

## SECTION 3

# MITIGATION

**Chapter 6** - Mitigation potential of sustainably managed forests

**Chapter 7** - Potential of forest products and substitution for fossil fuels to contribute to mitigation

**Chapter 8** - The potential of UK forestry to contribute to government's emissions reduction commitments



# MITIGATION POTENTIAL OF SUSTAINABLY MANAGED FORESTS

W. L. Mason, B. C. Nicoll, M. Perks

## Key Findings

Chapter

# 6

Many areas of British conifer forests will be due for felling in the next 10–20 years, which represents a major opportunity for adapting forests to future climate. Greater use of more southerly provenances is possible for all the major conifers so reducing their vulnerability to climate change. Managers should use a mix of forest management alternatives to obtain the best out-turn in terms of climate change mitigation and adaptation. Intimate species mixtures are only likely to be viable in broadleaved woods and mosaic mixtures should be preferred elsewhere.

Current policies seeking to diversify plantation forests through changes in species and structure may cause a decline in carbon sequestration unless this is offset by the use of more productive genotypes. When planning future planting programmes, greater emphasis should be given to species carbon content, and to their rates of carbon sequestration.

Forest planning and management must take uncertainty and risk into account. Current policies are resulting in more stands being retained for longer which will increase the risk of windthrow and disturbance to forest and soil carbon stocks. Stands which are currently marginal because of soil moisture requirement are likely to prove vulnerable to climate change adding to the threat from established and new pests and pathogens. Improved methods of forest planning are needed that take uncertainty into account, increase the resilience of British forests to climate change and enhance their role in carbon sequestration. These methods will need to be supported by appropriate training.

Mitigation involves all actions that help reduce net emissions of greenhouse gases or otherwise stabilise their concentration in the atmosphere. These actions include maintaining and enhancing long-term carbon stocks in trees, woodlands and forests and the use of woodfuel from sustainably managed forests as a substitute for fossil fuels. These represent additional management objectives for forestry and introduce the need to review those forest practices that may detract from the carbon storage by forests.

Mitigation will also involve an examination of energy use, particularly in timber transport. Adaptation of forests and forestry is examined in Section 4, but it is important to acknowledge that the two are closely linked: the mitigation contribution of forests and forestry in the future will depend on how well they are adapted to changing climate.

The potential role of sustainable forest management in combating change is clear (see Chapter 11). At a European level, a major means by which forestry can mitigate climate change is through alteration in

management practices to increase the carbon density (i.e. the tonnes of carbon per ha) of forests (Nabuurs *et al.*, 2007: Table 9.3). However, the potential for enhancement of carbon sinks within British forests is influenced by stand development phase, the approach to forest management, soil type, other site factors, species and provenance choice. Therefore, the subsections which follow describe the relative impact of each of these variables on forest carbon in the UK, and the interaction with afforestation, reforestation, machine operation and engineering. Future research needs are identified which will improve our



understanding of sustainable forest management in relation to climate change mitigation.

## 6.1 Stand development phases

The benefits provided by forests vary with tree age and forest structure. Wood yields are usually maximised in stands of regularly-spaced stems of similar size, perhaps 15–20 m tall, which can be efficiently harvested by modern machinery. By contrast, public preference is for tall, large trees, and varied spacing with multilayered canopies (Ribe, 1989; Lee, 2001). Certain animal and plant species prefer the open habitat that occurs after the felling of one generation of trees and which lasts until the young regenerating trees have closed canopy. This succession from open conditions to a closed canopy and then the gradual break-up to a more open stand structure lasts at least a century in most British forests. In carbon budget terms, this amounts to a stand moving from being a carbon source (due to stand and soil disturbance during harvesting and ground preparation), to a sink during tree regrowth, and then progressively to being a growing carbon store with a reduced sink strength (see Chapter 3).

This succession can be described using the four phases of stand development that form the basis of a widely-used model of temperate forest stand dynamics (Oliver and Larson, 1996). The first phase ('stand initiation') covers the period when trees are establishing on a site and have not formed a canopy so that grasses, herbaceous plants, and other vegetation are still present. In the subsequent 'stem exclusion' phase, the trees have formed a continuous canopy and compete with each other for light, moisture and nutrients. Ground vegetation only persists if the canopy trees allow sufficient light to penetrate to the forest floor. In the third phase ('understorey reinitiation'), the canopy starts to open up as a result of competition ('self-thinning') and other processes. Light transmittance through the stand canopy increases, and tree saplings and woody shrubs can colonise and develop in the understorey. Stands in the last phase ('old growth') are characterised by the presence of big old trees, substantial canopy gaps, groups of saplings that regenerated in the previous phase

now reaching the canopy, and appreciable numbers of standing dead mature trees.

Species composition and management practice affect the duration of each phase and this also affects the forest carbon cycle. Thus, planting of fast-growing species combined with effective weed control results in rapid dominance of the site by the planted trees and a quick return to a situation where the stand (including the soil) is a net carbon sink. By contrast, poor establishment practice can result in an extended stand initiation phase and a lengthy period where the stand is at best 'carbon neutral'. Stand initiation is the phase when managers can best change species or introduce a range of provenances to increase forest resilience to climate change. Management intervention in the subsequent phases is essentially a means of manipulating the developing carbon store (Millar *et al.*, 2007). Regular thinning of stands in the stem exclusion phase provides wood products to substitute for fossil fuels or to displace more energy intensive construction materials (see Chapter 7). Thinning also maintains the growth rate of the remaining trees for longer so that the period when the forest is sequestering carbon is extended.

