Forestry Commission

Research Report

Marginal abatement cost curves for UK forestry

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Summary

- Comparing the cost-effectiveness of different climate change mitigation measures is essential in minimising the cost of meeting national greenhouse gas (GHG) reduction targets.

- The costs of different measures and their potential to reduce GHG emissions or sequester atmospheric GHGs can be depicted using a Marginal Abatement Cost Curve (MACC). A MACC seeks to rank measures from the cheapest to the most expensive.

- Approaches to estimating MACCs and the cost-effectiveness of forestry measures vary. Abatement levels may be based either upon maximum technical potentials, or estimated feasible potentials, and cost estimates upon the costs to the private sector, or the social costs to the economy as a whole.

- Estimates from previous UK MACC studies suggest that forestry measures are generally highly cost-effective compared to government estimates of the social value of carbon used in policy appraisal. However, estimates are sensitive to the species planted, forest management regimes, environmental conditions, the extent of co-benefits and the precise methodology adopted.

- Eighteen recommendations for developing UK MACCs covering forestry emerged from this review. It is recommended that the approach in current government guidance is followed to facilitate direct comparison with cost-effectiveness estimates for other sectors. Computing indicators such as the net present value (excluding the value of carbon benefits) divided by the summed discounted carbon savings, as well as the annual cost per tonne of carbon dioxide sequestered, should also be considered to aid comparisons between forestry measures.

- A conservative approach to allowing for non-permanence risks is recommended, possibly along similar lines to the *Woodland Carbon Code*. This involves accounting for abatement up to a maximum long-run mean level, and reducing carbon benefits associated with a measure by adopting a buffer approach.

- The overall effect of forests on GHG balances depends on a range of processes and not simply on carbon sequestration in above-ground biomass. It is recommended that a complete set of carbon pools and GHG fluxes be covered where estimates are available, with spatial variation also taken into account.

1. Introduction

Climate change mitigation is a top policy priority of the UK government, and it is considered to be one of the greatest challenges facing the world at present. In collaboration with EU partners and other governments, the UK government is seeking to limit global average temperature rise to below 2°C in order to prevent 'dangerous climate change'. Adverse impacts associated with exceeding the 2°C threshold are envisaged to include extinction of around 20% of species (www.decc.gov.uk). The urgency of climate change mitigation is further underlined by those scientists who consider the existing atmospheric concentration of over 390 ppm of CO_2 (Arvizo *et al.*, 2011) too high to sustain if the 2°C threshold is not to be exceeded, and who recommend rapid reduction to no higher than 350 ppm of CO_2 (e.g. Hansen *et al.*, 2008).

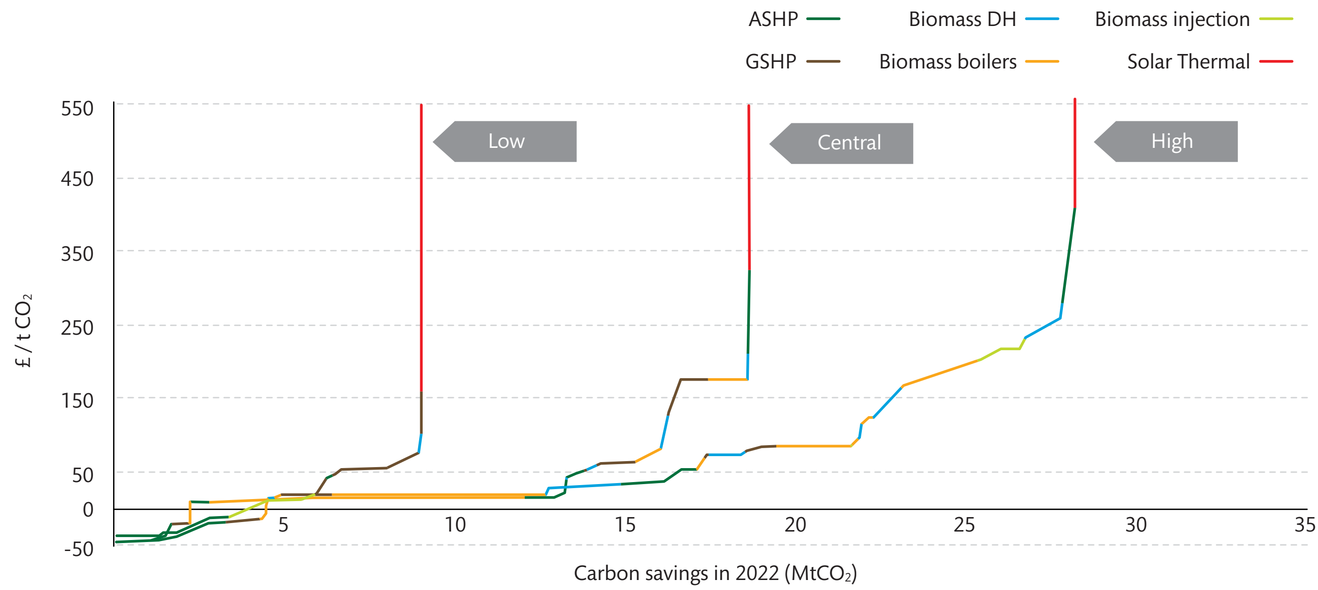
One of the priorities of the UK Department for Energy and Climate Change is to ensure UK carbon budgets are met efficiently. Comparing the cost-effectiveness of climate change mitigation options is essential in minimising the cost of meeting national greenhouse gas (GHG) reduction targets. Cost-effectiveness is generally considered a necessary condition, but not by itself sufficient, for efficient policies. (See discussion in Bosello, Giupponi and Povellato, 2007.)

The costs of different measures and their potential to reduce GHG emissions or sequester atmospheric GHGs can be depicted using a Marginal Abatement Cost Curve (MACC). This shows measures ranked from left to right from the cheapest to most expensive, illustrating the costs of achieving incremental levels of emissions abatement under specific scenarios. (See the Committee on Climate Change definition at www.theccc.org.uk/glossary) Example MACC curves for renewable heat are shown in Figure 1.

Interpretation of MACCs is fairly straightforward. A single line segment (or bar) is used to represent each measure. Its horizontal width represents the abatement potential in units such as million tonnes of carbon dioxide equivalent ($MtCO_2e$). Its vertical height above the horizontal axis represents the unit cost (e.g. in £/tCO_2e). The area between the line segment and the horizontal axis (the area of the bar) represents the total cost (e.g. in £ million). In Figure 1, for example, total abatement of 18 $MtCO_2e$ can be delivered in 2022 under the central scenario at a unit cost ranging between around -£50 per tCO_2 for some air source heat pump applications to over £300 per tCO_2 for solar thermal, with biomass boilers providing about half the total carbon savings, most at £10–£20 per tCO_2.

