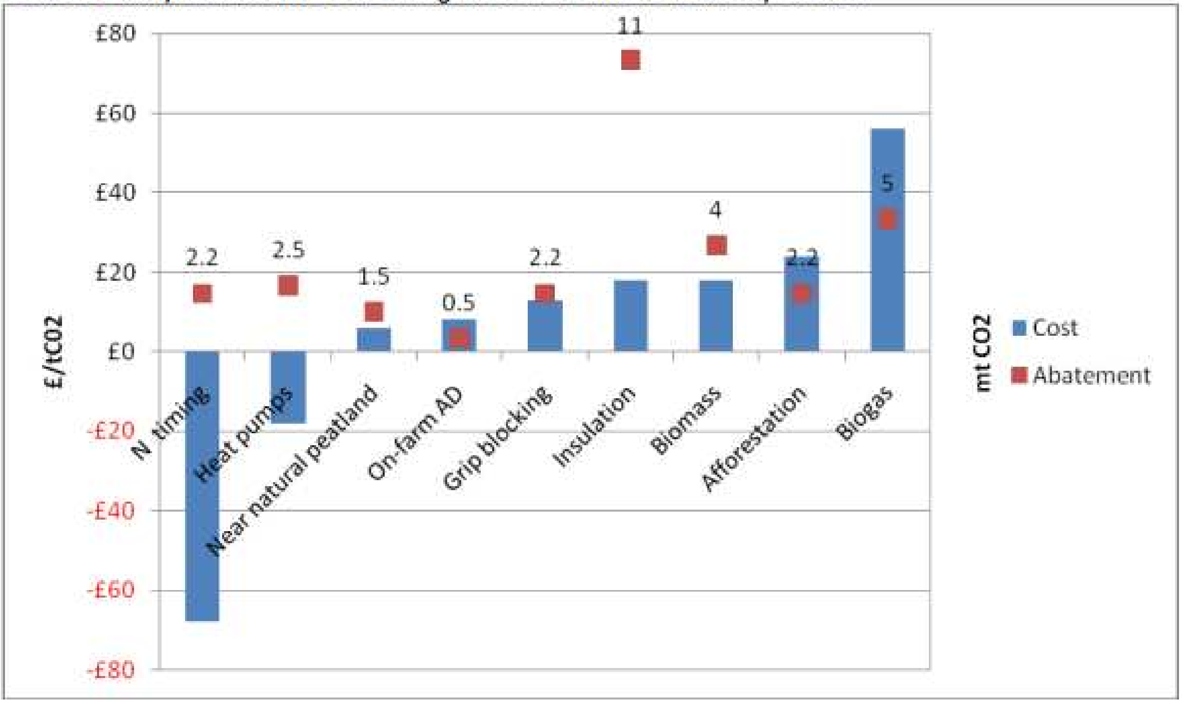
[136] ADAS (2011). Feasibility of GHG mitigation methods. Report to Defra Project AC0222.

[137] http://www.iucn-uk-peatlandprogramme.org/sites/all/files/Illustrative%20Economics%20of%20Peatland%20Restoration,%20June%202011%20Final.pdf

[138] Read, D.J., Freer-Smith, P.H., Morison, J.I.L., Hanley, N., West, C.C. & Snowdon, P. (eds). 2009. Combating climate change – a role for UK forests. An assessment of the potential of the UK’s trees and woodlands to mitigate and adapt to climate change. The synthesis report. The Stationery Office, Edinburgh. http://www.tsoshop.co.uk/gempdf/Climate_Change_Synthesis_Report.pdf

[139] MacLeod et al. (2010). Review and update of UK marginal abatement cost curves for agriculture. Final report to the Committee on Climate Change. http://www.theccc.org.uk/wp-content/uploads/2010/12/pr_supporting_research_SAC_agriculture.pdf