Afforestation is best considered as a special case of the stand initiation phase which takes place on agricultural or other land far from suitable seed sources where planting is the most reliable way to develop forest conditions. Past management may also have depleted the soil nutrient reserves, particularly in the uplands, so that remedial fertiliser may be required to facilitate the start of the forest cycle. At the other end of the forest development cycle, old growth stands can revert to open ground if browsing pressure or vegetation change reduce regeneration success and result in the loss of the forest habitat.

Forests managed solely for wood production tend to have a high proportion of stands in the stand initiation and stem exclusion phases whereas those managed for multifunctional objectives (including timber) will tend to have representation across all phases. The estimated distribution of these phases in British forests in 2000 (Table 6.1) shows that they are currently dominated by fast-

**Table 6.1**

Area (thousand ha) of conifer and broadleaved high forest within Great Britain by four stand development phases and percentage distribution (brackets) in 2000 (adapted from Mason, 2007: Table 3).

Forest type	Stand initiation	Stem exclusion	Understorey reinitiation	Old growth
Conifers	219.5 (17)	1067.8 (77)	73.0 (5)	19.1 (1)
Broadleaves	57.9 (7)	269.6 (30)	376.9 (43)	176.3 (20)

growing conifer stands in the stem exclusion phase where carbon sequestration rates are highest. However, many of these stands will be due for felling in the next 10–20 years (Mason, 2007) which represents a major opportunity for directing forestry management towards addressing climate change issues. This will require assessment of the trade-offs between management of forests as carbon sinks vs management for other objectives such as recreation, biodiversity and timber (see Section 5).

## 6.2 Forest management alternatives and their implications for carbon budgets

Forest operations such as soil cultivation, weed control, thinning and timing and extent of felling, all result in spatial and temporal variations in forest carbon budgets. Forest management alternatives (FMAs) consist of a particular pattern of stand development supported by characteristic forest operational processes. FMAs can be defined by the general management objectives and a corresponding intensity of forest resource manipulation. Each FMA will have different carbon stocks and rates of sequestration (Table 6.3).

Duncker *et al.* (2008) identified five FMAs in Europe which, arranged in order of increasing intensity of wood biomass removal, are:

- Unmanaged forest nature reserve (FMA 1);
- Close-to-nature forestry (FMA 2);
- Combined objective forestry (FMA 3);
- Intensive even-aged forestry (FMA 4);
- Wood biomass production (FMA 5).

Features used to distinguish between these FMAs include: species composition, management of stand density and/or pattern, age pattern/phases of development, stand edges/boundaries, amount and intensity of timber and biomass removal, and site conditions. The amount of external energy used in operational processes also differs between management alternatives. The five FMAs encompass the three options for forest carbon management outlined by Broadmeadow and Matthews (2003). Thus, an unmanaged forest nature reserve is equivalent to ‘carbon reserve management’, where there is a gradual accumulation of carbon stocks primarily within deadwood and soils. Close-to-nature forestry is a ‘selective intervention carbon management’ approach

with the harvesting of high-quality timbers to replace more carbon intensive structural materials in housing (see Chapter 7). Combined objective forestry contains elements of both ‘selective intervention carbon management’ and ‘carbon substitution management’. The latter involves an emphasis on managing forests for products which reduce net fossil fuel consumption in the wider economy such as construction timbers, boards and paper. Intensive even-aged management and wood biomass production are FMAs which focus on carbon substitution.

The salient characteristics of each FMA are outlined below.

### 6.2.1 Unmanaged forest nature reserve

The main objective of an unmanaged forest nature reserve is to allow natural processes and disturbances (e.g. windthrow) to create natural, ecologically valuable habitats. It will tend to be dominated by stands in the old growth and understorey reinitiation phases. The trees continue to accumulate carbon as a multilayered canopy ensuring continued woody biomass growth after local disturbance (*cf.* Luyssaert *et al.*, 2008). FMA 1 represents a ‘saturated’ carbon stock with balanced above-ground fluxes but continued soil carbon accumulation. No operations are allowed in a forest reserve that might change the nature of the area. Examples in British forests include National Nature Reserves or long-term biological retentions. The soil disturbance after windthrow will result in some loss of carbon (see 6.3 below).

### 6.2.2 Close-to-nature forestry

The aim here is to manage a stand with the emulation of natural processes as a guiding principle. Financial return is important, but management interventions must enhance or conserve the ecological functions of the forest. Timber can be harvested and extracted, but some standing and fallen deadwood is left, which may reduce productivity. Only native or site adapted tree species are chosen. Natural regeneration is the preferred method of establishing new seedlings. The rotation length is generally much longer than the age of maximum mean annual volume increment (MMAI – see Glossary) and harvesting uses small-scale removals resulting in the development of an irregular and intimately mixed stand structure. The understorey reinitiation phase features prominently in FMA 2 and high long-term carbon stocks will result from this form of management. Stands in forests such as Glentress, Fernworthy and Clocaenog managed under a continuous cover forestry (CCF) or low impact silvicultural system (LISS), would fall within this FMA.