For measures where the height of the line is negative, this indicates a cost saving can be made by implementing the measure (which may be indicative of existing market failures). Were the government to impose an economy-wide 'floor price' for carbon, all abatement opportunities up to this price level (net of transactions costs and normal industry rates of return) on a MACC based upon private sector costs might be expected to be undertaken as they would be financially viable.

Figure 1 UK Marginal Abatement Cost Curves for renewable heat in 2022.



Source: CCC (2011, p. 125). ASHP – air source heat pumps; DH – district heating; GSHP – ground source heat pumps. Where a technology appears more than once in a curve, this reflects different applications.

Approaches to estimating MACCs vary. For forestry measures, abatement estimates may focus on GHG sequestration by trees, in soils and other carbon pools within the forest. Alternatively, they may extend to wider abatement benefits associated with carbon storage in harvested wood products, and fossil fuel substitution benefits in energy generation and in use of wood instead of more fossil fuel intensive materials such as concrete and steel. Abatement levels may be based either upon maximum technical potentials, or estimated feasible potentials. Cost estimates may be based upon the costs to the private sector of implementing measures, or the social costs to the economy as a whole. The latter may extend to considering transaction and policy implementation costs, and ancillary costs and benefits, including life-cycle analysis of effects in related sectors. (Further distinctions in underlying approaches can be drawn between project, technology, sector, and macroeconomic costs – see Ekins, Kesicki and Smith, 2011.) Cost estimates are sensitive to a range of underlying assumptions including the discount rate (or rates) assumed, interactions between measures and path dependence associated with the influence of past choices, and investment decisions on the costs of implementing measures in the future. (Adoption of the Qwerty keyboard is often considered a classic example of path dependence whereby investments associated with an initial choice led to subsequent failures to adopt more efficient technology).

As estimation of a MACC is dependent upon the number of years assumed to elapse after each measure is introduced and abatement profiles over time, it provides a static snapshot of the abatement potential at a particular date. Thus, it is sensitive to the reference date chosen. It also depends upon the method adopted to establish the baseline from which additional abatement is measured (Moran *et al.*, 2008). To the extent that cost and abatement profiles of measures, and scope for their introduction differ between countries, MACCs are country specific.

The aims of this short note are twofold: first to provide a brief review of previous studies which have estimated MACCs covering the UK forestry sector, and, secondly, to provide recommendations for future work in this area.

2. Previous studies

Several previous studies have developed global MACCs covering forestry measures (e.g. McKinsey, 2009). Although providing useful international comparators, they do not specifically examine UK forestry options.

Modelling approaches to estimating national-level MACCs vary. They may use a 'top-down' approach based upon a macroeconomic general equilibrium model covering all sectors of the economy. This approach proceeds by imposing an economy-wide emissions constraint. The model is then used to identify the new economy-wide equilibrium. One of the strengths of this approach is the ability to take account of inter-sector dependencies. Alternatively, a 'bottom-up' approach may be taken that focuses on abatement costs in particular sectors. This approach is better able to represent the characteristics of and specific technologies in the sectors focused on, and account for detailed costs and benefits associated with adopting particular measures. (For further discussion on the different approaches see Delarue, Ellerman and D'haeseleer, 2010; MacLeod *et al.*, 2010.)

The only study to have estimated a MACC for the UK economy as a whole identified (McKinsey, 2007) did not extend to explicit consideration of woodlands. None of the 120 GHG abatement options considered was a forestry measure. In practice, therefore, only bottom-up approaches have been used to date in estimating MACCs that explicitly cover UK forestry measures.

A literature search identified three primary studies estimating MACCs that include UK forestry measures. These are Radov *et al.* (2007) (Study 1), Moran *et al.* (2008) (Study 2) and ADAS (in prep) (Study 3). Results from the last-mentioned report are also published in Matthews and Broadmeadow (2009).

In addition, there have been some modest extensions of these, notably Nijnik *et al.* (2009), Moran *et al.* (2011) and indicative estimates made by Professor Colin Price of Bangor University as part of a review of the Read Report (Read *et al.*, 2009) that illustrate the significance of some underlying assumptions. Studies that cover UK forest carbon valuation but do not consider the cost-effectiveness of measures, including Bateman and Lovett (2000), Willis *et al.* (2003) and Valatin and Starling (2011), are not considered by this review. However, results of a recent study that includes estimates of the climate change mitigation cost-effectiveness of woodland measures at project level (Nisbet *et al.*, 2011) are noted.

The following subsection compares the approaches taken in each of the three studies. Fuller summaries of each are provided in the Appendix.

Estimating cost-effectiveness

Current government guidance on estimating cost-effectiveness in appraisal and evaluation (DECC and HM Treasury, 2010, p. 25) recommends deriving the cost-effectiveness of a measure by dividing its net present value (NPV) excluding the present value of the carbon benefits (but including other benefits) by the (negative of the) total tonnes of carbon dioxide equivalent (tCO_2e) saved:

$$\text{Cost-effectiveness } (£/tCO_2e) = \\ \text{NPV (excluding carbon) / - } tCO_2e \text{ saved}$$

Net GHG savings are excluded from the NPV in computing the cost-effectiveness of a measure in order to estimate a net cost per tonne of carbon dioxide equivalent saved that can then be compared with an indicator of the social value of these benefits. The GHG benefits excluded are either in the 'traded sector' covered by the EU Emissions Trading Scheme (ETS), or those in the 'non-traded sector' not covered by the EU ETS, depending upon the focus of the analysis. Where a measure increases consumers' disposable income because it saves them money, only GHG savings net of the 'rebound effect' (increased energy use due to these higher incomes) are accounted for (DECC and HM Treasury, 2010, pp. 15–16).

Whether a measure is cost-effective is determined by comparing the cost per tonne of carbon dioxide equivalent abated with the relevant cost comparator. In order to reflect a societal perspective on the value of the climate change mitigation benefits, the cost comparator is based upon estimates of the social price of carbon. (For discussion of distinctions between social and market carbon values see Valatin, 2011.) Providing a benchmark by which to judge whether a measure is cost-effective, the cost comparator is computed as a weighted average discounted social price of carbon. The weights used are the proportion of carbon savings in each year. The social price of carbon is taken from DECC social value of carbon central estimates (traded or non-traded sector). Discounting is based upon the approach recommended in the Treasury Green Book. Current UK government guidance for policy appraisal includes central social value of carbon estimates for 2011 of £52 per tCO_2e (£190 per tC) for non-ETS sectors at 2009 prices, rising over time to a peak of £308 per tCO_2e (£1129 per tC) in 2077, thereafter declining (DECC, 2010, Table 3).

Although similar, not discounting GHG abatement in estimating the cost-effectiveness of a measure and comparing this to a cost comparator based upon discounted social prices of carbon is not exactly equivalent to discounting the GHG savings in estimating the cost-effectiveness and then comparing this to an undiscounted cost comparator. (Although often providing the same result, cases where a measure is accepted as cost-effective under one approach but not under the other can easily be demonstrated numerically using Excel, for example.) The guidance does not explain why the approach based upon undiscounted carbon benefits is recommended. However, it notes that checking whether a policy results in a positive NPV is sufficient in most cases to determine whether a policy is cost-effective or not (DECC and HM Treasury, 2010, p. 25) – an approach which, by contrast, implicitly involves discounting the carbon benefits.