Chart 1 *Example illustrative GHG mitigation costs and abatement potential*



7 Conclusions

1. Two measures of cost-effectiveness were used in the study. The conventional measure (£ per tCO_2e) fails to capture the change in expected carbon values over time. But it is the metric in common use and the only one that allows comparison with other abatement options. A value based metric (£ per £CO_2e) was also used. This has the merit that it takes into account expected increases in carbon values over time.
2. Forest Research provided most of the technical data on which the cost-effectiveness (CE) estimates were based. The soil emission/retention data were subject to considerable uncertainty but found to be an important component of net retention. Greater precision on emissions associated with new planting is highly desirable.
3. The main analysis was over a 186 year horizon to 2200. Investment over such a time period is subject to considerable uncertainty. Whilst tree growth rates and establishment costs can be defined with reasonable precision, some elements in the appraisal could not be specified with precision. These include the future social opportunity cost of land, timber prices, and the carbon abatement derived from substituting woodfuel for other energy sources and timber for other materials. The potential for abatement from product substitution and end-of-life use of timber merit more detailed research than was possible in this study.
4. The forestry options differed hugely in their profile of net carbon retention over time, depending on the profile of soil emission/retention, sequestration in timber, emissions after harvesting and the extent to which output was used for woodfuel or timber. Savings in emissions in heat and power generation from woodfuel substitution were a major element in the retention achieved by SRF and conifer systems.
5. Lowland and upland conifers were the most cost-effective of the forest systems investigated. Costs per tCO_2e were generally in the range £21-30. Forest systems with costs <£50 per tCO_2e also included broadleaves (permanent, managed for biodiversity and game) and continuous cover forestry (CCF). Short rotation forestry (SRF), broadleaves managed for timber and carbon, and farm woodlands were less cost-effective. However, the short rotation forestry (SRF) was modelled as a rotational rather than a coppice and this has higher costs.
6. Conifers performed best (in CE terms) in lowland England whereas upland conifers, permanent broadleaves and CCF were more cost-effective in Scotland. This was in part a reflection of lower costs for land and establishment in Scotland.
7. Levels of additional planting per year under a carbon-focussed policy were defined for each region. The MACC demonstrated that around 5,000 ha per year (delivering 1.36 $mtCO_2e$ abatement) could be planted at a cost of less than £30 per tCO_2e[140]. At a cost of up to £40 per tCO_2e, 6,500 ha could be planted and this would deliver 1.8 $mtCO_2e$ of abatement.
8. When CE was defined in 'value' terms as (£ per £CO_2e) the ranking of the forestry options was broadly similar. Upland conifers typically had CEs in the £0.1-0.2 per £CO_2e with most lowland conifers and permanent broadleaf options in the £0.2-0.6 range. Using this criterion most of the forestry options with the exception of SRF had CEs of <£1.0 per £CO_2e and were therefore cost-effective.

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[140] This is the cost of planting the last ha. The mean cost of planting would be lower.

9. Forestry's contribution to meeting emissions reduction targets in the short term is constrained for certain species and where planting takes place on organo-mineral soils. On mineral soils forestry typically achieved net retention rates exceeding 100 tCO2e per ha by 2050.

10. DECC give low, central and high forecasts of future non-traded carbon values. The sensitivity of the value based CE measure (£ per £CO_2e) to non-central prices was tested. At the low carbon price the cost-effective options were permanent broadleaves in Scotland and Wales, upland and lowland conifers in all countries and CCF in Scotland remained cost-effective. The effect of lower carbon prices was to restrict cost-effective planting to low cost sites. At the high carbon price all systems with the exception of 15 year SRF were cost-effective.

11. A scenario of increasing real timber prices by 1% per year significantly improved the CE of those systems where timber was harvested. However, the case for applying such a scenario is unclear. A more conservative basis is to use constant real prices.

12. A 50% level of wood substitution for other construction materials was explored but the impact was limited because substitution would only occur from the end of the first rotation when DECC forecast very low carbon emissions from power generation.

13. There may be other benefits from woodland planting mainly from impacts on landscape and biodiversity. Much will depend on the location of planting and its proximity to population centres. It was not possible to define the scale or value of such benefits with a degree of certainty that would have allowed their inclusion in the analysis. Any such benefits would improve the cost-effectiveness of woodland creation especially in England where the population of beneficiaries is greater.

14. There can be no guarantee that the management (especially thinning and clearfell) assumed in the models would take place in practice. This execution risk is unlikely to be major because the limited evidence from this study suggests that low intervention systems may be more effective in carbon retention than those involving multiple thinning and/or clearfell. The risk of impermanence due to disease, wind, climate change or poor management is probably more important but this was addressed by applying a 15% reduction in the outputs of timber and carbon. Consideration should be given to forestry as an element in a portfolio approach to abatement given its distinctive risks and abatement profiles.