### 6.2.3 Combined objective forestry

In this FMA, management explicitly pursues a combination of economic (timber production) and non-market objectives. Mixtures of tree species are often promoted, comprising both native and introduced species suitable for the site. Natural regeneration is the preferred method of restocking, but planting is also widely used. Site cultivation and/or fertilisation may be carried out to speed up the development of a young stand. The rotation length is either similar to (in conifers) or longer than (broadleaves) the age of MMAI and the harvesting system is generally designed around small-scale clearfelling with groups of trees retained for longer periods to meet landscape and biodiversity objectives. Annual carbon sequestration benefits are lower than in other FMAs but this option provides a diverse species mix reducing risk. Characteristic stands are in the understorey re-initiation or late stem exclusion phase. Forest management aims to produce sawlogs as a primary timber product. Forests in areas of high landscape value such as the Trossachs, Snowdonia, and the Forest of Dean conform to FMA 3.

### 6.2.4 Intensive even-aged forestry

The main objective in intensive even-aged forestry is to produce timber, although landscape and biodiversity issues may feature as secondary objectives. Typical stands tend to be even-aged, in the stem exclusion phase, and composed of one or very few species. Any species can be suitable provided it is site adapted and non-invasive, and planting is the preferred method of regeneration. Intensive site management including cultivation and weed control is used to ensure rapid establishment. Genetically improved material is often planted where available. The rotation length is often less than or similar to the age of MMAI and clearfelling is normal practice. FMA 4 returns high annual sequestration for sites with medium-high productivity, while thinning strategy affects the total carbon budget. Stands in areas of high wind risk may not be thinned. In some cases, whole tree harvesting may occur but residues are normally left on site. This type of management is typical of many planted forests in Britain such as in Thetford, Kielder and Argyll.

### 6.2.5 Wood biomass production (or short rotation forestry or energy forestry)

The main objective is to produce the highest amount of small dimension wood biomass or fibre. Tree species selection depends mainly on the economic return, as long as the species is not invasive. Pure stands of

single species are generally favoured and intensive site management may occur to ensure rapid canopy closure. Stands cycle between stand initiation and stem exclusion with a short rotation period, i.e. from 5–25 years depending on species characteristics and the economic return. The intensity of harvesting is at its maximum compared with the other alternatives. The final felling is a clear-cut with removal of all woody residues, if there is a suitable market. This represents the most intensive version of 'carbon substitution' management and maximum carbon sequestration rates for highly productive sites (see Chapter 8). If managed like traditional coppice crops with only stem wood harvested, this alternative can also combine reasonable rates of carbon sequestration with careful management of soil carbon stocks. FMA 5 is currently rare in British forestry but examples include poplar and willow short rotation crops grown to produce biomass, sweet chestnut coppice in parts of lowland Britain, dense stands of naturally regenerated conifers which are cleared for wood fuel, and experimental trials of species such as eucalypts, birch and aspen for energy production.

### 6.2.6 Current distribution of FMAs

In Table 6.2 we estimate the current distribution of these FMAs across the UK forest resource. They indicate predominance of intensive even-aged forestry and, to a lesser extent, combined objective forestry which reflects the expansion of plantation forests in the UK during the last century. The estimates may not allow for the recent under-management of smaller private woodlands in parts of the UK so the proportion of the 'unmanaged' FMA may be higher than is suggested. An important point highlighted by this analysis is the need to obtain better data on the types of forest management being practised in the UK and their distribution.

There will be variation between FMAs both in terms of the carbon stocks retained in the trees and in the rates of sequestration that can be expected (Table 6.3). In general terms, the higher the carbon stock, the lower will be the rate of sequestration and vice versa. The prevalence of intensive even-aged forestry in the UK means that data for other forest management alternatives are limited. For example Patenaude *et al.* (2003) quote values of around 400 tCO<sub>2</sub>e ha<sup>-1</sup> in the carbon stocks of the tree and shrub component of a broadleaved semi-natural unmanaged nature reserve which is half the value predicted for a Sitka spruce stand on an equivalent regime (Morison *et al.*, 2009). The latter is extrapolated from models derived from intensive even-aged forestry and the estimated carbon

**Table 6.2**  
Estimated percentage distribution of UK forests by FMA in 2005 and possible changes by 2025 (see Notes for further detail).

Year	Forest management alternative				
	Unmanaged forest nature reserve (FMA 1)	Close to nature forestry (FMA 2)	Combined objective forestry (FMA 3)	Intensive even-aged forestry (FMA 4)	Wood biomass production (FMA 5)
2005	2.5	7	35	55	0.5
2025	5	15	50	25	5

**Notes:** 1. The prime data source for these estimates is the report on the State of Europe's Forests (MCPFE, 2007) with interpretation by the authors. 2. It is assumed that all single species stands are predominantly intensive even-aged forestry, and that 2–3 species stands indicate combined objective forestry, although some of the latter may represent close-to-nature forestry. 3. Unmanaged forest nature reserves are calculated as those forests falling into MCPFE classes 1.1 and 1.2 (i.e. 'no active intervention' and 'minimum intervention') plus an allowance for the areas of commercial forests set aside as non-intervention areas under the UKWAS protocols. 4. Close-to-nature forestry is taken as being equivalent to MCPFE class 1.3 (i.e. conservation through active management) but with some increase to allow for the increasing commitment to this type of management in Forestry Commission forests. This MCPFE class may contain a small area of nature reserves which are managed under coppice systems, but there is no easy way of identifying these separately. 5. Wood biomass production is thought to have been little practised in 2005. 6. The estimates for 2025 represent the authors' estimates of the impact of current policy trends.