Estimates from previous UK MACC studies (summarised in Table 1) suggest that forestry measures are generally highly cost-effective. A similar conclusion is also drawn for the 'Slowing the Flow' flood risk reduction project in North Yorkshire (Nisbet *et al.*, 2011) based upon the method recommended in current government guidance (DECC and HM Treasury, 2010), with cost-effectiveness estimates for woodland creation measures of between -£62 and £3 per tCO_2e reported.

However, direct comparison of these estimates of the cost-effectiveness of UK woodland creation measures is hampered by the differing approaches used which are not always specified in detail. For example, it is unclear how the indicative MACC estimates in Radov *et al.* (2007, Fig. 8.1, p. 93) are derived. Similarly, although utilising a method consistent with analysis for other sectors allowing for path dependence and granularity of measures (i.e. changing marginal implementation costs) and a control panel of variables (emissions factors, discount rates, energy output prices etc), the precise methodology used in Moran *et al.* (2008) is not described in detail. According to both ADAS (in prep, p. 2) and Matthews and Broadmeadow (2009, p. 156), however, cost-effectiveness is computed in Moran *et al.* (2008) as the NPV divided by the total carbon savings, a similar approach in not discounting carbon benefits to that recommended in current government guidance (DECC and HM Treasury, 2010). This appears to be confirmed in Moran *et al.* (2011). Reporting an identical cost-effectiveness estimate to that in Moran *et al.* (2008) of -£7.12 per tCO_2e for the 'central feasible potential' of carbon sequestration associated with planting Sitka spruce, Moran *et al.* (2011, p. 544) adopt the following formulation (estimates on the right hand side of the equation are net of the baseline costs and abatement, respectively):

$$\text{Cost-effectiveness } (£/tCO_2e) = \text{net lifetime cost / net lifetime abatement}$$

A related paper by Nijnik *et al.* (2009, p. 10) similarly computes the cost-effectiveness of woodland creation as

Table 1 Cost-effectiveness of UK forestry measures.

	Study 1	Study 2	Study 3	Price (unpublished[2])
Time period(s) covered	i) 2009–12 ii) 2009–17 iii) 2009–22	to 2022	i) to 2022 ii) to 2050	Perpetual series of rotations
Baseline land use	Arable	Sheep	Rough grazing/ uncultivated	Not applicable
Carbon benefits covered	Seq	a) Seq b) SeqSbm c) SeqSbf	a) Seq b) SeqSbm(m) c) SeqSbm(h)	a) Seq b) Seqd
Tree species and yield class options considered	2	1	14[1]	1
Woodland creation cost-effectiveness (£/tCO_2e)	~£20 to ~£40	a) -£7 b) -£2 c) -£6	a) -£61 to £103 b) -£61 to £73	a) £31 to £39 b) £19[3]
Forestry management cost-effectiveness (£/tCO_2e)	Not considered	b) £1 c) £12[4]	c) -£52[5]	Not considered

Notes: Carbon benefits covered: Seq – carbon sequestration; SeqSbm – carbon sequestration and materials substitution; (m) – 'medium' materials substitution; (h) – 'high' materials substitution benefits; SeqSbf – carbon sequestration and fossil fuel substitution benefits in energy generation; Seqd – carbon sequestration and displacement (including carbon storage in harvested wood products and fossil fuel substitution benefits in materials and energy generation).

1 MACC estimates for England (ADAS, in prep, Table 5.3, p. 41) focus upon five options.
2 Estimates shown include re-release of carbon sequestered (e.g. due to harvesting, or decay/combustion of wood products).
3 Illustrative figure used for displacement.
4 Assumes shortened rotation length (59 years to 49 years).
5 Assumes increased management of currently under-managed woodland. (Cost-effectiveness not estimated for medium substitution benefits or carbon sequestration alone due to apparent negative abatement potential.)

a function of the net present value of forestry ($NPV_{Forestry}$) minus the net present value of the opportunity cost of converting agricultural land to forestry (NPV_{Farm}):

$$\text{Cost-effectiveness } (£/tCO_2e) = (NPV_{Forestry} - NPV_{Farm}) \text{ / change in the carbon stock}$$

Similarly assuming coniferous afforestation based upon 49-year rotations, Nijnik *et al.* (2009) provide cost-effectiveness estimates for planting on different types of agricultural land, which at a 3.5% discount rate range from £8 per tCO_2e for planting on sheep pasture to £48 per tCO_2e for planting on wheat fields. (The corresponding range at a 7% discount rate is £15 per tCO_2e to £55 per tCO_2e.)

However, in contrast to Moran *et al.* (2008, 2011), who focus upon shortening rotation length for existing woodlands from an assumed current baseline of 59 to 49 years, the forestry management measure Nijnik *et al.* (2009) consider involves increasing rotation length. Assuming a current baseline of 49-year rotations, they focus upon maximising mean annual carbon sequestration by increasing rotation length from 49 to 59 years (the point at which mean annual increment is highest), with cost-effectiveness defined as (Nijnik *et al.*, 2009, p. 13):

$$\text{Cost-effectiveness } (£/tCO_2e) = (NPV_{49years} - NPV_{59years}) \text{ / change in the carbon stock}$$

Moran *et al.* (2008, 2011) find that reducing rotation length is cost-effective (£1 to £12 per tCO_2e) once carbon substitution benefits are included. If carbon sequestration alone is accounted for, Nijnik *et al.* (2009) report that increasing rotation length is cost-effective (£3 per tCO_2 at a 3.5% discount rate), and is more cost-effective where a higher discount rate is applied. The conflicting nature of these results illustrates the importance of the breadth of carbon benefits focused upon in deriving cost-effectiveness estimates. (This issue is also discussed by Nijnik *et al.*, 2009.)