15. This study has identified the need for better information on the social opportunity cost of land, product substitution and end-of-life woodfuel substitution. There is also a need for a more comprehensive modelling of forest management systems to identify which establishment (species, spacing) and management (thinning and clearfell or non-intervention) regimes are most cost-effective for promoting net carbon retention. The limited range of systems examined in this study was unable to do this in the detail required but such information is important as a guide to policy.

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8 Annex 1

Table 8.1: Fitted price size curves for standing conifers (£ per cu m)

Average volume per tree (m3)	England (£ per cu m)	Scotland (£ per cu m)	Wales (£ per cu m)
Size band to			
.037	10.07	0.40	3.45
.100	13.47	5.17	4.20
.150	14.88	7.15	4.80
.200	15.88	8.55	5.41
.250	16.65	9.64	6.01
.350	17.29	10.53	6.61
.460	18.69	12.50	8.42
.550	19.22	13.25	9.32
.650	19.83	14.09	10.53
.750	20.34	14.81	11.73
.850	20.79	15.44	12.94
.950	21.18	15.99	14.15

Table 8.2: Fitted price size curves for standing broadleaves (£ per cu m)

Average volume per tree (m3)	England (£ per cu m)	Scotland (£ per cu m)	Wales (£ per cu m)
Size band to			
0.10	6.00	6.00	6.00
0.15	8.00	8.00	8.00
0.20	11.00	11.00	11.00
0.25	12.00	12.00	12.00
0.30	13.00	13.00	13.00
0.35	15.00	15.00	15.00
0.40	15.50	15.50	15.50
0.45	16.50	16.50	16.50
0.50	17.50	17.50	17.50
0.55	18.50	18.50	18.50
0.60	19.00	19.00	19.00
0.65	19.50	19.50	19.50
0.70	20.50	20.50	20.50
0.75	21.00	21.00	21.00
0.80	22.00	22.00	22.00
0.85	22.50	22.50	22.50
0.90	23.00	23.00	23.00

Average volume per tree (m3)	England (£ per cu m)	Scotland (£ per cu m)	Wales (£ per cu m)
0.95	23.50	23.50	23.50
1.00	24.00	24.00	24.00
1.05	25.00	25.00	25.00
1.10	25.50	25.50	25.50
1.15	26.00	26.00	26.00
1.20	26.50	26.50	26.50
1.25	27.00	27.00	27.00
1.30	27.50	27.50	27.50
1.35	28.00	28.00	28.00
1.40	28.50	28.50	28.50
1.45	29.00	29.00	29.00
1.50	29.50	29.50	29.50
1.60	30.00	30.00	30.00
5.00	30.00	30.00	30.00

9 Annex 2

Table 9.1 Mean net carbon retention and cost-effectiveness of forest systems (see notes at end of Table for colour coding and soil/previous use code)