**Table 6.3**  
Indicative estimates of whole tree carbon stocks (tCO<sub>2</sub>eq ha<sup>-1</sup>) and annual mid-rotation rates of carbon sequestration (tCO<sub>2</sub>eq ha<sup>-1</sup> year<sup>-1</sup>) that may apply to each FMA (values in parentheses are extrapolated from other measures – see Notes for further detail).

Forest management alternative	Forest management alternative				
	Unmanaged forest nature reserve (FMA 1)	Close-to-nature forestry (FMA 2)	Combined objective forestry (FMA 3)	Intensive even-aged forestry (FMA 4)	Wood biomass production (FMA 5)
Carbon stocks	800	500	(450)	400	(200)
Annual rates	6	(11)	(16)	22	29

**Notes:** 1. Principal data sources used are Morison *et al.* (2009: Table 3.1 and Figures 3.2–3.6) for carbon stocks, Jarvis and Linder (2007) and Luysaert *et al.* (2008) for rates. Values in brackets are extrapolations made by the authors. Sitka spruce is assumed as the species. 2. Extrapolations are based on the assumptions that: (a) carbon stocks in wood biomass production will be a function of the shorter rotation – half or less that of intensive even-aged forestry; (b) carbon stocks in combined-objective forestry are higher than intensive even-aged forestry because of a longer rotation, but the amount of increase is reduced because of likely admixture with less productive species; (c) similarly rates in close to nature and combined objective forestry are likely to be lower than for intensive even-aged forestry because of the greater age of the trees and the presence of less productive species mixtures.

stocks will vary with tree age and site productivity (e.g. Black *et al.*, 2009). The validation and refinement of such estimates is an urgent research requirement.

One consequence of recent forest policies in the UK is a shift in the balance of FMAs away from the dominance of intensive even-aged forestry, based on single species stands towards a greater representation of combined objective and close-to-nature forestry regimes (Table 6.2). While the diversification of species and stand structures that will result from this change is likely to increase the resilience of the forests to climate change, there is potentially a decline in carbon sequestration rates, unless this is offset by the use of more productive genotypes (see below) and/or extended afforestation programmes. Greater use of fast growing species on short rotations as part of wood biomass production may also help to maintain the current rate of carbon sequestration in British forests.

There are also abiotic risks associated with this change in the balance of FMAs, since all the less 'intensive' regimes will result in trees being retained for longer before harvesting, thereby increasing the risk of wind damage. This risk would be compounded by any deterioration in the wind climate, e.g. an increased frequency of major storms (Ray, 2008; Schelhaas *et al.*, 2003). This is of considerable concern as substantial areas of UK forests are sited on exposed sites and/or shallow rooting soils where the risks of wind damage are substantial (Quine *et al.*, 1995). Obtaining better understanding of the potential changes in wind climate and adapting existing wind risk models (e.g. ForestGALES; Gardiner *et al.*, 2000) to cope with more varied stand structures will help manage the risk across FMAs. Furthermore, increased winter rainfall could increase soil waterlogging and so reduce tree stability in stormy weather (Ray, 2008; see 5.1.5, Chapter 5).

It is unlikely that any single FMA can be considered as the optimum solution for adapting British forests to climate change and the FMAs should be considered as options to be used in combination depending upon site, management objectives, and species composition (Millar *et al.*, 2007). Guidance should be developed for forest managers, which will outline the interactions between FMA, wood utilisation, and forest carbon management (Matthews *et al.*, 2007). This guidance will require an improved understanding of the ways that management can affect the carbon contained in forest soils.

## 6.3 Carbon management and forest soils

### 6.3.1 Soil carbon stocks

Forest soils can contain more carbon than that retained within tree woody biomass, particularly in the case of peat-based soils common in the upland areas of the UK (Broadmeadow and Matthews, 2003; Janzen, 2004, see also Chapters 3 and 8). For instance, Greig (2008) estimated that the carbon stored in the soils of Kielder forest was 3.5–4.5 times that found in the above ground tree biomass. The stability of this store is of primary importance to climate change mitigation and therefore there is a need for an accurate inventory and monitoring programme.