Each of the studies reviewed takes opportunity costs of converting land to forestry into account. However, approaches vary depending whether this is based upon annual agricultural opportunity costs (Moran *et al.*, 2008; Nijnik *et al.*, 2009; ADAS, in prep), or upon loss of annual agricultural subsidies and a one-off loss of land value on conversion to woodland (Radov *et al.*, 2007). ADAS (in prep), by contrast with the other studies, estimate the cost-effectiveness of woodland creation measures on a per hectare basis by dividing the net cost per year (calculated as an annuity value equivalent) by the abatement achieved on average per year over 100 years (including carbon sequestration, and either no, medium or high timber substitution benefits):

$$\text{Cost-effectiveness } (£/tCO_2e) = \text{net cost per year / average annual abatement}$$

The net annual cost is calculated by subtracting the annual equivalent revenue calculated over 100 years from the annual equivalent cost estimated over one rotation. The equivalent annual revenue is calculated as the annuity equivalent at 3.5% of the present value of the timber revenues plus any carbon substitution in electricity generation valued at central price estimates for EUAs (EU allowance units) under the EU ETS. (Inclusion of the latter is consistent with the DECC approach to cost-effectiveness as substitution in electricity generation is assumed to occur in the 'traded sector' and this is not accounted for in average abatement estimates used which relate to the 'non-traded sector'.) The equivalent annual cost ($EAC_{Forestry}$) is calculated as the annuity equivalent at a discount rate (r) of 3.5% of the present value of the establishment or restocking cost ($COST_{Forest}$) plus the opportunity cost of land (A). The precise formula used over the rotation length (T) assumed is not specified. However, it appears to match the method used by the PMT function in Excel (which returns the periodic payment for a loan based on constant payments and a constant interest rate):

$$EAC_{Forestry} = \frac{COST_{Forest} * r}{1 - (1 + r)^{-T}} + A$$

Due to the inclusion of the additional discount rate terms in the latter equation, the approach in ADAS (in prep) appears more akin to methods in which carbon benefits are discounted than that recommended in current Treasury guidelines (DECC and HM Treasury, 2010), which, as discussed above, does not involve discounting these. However, the precise relationship is not straightforward, not least as cost and revenue annuity values are generally estimated over different time horizons. Reasons for comparing costs as annuity equivalents are not discussed in ADAS (in prep), but probably relate to seeking a common basis for comparing forestry options with different rotation lengths, even if the choice of comparisons of annual equivalent costs over a single rotation and of revenues over a 100-year period appears somewhat arbitrary.

By contrast, indicative cost-effectiveness estimates derived by Colin Price for a review of the Read Report address both comparability and optimality issues through the use of a model that maximises NPV over a perpetual series of rotations by changing the rotation length. The model takes account of both carbon and timber benefits, with the marginal cost of carbon estimated by setting the 'carbon price' such that the cumulative NPV is zero. By focusing upon a perpetual series of rotations, the model also avoids the potential problem of needing to assume carbon sequestration benefits are permanent rather than subject to any decline after the particular time horizon focused on (e.g. due to subsequent harvesting). The model takes broad account of displacement benefits, including carbon storage in harvested wood products, as well as substitution benefits of using wood instead of more fossil fuel intensive materials and in energy generation. The results suggest that methodological differences, such as whether differences in the timing of carbon benefits are accounted for by discounting, and the types of carbon benefits covered, as well as the treatment of future releases of carbon (e.g. due to subsequent timber harvesting and decay of wood products), can lead to large differences in cost-effectiveness estimates. The indicative estimates illustrate how using undiscounted carbon benefits results in much lower estimates of carbon abatement costs (£6 per tCO_2e) than if carbon benefits are discounted (£13–£18 per tCO_2e), or if both discounting and subsequent re-release of carbon are included (£31–£39 per tCO_2e).

Table 2 provides a summary of some of the differences in focus and underlying assumptions between existing studies, including differences in the carbon pools covered, and the cost and timber price profiles assumed. These affect the cost-effectiveness estimates, but in general do not appear to have been subject to systematic sensitivity analysis in any of the studies reviewed.

Reflecting relatively low returns in the previous agricultural uses assumed (Table 1), levels of annual agricultural opportunity costs assumed in previous studies may appear relatively minor compared to the woodland establishment costs (Table 2), but present value equivalents over a timeframe typical of forestry projects can exceed the woodland establishment costs. This is generally the case, for example, if the annual agricultural opportunity costs are converted over a 100-year time-frame at Treasury Green Book discount rates (HM Treasury, 2003), as this would imply corresponding present values per hectare in the range of £3578–£4412 for Radov *et al.* (2007), of £4204 for Moran *et al.* (2008), and between £1491–£10434 for ADAS (in prep).

Table 2 Differences of focus and underlying assumptions in previous UK studies.

	Study 1	Study 2	Study 3	Price (unpublished)
Geographical focus	UK	UK	GB[1]	Not applicable
Carbon pools covered	T,S[2]	T,L and S[3]	T,L,S and HWP	T
Opportunity cost (£/ha/year)	£120–£148[4]	£141	£50–£350[5]	£150
Loss in land value (£/ha)	£2500[6]–£7500[7]	Not included separately	Not included separately	Not included separately
Establishment cost(s)[8] (£/ha)	£1250[6]–£3000[7]	£1250	£1310–£5400[9]	£2000
Timber price profile	n.a.	2.5% pa increase[10]	2% pa increase[11]	Unspecified[12]
Value of carbon substitution in electricity generation	Not included	Not valued separately[13]	£21 per tCO_2e (2009) – £200 per tCO_2e (2050)	Not valued separately
Discount rate applied	7%	3.5%	3.5%	Unspecified[14]

Notes: Carbon pools covered: T – Tree; L – litter; S – Soil; HWP – harvested wood products.
1 Cost estimates based upon applying Forestry Commission England standard cost models, rather than GB ones.
2 Radov *et al.* (2007, Table 3-1, p. 35) includes an estimate of 3.41 tCO_2e/year for the soil carbon storage potential of converting arable land to woodland, while Radov *et al.* (2007, p. 37) state that increased carbon storage is estimated at around 0.79 tCO_2e/ha/year.
3 An average carbon sequestration rate of 3.6 tC/ha/year over a rotation is assumed, with an additional rate of uptake in soils and dead organic matter of 1.5 tC/ha/year.
4 The estimates relate to loss of single farm payments for two afforestation examples (Sitka spruce on acid grassland and lowland oak, respectively).
5 Opportunity cost based upon net farm income adjusted for rent (and reduced by 25% to allow for environmental and sporting benefits, and the use of more marginal land).
6 Estimate relates to planting Sitka spruce on acid grassland (Radov *et al.*, 2007, p. 38).
7 Estimate relates to planting lowland oak (Radov *et al.*, 2007, p. 38).
8 Land purchase costs not included. Replanting cost assumed to be the same as the original establishment cost.
9 Separate cost estimates are provided with and without fencing, with the latter used in deriving cost-effectiveness measures. (With fencing cost estimates range up to £6700 per ha.)
10 Based upon Forestry Commission softwood standing sales prices.
11 For (a) softwood: based upon Forestry Commission standing sales price by size grade in 2007/08; (b) hardwood: £5–£18.9 per m^3; (c) short rotation coppice: £3 per tonne.
12 Price level in second half of 20th century is similar to that assumed in Moran et al. (2008).
13 Moran *et al.* (2008, p. 94) assume carbon substitution benefits of either 257 tCO_2e/ha for benefits of substituting fossil fuels in the energy sector or 2576 tCO_2e/ha for materials substitution based upon estimates for current practices in energy, and steel and concrete production (drawing upon estimates provided by Forest Research).
14 Protocol recommended based upon discounting whole profile of fluxes, but rate unspecified.