Forest System	Country	Region	Soil / Previous Use	Net retention (tCO$_2$e/ha mean)	Net retention (tCO$_2$e/ha mean)	Cost Eff. (£PV Exc C/ £PV CO$_2$e)	Cost Eff. (£PV excl C /tCO$_2$e/ha mean)
Date				2050	2200	2200	2200
SRF 15 year	England	EE&EM	MG/A	91	224	+2.7	+188
SRF 15 year	England	EE&EM	MG/P	14	134	+4.1	+315
SRF 15 year	England	SEE	MG/A	91	224	+3.0	+207
SRF 15 year	England	SEE	MG/P	14	134	+4.5	+346
SRF 15 year	England	SWE	ML/P	7	126	+4.7	+366
SRF 15 year	England	WM&NWE	ML/P	7	126	+4.3	+334
SRF 15 year	England	YH&NEE	OMG/P	-35	68	+3.6	+337
SRF 15 year	Scotland	Central Scotland	OML/P	-51	7	+7.8	+3,162
SRF 15 year	Scotland	Grampian	MG/P	6	80	+3.2	+286
SRF 15 year	Scotland	H and I	OMG/P	-43	14	+5.0	+1,136
SRF 15 year	Scotland	Perth and Argyll	OMG/P	-43	14	+6.7	+1,540
SRF 15 year	Scotland	South Scotland	OML/P	-42	60	+2.3	+229
SRF 15 year	Wales	Wales	OMG/P	-35	68	+3.6	+337
SRF 25 year	England	EE&EM	MG/A	135	351	+1.3	+84
SRF 25 year	England	SEE	MG/A	135	351	+1.4	+96
SRF 25 year	England	SWE	ML/P	51	253	+1.9	+132
SRF 25 year	England	WM&NWE	ML/P	51	253	+1.7	+116
SRF 25 year	England	YH&NEE	OMG/P	9	195	+1.1	+82
SRF 25 year	Scotland	Central Scotland	OML/P	-13	134	+1.3	+107
SRF 25 year	Scotland	Grampian	MG/P	44	208	+1.0	+72
SRF 25 year	Scotland	H and I	OMG/P	-5	142	+0.9	+72
SRF 25 year	Scotland	Perth and Argyll	OMG/P	-5	142	+1.3	+101
SRF 25 year	Scotland	South Scotland	OML/P	3	193	+0.6	+45
SRF 25 year	Wales	Wales	OMG/P	10	201	+1.1	+80
Farm woodland	England	EE&EM	MG/A	164	314	+0.4	+48
Farm woodland	England	EE&EM	MG/P	94	233	+0.4	+65
Farm woodland	England	SEE	MG/A	155	283	+0.5	+69
Farm woodland	England	SEE	MG/P	86	202	+0.6	+96
Farm woodland	England	SWE	ML/P	88	227	+0.5	+81
Farm woodland	England	WM&NWE	ML/P	82	220	+0.4	+66
Farm woodland	England	YH&NEE	OMG/P	42	143	+0.4	+79
Farm	Scotland	Central Scotland	OML/P	0	84	+0.5	+108

Forest System	Country	Region	Soil / Previous Use	Net retention (tCO_2e/ha mean)	Net retention (tCO_2e/ha mean)	Cost Eff. (£PV Exc C/ £PV CO_2e)	Cost Eff. (£PV excl C /tCO_2e/ha mean)
woodland							
Farm woodland	Scotland	Grampian	MG/P	66	229	+0.3	+40
Farm woodland	Scotland	H and I	OMG/P	21	170	+0.3	+47
Farm woodland	Scotland	Perth and Argyll	OMG/P	19	118	+0.4	+76
Farm woodland	Scotland	South Scotland	OML/P	29	129	+0.3	+63
Farm woodland	Wales	Wales	OMG/P	46	160	+0.4	+72
Broadleaf1	England	EE&EM	MG/A	109	461	+0.4	+61
Broadleaf1	England	EE&EM	MG/P	40	379	+0.4	+74
Broadleaf1	England	SEE	MG/A	126	530	+0.4	+61
Broadleaf1	England	SEE	MG/P	57	449	+0.4	+72
Broadleaf1	England	SWE	ML/P	33	373	+0.5	+84
Broadleaf1	England	WM&NWE	ML/P	27	356	+0.5	+77
Broadleaf1	England	YH&NEE	OMG/P	-5	320	+0.2	+41
Broadleaf1	Scotland	Central Scotland	OML/P	-12	209	+0.2	+46
Broadleaf1	Scotland	Grampian	MG/P	4	254	+0.3	+41
Broadleaf1	Scotland	H and I	OMG/P	-41	195	+0.2	+46
Broadleaf1	Scotland	Perth and Argyll	OMG/P	-22	272	+0.2	+38
Broadleaf1	Scotland	South Scotland	OML/P	-17	297	+0.2	+32
Broadleaf1	Wales	Wales	OMG/P	-5	320	+0.2	+42
Broadleaf2	England	EE&EM	MG/A	119	246	+1.1	+140
Broadleaf2	England	EE&EM	MG/P	50	165	+1.3	+210
Broadleaf2	England	SEE	MG/A	159	285	+1.0	+128
Broadleaf2	England	SEE	MG/P	90	203	+1.1	+179
Broadleaf2	England	SWE	ML/P	44	158	+1.5	+245
Broadleaf2	England	WM&NWE	ML/P	44	158	+1.3	+218
Broadleaf2	England	YH&NEE	OMG/P	6	106	+0.6	+151
Broadleaf2	Scotland	Central Scotland	OML/P	7	114	+0.4	+104
Broadleaf2	Scotland	Grampian	MG/P	30	136	+0.5	+101
Broadleaf2	Scotland	H and I	OMG/P	-15	77	+0.5	+148
Broadleaf2	Scotland	Perth and Argyll	OMG/P	13	120	+0.5	+113
Broadleaf2	Scotland	South Scotland	OML/P	16	93	+0.5	+125
Broadleaf2	Wales	Wales	OMG/P	6	106	+0.8	+167
Up. conifer	England	WM&NWE	ML/P	98	337	+0.2	+27
Up. conifer	England	YH&NEE	OMG/P	61	284	+0.2	+33
Up. conifer	Scotland	Central Scotland	OML/P	55	278	+0.2	+27
Up. conifer	Scotland	Grampian	MG/P	81	304	+0.2	+26
Up. conifer	Scotland	H and I	OMG/P	37	244	+0.2	+30