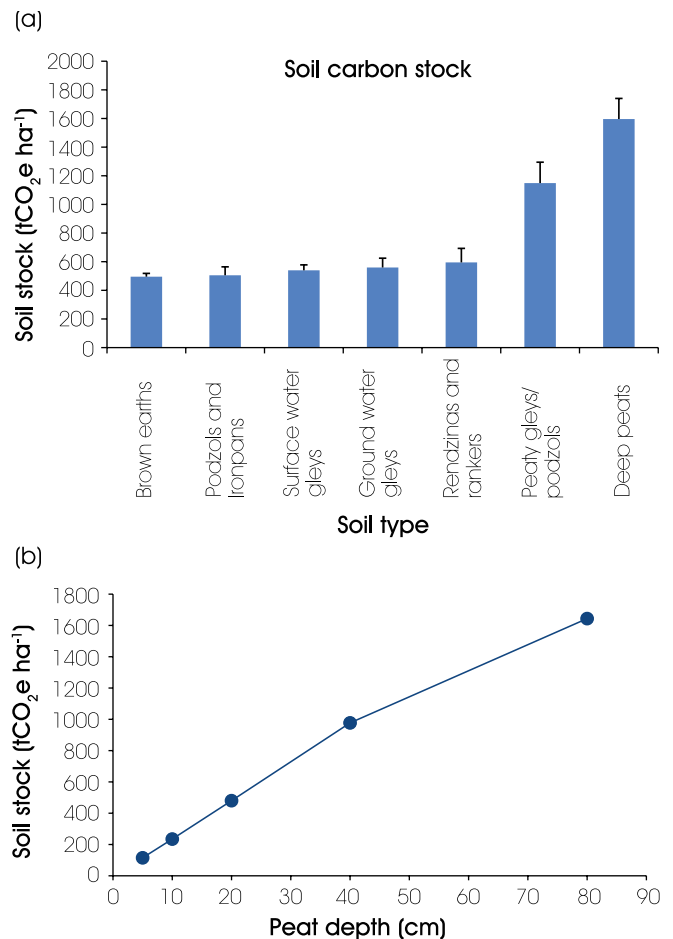
Estimates of carbon content in forest soils vary between 90 and 2500 tCO<sub>2</sub>e ha<sup>-1</sup>, depending on soil depth, soil density, site type and management (Morison *et al.*, 2009). Soils can essentially be split into non-organic (mineral) and organo-mineral/peaty soils (peaty-gleys, peaty podzols and deep peats). Organo-mineral soils have been reported to contain between 235 and 418 tCO<sub>2</sub>e ha<sup>-1</sup> in the horizons between 5 and 20 cm depth. However the carbon stock can reach between 620–1400 tCO<sub>2</sub>e ha<sup>-1</sup> depending on the age of the stand and the depth of the organic horizon. In peat soils (i.e. peat layer depth >40 cm) up to 1000 tCO<sub>2</sub>e ha<sup>-1</sup> can be held in the peat of 0–40 cm depth (Morison *et al.*, 2009).

Measured soil carbon stocks for different soil and forest types from 167 forest plots across Great Britain in 2007 ranged between 400 and 1800 tCO<sub>2</sub>e ha<sup>-1</sup> (Figure 6.1; Vanguelova pers. comm.). Carbon content varied with soil depth, soil type, forest type and stand age. Carbon stocks across the different soil types decreased in the order: deep peats > peaty gleys > rendzinas and rankers > ground

water gleys > surface water gleys > podzols and ironpans > brown earths. The average carbon content across the non-organic soils was 539 tCO<sub>2</sub>e ha<sup>-1</sup> while on peaty soils and deep peats carbon stocks of 460–2000 tCO<sub>2</sub>e ha<sup>-1</sup> were found depending on peat layer depth. These stocks are in line with other measured carbon stocks for a range of forest soil types (Zerva and Mencuccini, 2005a; Zerva *et al.*, 2005, Carey *et al.*, 2008, Benham, 2008).

Figure 6.1

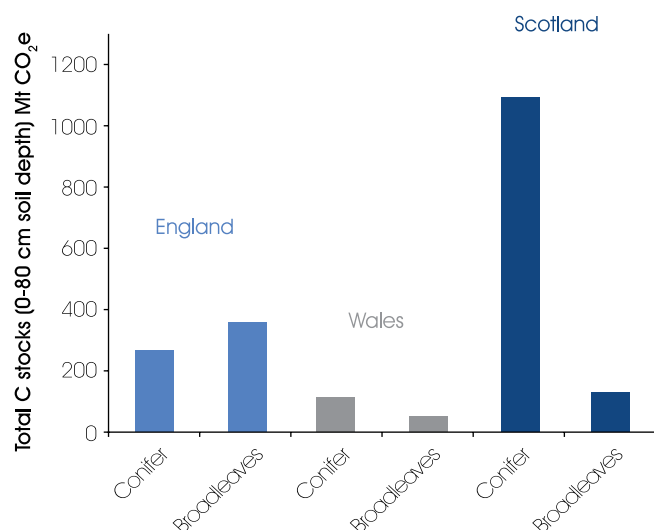
(a) Total soil carbon stocks (tCO<sub>2</sub>e ha<sup>-1</sup>, excluding litter) for each main soil group measured to a depth of 80 cm. Bars represent averages of total of 127 UK forest plots. Error bars represent the standard errors of the mean.  
(b) Soil carbon stocks (tCO<sub>2</sub>e ha<sup>-1</sup>) for deep peat soils are related to peat layer depth.



Scaling up these values for particular soil types across the forested areas of the UK (Figure 6.2) shows that forest soil carbon stocks were greater under conifers compared to broadleaves and highest in Scotland and lowest in Wales. Peaty gleys contributed most to the total carbon stock in Scotland, while brown earths and podzolic soils made the largest contribution in Wales and brown earths and surface water gley soils in England.