3. Discussion and recommendations

A fundamental question in considering how best to develop further work on forestry MACCs is which indicator or indicators of cost-effectiveness to use. As we have seen, the approaches adopted in previous studies differ. Furthermore, there are other approaches too. These include an approach advocated by Colin Price (personal communication) of estimating a rental cost of carbon to reflect the annual cost of retaining carbon sequestered in woodland by dividing the annual cost of maintaining a normal distribution of yield classes by the mean carbon stock over a rotation. Alternatively, to take account of time preference (e.g. for climate change mitigation to occur sooner rather than later), cost-effectiveness can be estimated by dividing the NPV by the summed discounted carbon flows (Colin Price, personal communication). The latter approaches appear more theoretically sound than the recommended approach (DECC and HM Treasury, 2010) of dividing the NPV by the undiscounted change in GHG abatement, and then comparing this with a discounted cost comparator. However, accounting both for time preference and a perpetual series of rotations does not fit easily with adopting the Treasury Green Book declining discount rate, which adds significant complexity to estimating cost-effectiveness in this case.

1. To facilitate comparisons with cost-effectiveness estimates for measures in other sectors, it is recommended on pragmatic grounds that the approach in current government guidance is adopted as the principal focus in estimating the cost- effectiveness of UK forestry measures in further work on developing MACCs.

2. To aid comparisons between forestry measures, it is recommended on theoretical grounds that other cost-effectiveness indicators such as the annual cost of locking up a tonne of carbon for a year, and also dividing the NPV (excluding the value of carbon benefits) by the summed discounted carbon flows, are also considered.

In so far as the levels of abatement achieved under national targets for GHG reductions are of primary interest, the most appropriate time horizons to focus upon in computing cost-effectiveness indicators are likely to depend upon the time-frames associated with these targets. These are unlikely to match the time-spans for complete rotations. Comparison of abatement levels over incomplete rotations and over different rotation lengths are unlikely to yield estimates that are representative over time and are potentially misleading.

3. To facilitate comparison of forestry measures, computing cost-effectiveness indicators over full rotations (including accounting for re-release of carbon on harvesting) and over a perpetual series of rotations should be considered to supplement analysis over policy-relevant time-frames.

4. Estimates should ideally be based upon explicit economic modelling of rotation length where a suitable model exists, if least-cost forestry measures are to be focused on.

MACC curves covering the forestry sector may be based upon a range of different species, yield class and management options, reflecting variations in species suitability and productivity between sites, and different management objectives.

5. Where the climate change mitigation cost-effectiveness of different species yield class or management options are to be compared directly, options considered should be potential alternatives for particular sites.

Permanence issues, both future re-release of the carbon sequestered through any subsequent harvesting and decay of wood products, and non-permanence risks (such as those associated with fire, windthrow, pests and diseases) do not appear to have been adequately accounted for in previous studies.

6. It is recommended that a more conservative approach to accounting for permanence issues is adopted in future. This might be along similar lines to the *Woodland Carbon Code* (Forestry Commission, 2011) involving counting abatement up to a maximum long-run mean level where subsequent timber harvesting is envisaged, and reducing the carbon benefits assumed by adopting a buffer approach to allow for non-permanence risks. Alternatively, it might allow for future costs of maintaining or replacing the abatement benefits lost by balancing future releases of carbon with equivalent additional abatement. This could be done either through accounting explicitly for subsequent costs of additional woodland creation, or by allowing for subsequent purchase of equivalent carbon units adopting an analogous approach to temporary crediting schemes for carbon offsets (see Valatin, 2011).

7. Potential changes in non-permanence risks should also be taken into consideration (e.g. associated with climate change) where estimates are available.

To date, little consideration has been given to spatial variation in abatement potential, in costs, in landowner preferences (e.g. compensation required to switch land to forestry), or other attributes. Maps of land available for woodland planting, or available subject to various planning restrictions, are available in some instances (e.g. for Wales see www.forestry.gov.uk/forestry/INFD-6J2GXD).

8. It is recommended that such maps be linked with other spatial datasets, such as soil maps, agricultural land-use and opportunity cost information, species suitability (e.g. Ecological Site Classification) and productivity (yield class) tools in order to help identify which forestry options to focus on and associated abatement potentials. These links could help improve aggregate estimates of abatement potentials and associated cost-effectiveness at regional and national levels. Potential for linking with spatial data being collected as part of the National Forest Inventory should also be explored.

9. In developing a spatial approach to estimating MACCs, potential links with related work (e.g. the UKERC bioenergy crop mapping project led by the University of Aberdeen to which Forest Research is contributing, covering short rotation coppice and short rotation forestry) could also usefully be explored.

Consideration of forestry options in estimating MACCs has focused primarily on woodland creation.

10. Fuller consideration should also be given to the cost-effectiveness of different forestry management approaches, including on the existing forest estate. These may include altering rotation lengths, adopting continuous cover forestry and using improved planting stock.

As we have seen, a range of underlying assumptions can influence cost-effectiveness estimates and the ranking of forestry options.

11. Where estimates are available, it is recommended that a complete set of carbon pools and GHG fluxes be covered, with changes compared to a baseline that takes account of emissions under the existing land use. Any wider effects expected to significantly influence the GHG balances of forestry options (e.g. associated with rising temperatures due to climate change) should also be accounted for where estimates are available.

12. Although care is needed in making inter-sector comparisons to avoid double counting the abatement accounted for in other sectors, consideration should be given to covering both carbon substitution and sequestration benefits when comparing the cost-effectiveness of different forestry options. Carbon storage in harvested wood products should also be accounted for where estimates are available.

13. For carbon substitution benefits, any expected changes over time (e.g. due to manufacture of concrete, steel or other wood substitutes becoming less carbon intensive, or use of improved planting stock) should ideally be taken into consideration. A decline in the carbon intensity of wood substitutes could reduce the cost-effectiveness of forestry measures involving substituting wood for more fossil fuel intensive materials, whereas use of improved planting stock may increase the cost-effectiveness of forestry measures.

14. Sensitivity analysis is recommended to determine how robust estimates are to altering underlying assumptions including climate change scenarios and, where substitution benefits are included, assumed end uses (e.g. domestic heating or electricity generation). To ensure replicability, assumptions need to be clearly stated, with references to underlying evidence and sources provided.

As noted at the end of section 2, agricultural opportunity costs have often implicitly been assumed to constitute the largest element of the cost of woodland creation measures. However, agricultural opportunity costs of converting farmland to woodland may be minimal in some cases. According to Defra's latest survey of UK agriculture, for example, almost a quarter of farms (22.1%) had a net farm income below zero (Defra *et al.*, 2010, Table 2.5, p.9). Were marginal or loss-making farms the ones subject to land use change, or marginal land within the farm used for woodland creation, landowner's opportunity costs associated with lost agricultural production might be expected to be around zero, or even negative. Similarly, from a societal perspective, opportunity costs may be zero or negative in many cases. Spencer et al (2008), for example, provide tentative estimates of positive and negative environmental impacts of UK agriculture, implying that total negative impacts in 2007 (£2600m) were more than double total positive impacts (£1200m). Their estimates suggest a net negative environmental impact of the order of -£75/ha. This might be added to an estimate of the social value of agricultural production itself. For example, subtracting total subsidies of £3013m in 2007 (£3196m in 2010) from total income from farming of

£2886m in 2007 (£4337m in 2010) implies an agricultural profit net of subsidies of -£7/ha in 2007 (£62/ha in 2010).