Forest System	Country	Region	Soil / Previous Use	Net retention (tCO$_2$e/ha mean)	Net retention (tCO$_2$e/ha mean)	Cost Eff. (£PV Exc C/ £PV CO$_2$e)	Cost Eff. (£PV excl C /tCO$_2$e/ha mean)
Up. conifer	Scotland	Perth and Argyll	OMG/P	61	285	+0.2	+26
Up. conifer	Scotland	South Scotland	OML/P	55	278	+0.2	+27
Up. conifer	Wales	Wales	OMG/P	85	331	+0.2	+30
Low. conifer	England	EE&EM	MG/A	210	501	+0.1	+21
Low. conifer	England	EE&EM	MG/P	140	419	+0.2	+25
Low. conifer	England	SEE	MG/A	180	428	+0.3	+37
Low. conifer	England	SEE	MG/P	111	347	+0.3	+46
Low. conifer	England	SWE	ML/P	134	413	+0.2	+35
Low. conifer	England	WM&NWE	ML/P	134	413	+0.2	+25
Low. conifer	England	YH&NEE	OMG/P	67	288	+0.2	+39
Low. conifer	Scotland	Central Scotland	OML/P	39	240	+0.2	+28
Low. conifer	Scotland	Grampian	MG/P	72	269	+0.2	+27
Low. conifer	Scotland	Perth and Argyll	OMG/P	46	246	+0.2	+27
Low. conifer	Scotland	South Scotland	OML/P	39	240	+0.2	+28
Low. conifer	Wales	Wales	OMG/P	85	331	+0.3	+39
Continuous cover	England	EE&EM	MG/A	196	452	+0.4	+60
Continuous cover	England	EE&EM	MG/P	127	371	+0.5	+74
Continuous cover	England	SEE	MG/A	163	449	+0.5	+72
Continuous cover	England	SEE	MG/P	93	368	+0.6	+88
Continuous cover	England	SWE	ML/P	120	364	+0.5	+86
Continuous cover	England	WM&NWE	ML/P	114	352	+0.5	+78
Continuous cover	England	YH&NEE	OMG/P	49	309	+0.3	+50
Continuous cover	Scotland	Central Scotland	OML/P	-7	189	+0.3	+56
Continuous cover	Scotland	Grampian	MG/P	60	260	+0.3	+40
Continuous cover	Scotland	H and I	OMG/P	16	200	+0.2	+45
Continuous cover	Scotland	Perth and Argyll	OMG/P	17	238	+0.2	+43
Continuous cover	Scotland	South Scotland	OML/P	38	288	+0.2	+32
Continuous cover	Wales	Wales	OMG/P	66	344	+0.3	+46

Note: values in red indicate negative mean net retention. Values in green are not cost-effective as assessed by cost per £PV CO$_2$e. Values in blue are cost-effective as assessed by cost per £PV CO$_2$e.

Note: MG = mineral gley; ML=mineral loam; OMG=organo-mineral gley; /P = previous land use pasture; /A= previous land use arable (see Table 3.5)