**Figure 6.2**  
Total carbon stocks (in CO<sub>2</sub> equivalents) in forest soils in England, Wales and Scotland for the two main forest types, estimated by up-scaling UK BioSoil results.



### 6.3.2 Impacts of disturbance on soil carbon

The effect of soil disturbance, whether due to anthropogenic (e.g. forest management activities) or climatic (e.g. catastrophic windthrow) causes, needs to be included in the calculations of forest carbon soil stocks. Site cultivation to provide a weed-free position for planting a young tree is a characteristic feature of establishment practice in British forestry, particularly in the uplands. However, the soil disturbance associated with this practice results in carbon losses, primarily through enhanced decomposition. The site will remain a net carbon source until uptake by growing biomass exceeds the soil losses which vary with the intensity of cultivation and soil type (Table 6.4 and Johnson, 1992).

There are few data on the potential contribution of soil disturbance on forest carbon balances. A study of root-soil plate volumes in an intensive even-aged (40-year-old) Sitka spruce forest in Scotland (Nicoll *et al.*, 2005) indicated that a volume of soil of 1882 m<sup>3</sup> ha<sup>-1</sup> would be disturbed if all trees were uprooted by windthrow. Stump harvesting operations will cause similar soil disturbance to windthrow, but current guidance on good practice for stump harvesting (Forest Research, 2009) recommends limiting disturbance to 60–70% of the site. Windthrow and stump harvesting would therefore be expected to result in around 750% and 450%, respectively of the soil disturbance from site preparation by excavator mounding reported by Worrell (1996). In Scandinavia, windthrow in the 2005 Gudrun storm resulted in a carbon sink reduction of around 3 million tonnes carbon, while the larger Lothar storm of 1999 may have resulted in losses of 16 million tonnes carbon (Lindroth *et al.*, 2009).

## 6.4 Consequences of woodland creation for soil carbon content

The current rate of afforestation in the UK is around 7500 ha per annum (see Chapter 1). If the objective of afforestation is to sequester the maximum quantity of carbon in the short term, the choice of species and site is paramount. Land-use change can result in dramatic changes in soil carbon stocks, with, for example, conversion of agricultural crop land to forest plantation having a positive effect and pasture to forest plantation having a negative effect on soil carbon (Guo and Gifford, 2002). Other reviews (Polglase *et al.*, 2000; Paul *et al.*, 2002) have found that changes in soil carbon after afforestation were generally limited in magnitude.

The major determinants of the extent of soil carbon change

**Table 6.4**  
The soil disturbance of site preparation treatments typical in upland UK forestry (after Worrell, 1996).

Treatment	Area affected (%)	Soil volume (m <sup>3</sup> ha <sup>-1</sup> )	
		Mean	Range
Ploughing	44–60	510	370–850
Mounding	26–35	250	170–340
Disc trench scarifying	20–32	170	110–280
Hand turfing	4–7	60	40–60
Hand screening	Negligible	Negligible	



under afforestation are soil type and previous land use. British studies have concentrated on peat soils where afforestation could cause significant initial carbon loss from the soil due to drainage and ploughing (see Chapter 3). This loss can be about 20–25% of the total carbon in the peat (Harrison *et al.*, 1997; Jones *et al.*, 2000). However, there are difficulties in these comparisons, particularly the assumption that soil carbon is in equilibrium prior to the disturbance. Hargreaves *et al.* (2003) measured fluxes on a deep peat site in Scotland following afforestation, and found the soil became a net source of carbon peaking with a flux of 14.6 tCO<sub>2</sub>e ha<sup>-1</sup> year<sup>-1</sup>, two years after planting. This net emission then fell to become a net sink of carbon with a maximum value of 7.3 tCO<sub>2</sub>e ha<sup>-1</sup> year<sup>-1</sup> occurring seven years after planting, before the size of the sink began to shrink. However, these data do not agree well with other studies of soils with lower carbon contents. An analysis of four upland UK afforestation sites by Reynolds (2007), coupled with modelling of biomass carbon accumulation showed that, despite a loss from the peat (soil) of 1.83 tCO<sub>2</sub>e ha<sup>-1</sup> year<sup>-1</sup>, the forest stand net ecosystem productivity (NEP, see Chapter 3 for definitions) was around 165 tCO<sub>2</sub>e ha<sup>-1</sup> over a 26-year period (6.3 tCO<sub>2</sub>e ha<sup>-1</sup> year<sup>-1</sup>). Zerva and Mencuccini (2005b), working on a peaty-gley site in northern England, found that the first 40-year rotation resulted in a decrease in soil carbon of 12.5 tCO<sub>2</sub>e ha<sup>-1</sup> year<sup>-1</sup>. They attributed this decline to accelerated decomposition caused by drainage and cultivation. Subsequently, in the second rotation there was a recovery of soil carbon (see Chapter 3). However, the estimates from these studies have a large degree of variation associated with them (*cf.* Conen *et al.*, 2005).