15. Future studies of the cost-effectiveness of woodland creation options should justify their approach to agricultural opportunity costs, whether focusing upon landowner's opportunity costs (e.g. total farm income or a proxy such as gross or net margins), or social opportunity costs (excluding subsidies and accounting for wider environmental impacts). Where estimates are available, sensitivity analysis for agricultural opportunity cost assumptions should take variations in opportunity costs between and within farms into account.

16. Any estimated land value impacts used should account for loss of option value due to replanting requirements after felling that preclude subsequent land use change, while avoiding double-counting capitalised values of agricultural opportunity costs (or other elements). To quantify impacts of woodland planting on land values and tease out relationships with farm returns, including the extent to which impacts differ for farms that are currently loss-making, new research may need to be commissioned. Adjusting land value impact estimates to ensure capitalised values are consistent with time horizons used in estimating the cost-effectiveness of forestry measures may also be required.

The inclusion of other ecosystem service benefits apart from carbon could be expected to significantly affect the ranking of forestry measures. Neglect of these wider benefits in estimating the cost-effectiveness of forestry measures is likely to lead to comparisons being misleading.

17. It is strongly recommended that other ecosystem service benefits apart from carbon (and also any disbenefits) are included in estimating the cost-effectiveness of forestry measures where associated marginal value estimates exist. This is in line both with current government guidance on estimating cost-effectiveness in appraisal and evaluation and with moves across government towards adopting an ecosystem services framework (DECC and HM Treasury, 2010, p. 19).

18. Where only non-monetary estimates for other ecosystem service benefits are available, it is recommended that these still be taken into account in comparing different forestry options (e.g. using multi-criteria analysis).

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Appendix: Summaries of marginal abatement cost curves studies

The approach adopted in each of the three primary studies estimating MACCs explicitly covering UK woodland creation measures is summarised separately below in chronological order.

Study 1

Market mechanisms for reducing GHG emissions from agriculture, forestry and land management

The 'indicative' MACC estimated in this study draws upon values based upon a literature review and expert judgement. Radov *et al.* (2007, Fig. 8.1, p. 93) suggest that afforestation options can be divided roughly evenly between 'low cost' (~£20 per tCO_2e) and 'high cost' (~£40 per tCO_2e) afforestation (compared to a central social cost of carbon of ~£25 per tCO_2e). Varying over time, these are estimated to offer a total potential additional abatement of 0.77 $MtCO_2e$ in 2020 (Radov *et al.*, 2007, Table ES-5, p. vi). The latter estimate is based upon assuming an additional 6000 ha of woodland is planted each year until 2020 above the planting rate of 8000 ha of woodland in 2006 (Radov *et al.*, 2007, p. 37). The species planted and yields assumed are not specified, although incentives required specifically for landowners to convert lowland agricultural land to oak woodland, and low value acid grassland to Sitka spruce plantation are considered. These suggest an annual payment to the landowner of between £10 and £50 per tCO_2 may be needed in order to encourage woodland creation. The level required is sensitive to factors including the tree species planted, rate of sequestration, rotation length, category of land, reduction in land value on conversion from woodland to agriculture, loss of agricultural subsidies and level of woodland establishment grants. (In the case of conversion of lowland agricultural land to oak woodland, a loss in land value of £7500 per ha is suggested, while for conversion of low value acid grassland to Sitka spruce plantation the loss is assumed to be a third of this.) The estimates assume a 7% discount rate and do not take into account expected future timber revenues. In the absence of up-front grant schemes, it is argued that a carbon price in excess of £100 per tCO_2 may be needed (Radov *et al.*, 2007, p. 38). The issue of ensuring carbon is permanently sequestered is noted (Radov *et al.*, 2007, p. 39), but does not appear to be explicitly addressed in deriving the estimates.

Study 2

Marginal Abatement Cost Curves for agriculture and land use, land-use change and forestry sectors out to 2022, with qualitative analysis of options to 2050

The abatement potential of forestry measures in developing a MACC are 'illustrative' (Moran *et al.*, 2008, p. 88) and based upon a coniferous afforestation scenario (with 49-year rotations), and altering the management of existing woodland by adopting shorter (49-year) rotations than assumed under the existing 'baseline' (59-year rotations). The shorter rotations are argued to be closer to the economic optimum than under the 'baseline' case. A focus on conifers is selected to be illustrative of technical potential, rather than due to the likelihood of widespread adoption, and subsequent replanting is assumed in each case.

Distinguishing abatement potentials from sequestration and substitution, Moran *et al.* (2008, p. 87) note that estimates of the latter are incomplete and associated savings may not accrue in the UK (e.g. if it results in imported wood being displaced, or if the wood is exported). It is further suggested that they may be lower than assumed if downstream costs associated with biomass use were incorporated, or resources shift from energy-intensive industries into other emitting activities. Although use of biomass instead of other fuels may be more costly, it is noted that distinguishing the additional costs is not straightforward if the carbon benefits are already reflected in existing incentive structures and the market price for woodfuel (Moran *et al.*, 2008, p. 11). In addition, non-market costs may arise where use of woodfuel results in increased emission of particulates.

The full technical potential (defined for a measure that has already been demonstrated as the upper limit on abatement associated with everyone who is able to implementing the measure irrespective of the cost) is estimated at 1.96 $MtCO_2e$ in 2022 for the afforestation scenario. This estimate is derived by subtracting Centre for Ecology and Hydrology (CEH) 'mid emissions scenario' baseline estimates of -6.79 $MtCO_2e$ that assume continuing 2005 planting rates of 8500 ha/year from CEH 'low emissions scenario' estimates of -8.75 $MtCO_2e$ that assume planting of 30 000 ha/year. (Confusingly, however, Moran *et al.*, 2008, Table 6.1, p. 92 switches the '30 kha/yr' label for woodland creation from the low to the high emissions scenario.) As the CEH estimates assume higher planting rates from 2006 while the Moran *et al.* (2008) estimates are based upon planting from 2009 onwards, it is assumed that the CEH estimates for 2019 apply to 2022. High, central and low feasible abatement potentials are estimated assuming 85, 50 and 10% adoption rates, respectively (Moran *et al.*, 2008, p. 93). The forests planted are assumed to comprise a mix equivalent to Sitka spruce yield class 16. (Sitka spruce currently accounts for around 50% of UK coniferous forests.) Average prices are taken from Forestry Commission data for conifer standing sales, with a 2.5% annual increase in real prices assumed. A £1250 planting cost is assumed, as is an annual £141 per ha opportunity cost of displacing sheep grazing on land with rough grazing potential (derived from the *Farm Management Handbook*: Beaton *et al.*, 2007). Both the afforestation and the forest management option are found to roughly break-even over their lifetimes (49 years and 100 years assumed, respectively), and hence imply a cost per tonne of carbon abated close to zero. The cost-effectiveness estimates range from -£7.12 per tCO_2e (afforestation/sequestration only) to £12.07 per tCO_2e (shorter rotation length/fossil fuel substitution) at 2006 prices (Moran *et al.*, 2008, Table 6.6, p. 97).

Nijnik *et al.* (2009) use a similar model of coniferous afforestation to Moran *et al.* (2008) to estimate the cost-effectiveness of increasing the rotation length of existing coniferous woodlands in order to maximise carbon sequestration. Cost-effectiveness is estimated as a function of the net present value of switching land from agriculture to woodland, where the NPV in forestry is calculated as (Nijnik *et al.*, 2009, p. 10):

$$NPV_{Forestry} = -C + pve^{-rT}$$

where *c* is the planting cost (£1250 is assumed as in Moran *et al.*, 2008), *p* is the price (taken from the average price for coniferous standing sales), *v* is the volume of timber, *r* the discount rate, *T* is a temporal variable, and (also as in Moran *et al.*, 2008) the assumed carbon sequestration rate is 3.6 tC/ha/year (for Sitka spruce YC16). At a 3.5% discount rate the NPV for a 49-year rotation is estimated as £733 per ha compared to that for a 59-year rotation of £358 per ha. (At a 7% discount rate both are negative at -£821 per ha and -£938 per ha, respectively.) If carbon sequestration benefits alone are focused on, the paper suggests that lengthening rotation length from 49 years to 59 years is cost-effective (involving costs of £10 per tC at a 3.5% discount rate and £3 per tC at a 7% discount rate), but this does not account for life-cycle analysis of the carbon substitution benefits of using wood products.

Study 3

Analysis of policy instruments for reducing greenhouse gas emissions from agriculture, forestry and land management – forestry options.

Cost-effectiveness is compared on the basis of the average annual changes in carbon calculated by dividing the cumulative carbon balance over 100 years by 100 (p. 15), implying no time preference for when carbon savings are achieved. Emissions, sequestration and emissions displacement are focused on, with three abatement measures considered: (i) no timber substitution benefits [SEQ+]; (ii) medium timber substitution benefits [SEQ++]; and (iii) high timber substitution benefits [SEQ+++]. No carbon savings associated with fossil fuel substitution benefits due to use of wood in electricity generation are assumed due to the sector being subject to a carbon cap and trade scheme and use of wood not expected to reduce the sector's overall emissions. (If wood were not used, the sector would have to find alternative ways of meeting its overall emissions target.) Instead these fossil fuel substitution benefits are valued using the DECC social values of carbon estimates for the traded sector (reflecting the cost of adopting alternative emission reduction measures within the EU ETS).

The cost of a forestry option is taken as the sum of establishment costs and the opportunity cost of land, minus any revenue from wood sales. Establishment costs are based upon Forestry Commission England standard cost models applying mainly to small areas (6 ha) planted under existing grant schemes, with lower costs assumed for coniferous planting (assumed to be larger areas). Without-fencing costs are used being considered more relevant to sites likely to be planted (p. 19). Opportunity costs are based upon average foregone net farm income adjusted for rent or rental value from the *Farm Management Handbook* (Beaton *et al.*, 2007), reduced by 25% to account for environmental and sporting advantages associated with woodlands and more marginal land being used (p. 22). For England, incomes from lowland cattle and sheep farms, mixed farms and general cropping farms are used. Comparable data are used for Scotland and Wales (p. 21). It is noted that opportunity costs of land may rise over time, especially where significant afforestation programmes are implemented, as reportedly has occurred with the National Forest in England (p. 22).

An equivalent annual cost (EAC) over one rotation is derived. This is calculated as the annuity equivalent at 3.5% of the present value of establishment and management costs plus the opportunity cost of land (p.14). A 100-year life is assumed where rotations are indefinite (on the assumption that cash flows beyond 100 years are beyond the planning horizon and have no present value). Estimates for the woodland creation options are shown in Table A1.

Table A1 Cost assumptions.

Option	Rotation length (years)	Establishment/ restocking cost (£/ha)		Establishment/ restocking cost (£/ha/year)	Agricultural income foregone (£/ha/year)	Equivalent annual cost (£/ha/year)
		With fencing	No fencing			
B1) SRF YC36 energy forests (*Eucalyptus nitens*)	8	4400	2600	378	350	728
B2) SRF YC20 energy forests (*Eucalyptus nitens*)	8	4400	2600	378	260	638
C) YC6 broadleaf farm woodland creation	80	6700	5400	202	350	552
D1) YC4 native woodland broadleaves	100	5370	4070	147	260	407
D2) YC4 native woodland Scots pine	50	3580	2600	111	50	161
E) YC16 SS/DF	50	3580	2600	111	260	371
F) Mixed YC6 oak/ash (50%)/YC 14 DF/larch (50%) continuous cover	80	4400	3500	131	190	321
G) YC12 SS/DF	50	3580	2600	111	160	271
H) YC12 SS managed on a continuous cover basis	100	3580	2600	94	160	254
I) YC12 SS/DF managed on a continuous cover basis	100	3580	2600	94	160	254
J) SRC YC20 willow	25	1310	1310	79	260	339
K) SRF YC12 native species sycamore, ash, birch (SAB)	15	5370	4070	353	260	613
L) SRF YC16 energy forests (*Eucalyptus nitens*)	12	3580	2600	269	260	529

Note: DF – Douglas fir; SS – Sitka spruce; SRC – short rotation coppice; SRF – short rotation forestry; YC – yield class.

Revenues for carbon substitution in electricity generation are assumed to be based upon central price estimates for EUAs increasing from £21 per tCO_2e in 2009 to £200 per tCO_2e in 2050. For timber, softwood revenues are based upon softwood prices for standing timber shown in Table A2 and are assumed to increase in real terms at 2% pa (p. 26).

Given the fragmentary data on hardwood prices (no equivalent price/size data are available, softwood prices were used, but with a lower limit of £5 per m^3 and upper limit of £18.9 per m^3 on the basis that chip prices from hardwood are likely to be similar to those from softwood (p. 27). A price of £3 per tonne was assumed for short rotation coppice. Standing crop prices for wood for chipping reportedly range from £0 to £4 per tonne at present (p. 27).

An equivalent annual revenue (EAR) over 100 years is derived. This is calculated as the annuity equivalent at 3.5% of the present value of the revenue stream over 100 years (p. 14). This is subtracted from the EAC to give the net cost per year.