By contrast, no studies have been published on the afforestation of mineral soils in the UK. On a mineral soil site afforested with Norway spruce in Denmark, Vesterdal *et al.* (2002) found that although in the top 5 cm of soil, carbon content increased over the first few years, the lower layers of soil lost carbon, leading to an overall loss of 0.73 tCO<sub>2</sub>e ha<sup>-1</sup> year<sup>-1</sup>. In Ireland, Black *et al.* (2009) report a mean annual increase in soil carbon content of 8.1–9.6 tCO<sub>2</sub>e ha<sup>-1</sup> year<sup>-1</sup> over the first 16 years of the rotation of high yield class (20–24 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup>) first rotation Sitka spruce stands established on surface water gley mineral soils. In Canada the attractiveness of afforestation for carbon sequestration was found to be highly sensitive to stand growth and yield (McKenney *et al.*, 2004). However, the impacts of afforestation on site carbon balance, specifically the effects of cultivation on soil carbon, are poorly defined and understood.

## 6.5 Species and provenance choice in British forests as affected by anticipated climate change

The choice of tree species that are planted and the resulting stand composition may have a major impact on the carbon sequestration capacity of the forest ecosystem (Hyvönen *et al.*, 2007). Broadmeadow *et al.* (2005) highlighted the need to select and use provenances and species that are more suited to the future climate, noting that sites which are currently marginal because of a species' soil moisture requirement are likely to prove problematic. Predictions of species response to climate change based on the Ecological Site Classification (ESC) decision support system (e.g. Broadmeadow and Ray, 2005; Ray, 2008) suggest that species suitability will change across Britain (see Section 2). For example, Corsican pine is anticipated to become more suitable across parts of southern and eastern England as a result of warmer temperatures, but this species is not currently recommended because of its susceptibility to red band needle blight (see Section 2). On drier sites in eastern Scotland, Sitka spruce will prove less well-adapted because of its sensitivity to summer drought, which raises questions concerning suitable replacement species. These predictions are based on average climate trends and do not allow for extreme events (e.g. the 2003 high temperatures in central Europe), which are more likely to influence species survival. The warming climate may permit the wider use of species that were previously not reliably cold-hardy within the British Isles. Examples include maritime pine and a range of other conifers, southern beeches, new poplar clones, various eucalypts and other broadleaved species. Information from existing trials suggests some of the species that might be suitable (Table 6.5) but systematic trials of potential new species are urgently needed to provide the knowledge base to underpin future planting programmes. However, it will not be possible to fully test some species because of the long lead times for forest development.

Choice of tree species should also reflect variation in carbon content between species as well the more traditional measures of volume increment found in current British yield tables (Edwards and Christie, 1981). Table 6.6 lists average carbon content of a number of major species used in Britain alongside the respective range of MMAI. The MMAIs quoted are for the valuable stemwood component and make no allowance for other components

Table 6.5

Potential species that might be considered in climate change adaptation strategies for production forestry in Britain.

Species for which there is existing UK-based knowledge of performance from operational trials/ forest gardens/arboreta	Species for which there is little or no UK trials data but expert knowledge suggests that they merit screening for UK potential
<b>Conifers</b>	
<i>Abies alba</i>	<i>Abies bornmuelleriana</i>
<i>Abies amabilis</i>	<i>Abies cephalonica</i>
<i>Abies nordmanniana</i>	<i>Pinus armandii</i>
<i>Cedrus atlantica</i>	<i>Pinus ayacahuite</i>
<i>Cedrus libani</i>	<i>Pinus brutia</i>
<i>Cryptomeria japonica</i>	<i>Pinus elliotii</i>
<i>Picea omorika</i>	<i>Pinus koraiensis</i>
<i>Picea orientalis</i>	<i>Pinus monticola</i>
<i>Pinus peuce</i>	<i>Pinus strobus</i>
<i>Pinus pinaster</i>	<i>Pinus taeda</i>
<i>Sequoia sempervirens</i>	<i>Pinus wallichiana</i>
<i>Thuja plicata</i>	<i>Pinus yunnanensis</i>
<b>Broadleaves</b>	
<i>Acer macrophyllum</i>	<i>Betula papyrifera</i>
<i>Acer saccharinum</i>	<i>Carya ovata</i>
<i>Alnus rubra</i>	<i>Eucalyptus</i> spp.
<i>Alnus viridens</i>	<i>Fagus orientalis</i>
<i>Eucalyptus gunnii</i>	<i>Fraxinus americana</i>
<i>Eucalyptus nitens</i>	<i>Fraxinus angustifolia</i>
<i>Juglans regia</i>	<i>Fraxinus pennsylvanica</i>
<i>Nothofagus obliqua</i>	<i>Juglans nigra</i>
<i>Nothofagus alpina</i> (syn. <i>N. procera</i> )	<i>Liriodendron tulipifera</i>
<i>Nothofagus pumilio</i>	<i>Quercus alba</i>
<i>Platanus</i> spp.	<i>Quercus frainetto</i>
<i>Populus</i> spp.	<i>Quercus pubescens</i>
	<i>Quercus pyrenaica</i>

such as branchwood and stumps. The carbon contents are derived from a limited number of samples and there may be variation due to growth rate or latitude as reported for Sitka spruce (Macdonald and Hubert, 2002). The ages of MMAI are more theoretical than practical, since many conifers are felled at younger and broadleaves at older ages than those cited below.