Cost-effectiveness (in £/tCO_2e/year) is calculated on a per hectare basis as the net cost per year divided by the abatement achieved on average per year over 100 years (p. 27). Estimates for the options focused upon are summarised in Table A3.

Similarly focusing upon estimates including medium timber substitution benefits [SEQ++], options are ranked in Table A4 in terms of cost-effectiveness.

MACCs for England are developed for 2022 and 2050 by listing five options (B1, B2, C, D1, E) in order of their cost-effectiveness with abatement potentials at these respective dates summed using results for the Seq++ assumptions and reference soils. Options that produced negative abatement in 2050 or had a cost exceeding £100 per tCO_2e abated were excluded (p. 41). The estimates are shown in Table A5 and imply that the total abatement is 0.68 $MtCO_2e$ in 2022 from 149 500 ha and by 2050 has increased to 5.87 $MtCO_2e$ from 471 500 ha (5.3% of the agricultural area in England, excluding existing woodland and 'other land'). The results show short rotation forestry crops deliver short-term reductions in net emissions but mainstream forestry options deliver low or negative abatement in the short-term and have to be regarded as much longer term options (p. 41).

Table A2 Standing coniferous timber prices 2007–08.

Average volume per tree (m^3)	GB average price (£/m^3)
Up to 0.074	3.86
0.124	4.64
0.174	7.39
0.224	9.22
0.274	12.31
0.424	12.59
0.490	12.23
0.599	12.87
0.699	13.57
0.799	14.23
0.899	22.36
0.999	20.26
1.000 and over	21.58

Table A3 Summary of the cost-effectiveness, and abatement potential in 2030.

Option	Abatement (tCO_2e/ha/ year)[1]	Revenue (£/ha/ year)	Cost (£/ha/ year)	Cost-effectiveness (£/tCO_2e) (Seq++)[1]	Abatement in 2030 ('000 tCO_2e) (Seq++)
B1) SRF YC36 energy forests (*Eucalyptus nitens*)	15.1 (13.2–20.1)	1557.9	640.7	-60.8	467
B2) SRF YC20 energy forests (*Eucalyptus nitens*)	9.5 (6.7–13.6)	865.5	573.2	-30.6	145
C) YC6 broadleaf farm woodland creation	5.2 (3.7–7.5)	87.9	464.4	72.7 (50.0–102.4)	437
D1) YC4 native woodland broadleaves	8.4 (5.6–12.5)	0.0	342.2	40.7	536
D2) YC4 native woodland Scots pine	7.0 (4.2–11.1)	0.0	148.3	21.1	Not applicable (negative abatement)
E) YC16 SS/DF	12.9 (9.2–18.7)	454.6	230.8	-17.3 (-24.2 – -12.0)	626
F) Mixed YC6 oak/ash (50%)/YC 14 DF/larch (50%) – continuous cover	7.9 (5.9–9.3)	184.7	273.3	11.2 (9.6–15.0)	234
G) YC12 SS/DF	9.1 (6.2–13.6)	318.5	230.8	-9.6 (-6.5 – -14.1)	181
H) YC12 SS managed on a continuous cover basis	9.7 (6.2–14.9)	322.3	214.0	-11.2 (-17.6 – -7.2)	107
I) YC12 SS/DF managed on a continuous cover basis	9.1 (5.8–14.0)	273.6	230.8	-4.7 (-7.4 – -3.1)	169
J) SRC YC20 willow	3.7 (3.7–10.6)	459.2	274.5	-50.3	79
K) SRF YC12 native species (SAB)	4.5 (4.5–11.4)	393.9	548.4	34.3	59
L) SRF YC16 energy forests (*Eucalyptus nitens*)	8.4 (8.4–15.3)	846.4	464.1	-45.3	219

1 The initial figure refers to the Seq++ estimate. Where a range is given, this covers Seq+ and Seq+++. Other abbreviations are as in Table A1.

Table A4 Ranking of options in terms of cost-effectiveness.

Option	Cost-effectiveness (£/tCO^2e) (Seq++)	Cost-effectiveness (£/tCO^2e) (Seq++) excluding traded carbon value	Abatement (tCO^2e/ha/year) (Seq++)
B1) SRF YC36 energy forests (Eucalyptus nitens)	-60.8	24.8	15.1
J) SRC YC20 willow	-50.3	58.6	3.7
L) SRF YC16 energy forests (Eucalyptus nitens)	-45.3	41.3	8.4
B2) SRF YC20 energy forests (Eucalyptus nitens)	-30.6	44.6	9.5
E) YC16 SS/DF	-17.3	-2.8	12.9
H) YC12 SS managed on a continuous cover basis	-11.2	-0.1	9.7
G) YC12 SS/DF	-9.6	5.3	9.1
I) YC12 SS/DF managed on a continuous cover basis	-4.7	8.1	9.1
F) Mixed YC6 oak/ash (50%)/YC 14 DF/Larch (50%) – continuous cover	11.2	25.9	7.9
D2) YC4 native woodland Scots pine	21.1	21.1	7.0
K) SRF YC12 native species (SAB)	34.3	114.6	4.5
D1) YC4 native woodland broadleaves	40.7	40.7	8.4
C) YC6 broadleaf farm woodland creation	72.7	75.8	5.2

Note: Negative cost-effectiveness estimates must be interpreted carefully. When a NPV excluding carbon sequestration benefits is positive, a reduction in sequestration results in a more negative cost-effectiveness estimate. Abbreviations as in Table A1.

Table A5 MACC Cost-effectiveness and abatement potential.

Option	Cost-effectiveness (£/tCO^2e)	2022		2050	
		Cumulative area ('000 ha)	Abatement in the year ('000 tCO^2e)	Cumulative area ('000 ha)	Abatement in the year ('000 tCO^2e)
B1) SRF YC36 energy forests (*Eucalyptus nitens*)	-60.8	13.0	350	41.0	619
B2) SRF YC20 energy forests (*Eucalyptus nitens*)	-30.6	19.5	452	61.5	822
E) YC16 SS/DF	-17.3	52.0	700	164.0	2431
D1) YC4 native woodland broadleaves	40.7	100.8	722	317.8	4238
C) YC6 broadleaf farm woodland creation	72.7	149.5	680	471.5	5878

Abbreviations as in Table A1.

Comparing the cost-effectiveness of different climate change mitigation measures is essential in minimising the cost of meeting national greenhouse gas reduction targets. The costs of different measures and their potential to reduce emissions or sequester greenhouse gases can be depicted using a Marginal Abatement Cost Curve. Previous studies have shown that UK forestry measures are generally highly cost-effective by comparison with government estimates of the social value of carbon used in policy appraisal. However, estimates are sensitive to a range of factors including the species planted, forest management regime, environmental conditions, co-benefits and methodology adopted. This review provides a comparison of previous approaches and underlying assumptions, and summarises the current approach to cost-effectiveness analysis for policy appraisal and evaluation recommended in government guidance. It also provides recommendations for future studies.

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