The figures in Table 6.6 suggest that greater emphasis should be given to species carbon content when planning future restocking programmes if carbon sequestration is the primary objective. For example, Sitka spruce stands growing at less than 12 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup> would be sequestering less carbon than Scots pine growing at 8 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup>, although the carbon stock in a given stand will

also depend upon the volume produced by each species. Similarly, the introduction of Douglas fir could increase the carbon density of upland spruce forests on higher yielding sites. In general the higher carbon content of most broadleaved species is offset by their much lower rate of growth, although in species with very long rotations (i.e. >100 years) such as oak, the carbon stocks averaged over time can be higher than in faster growing conifer stands (Vallet *et al.*, 2009). Increasing the growth rate of any given forest type will also increase the rate of carbon storage (Cannell and Milne, 1995), while the wider benefits of substitution should also be considered (see Chapter 7).

The afforestation programmes carried out in the last century, particularly in northern and western Britain,

Table 6.6

Timber carbon content ( $tCO_2e\ m^{-3}$ ), typical ranges of maximum mean annual volume increment (MMAI:  $m^3\ ha^{-1}\ year^{-1}$ ) and ages of MMAI for a range of conifers and broadleaves grown in Britain or which might be considered for planting under anticipated climate change (after Edwards and Christie, 1981; Lavers, 1983).

Conifers					Broadleaves				
Species	Scientific name	Carbon content	MMAI	Age	Species	Scientific name	Carbon content	MMAI	Age
Sitka spruce	<i>Picea sitchensis</i> (Bong.) Carr.	0.62	8–24	64–46	Oak	<i>Quercus robur</i> L., <i>Q. petraea</i> . (Matt.) Liebl.	1.12	4–8	90–68
Norway spruce	<i>Picea abies</i> L. Karst.	0.64	8–20	84–65	Birch	<i>Betula pendula</i> (Roth.), <i>B. pubescens</i> (Ehrh.)	1.10	4–12	49–40
Scots pine	<i>Pinus sylvestris</i> L.	0.84	6–12	82–69	Sweet chestnut	<i>Castanea sativa</i> Mill.	0.84	4–10	50–41
Corsican pine	<i>Pinus nigra</i> var. <i>maritima</i> (Ait.) Melville.	0.77	8–16	64–55	Ash	<i>Fraxinus excelsior</i> L.	1.10	4–12	49–40
Douglas fir	<i>Pseudotsuga menziesii</i> (Mirb.) Franco.	0.81	10–24	64–50	Beech	<i>Fagus sylvatica</i> L.	1.14	4–10	107–80
Japanese larch	<i>Larix kaempferii</i> (Lamb.) Carr.	0.81	6–14	56–41	Wild cherry	<i>Prunus avium</i> L.	1.03	4–12	50–40
European larch	<i>Larix decidua</i> Mill.	0.88	6–12	60–47	Hornbeam	<i>Carpinus betulus</i> L.	1.19	4–10	107–80
Hybrid larch	<i>Larix x eurolepis</i> Henry	0.74	6–14	56–41	Lime	<i>Tilia cordata</i> Mill., <i>T. platyphyllos</i> (Scop.)	0.92	4–10	50–41
Maritime pine	<i>Pinus pinaster</i> Ait.	0.79	6–14	71–54	Black poplar	<i>Populus nigra</i> L.	0.70	6–1	39–35
Grand fir	<i>Abies grandis</i> Lindl.	0.59	12–28	60–51	Rauli	<i>Nothofagus alpina</i> (Poep. and Endl.) Oerst.	0.77	8–18	45–35
European silver fir	<i>Abies alba</i> Mill.	0.73	12–22	73–64	Common alder	<i>Alnus glutinosa</i> L.	0.83	4–12	50–40

were largely based on a number of non-native conifers. Substantial knowledge has been accumulated on the site preferences of these species and the suitability of particular provenances for different regions of Britain (e.g. Samuel *et al.*, 2007 for Sitka spruce). For all the major conifers, greater use of more southerly provenances is possible (e.g. Oregon or Washington seed sources replacing Queen Charlotte Islands for Sitka spruce), and would be an effective means of adapting to predicted climate change. There may be a risk of unseasonal frosts affecting more southerly material, so careful matching of species and provenances to sites will be essential. The faster growth rates that will be obtained from more southerly provenances are likely to result in timber with lower density, at least in Sitka spruce (Macdonald and Hubert, 2002) and therefore in lower carbon content, with potential

implications for substitution. Tree improvement strategies can compensate for any decline in carbon content by selecting for higher wood density, as is possible in Sitka spruce (Moore *et al.*, 2009), but the benefits have yet to be fully explored.

By contrast, until recently, very limited work had been undertaken on provenance selection or other aspects of tree improvement for many native broadleaved species (Savill *et al.*, 2005). This situation is further complicated by the preference for using 'local' seed sources in many broadleaved woodlands (Hemery, 2008), since it is arguable that material from the near continent should be introduced (at least in southern Britain) to increase woodland resilience to climate change. Until recently, our ability to predict the likely impacts of climate change on species suitability,

growth rates and consequently carbon sequestration rates has been greater for introduced rather than native species (see recent work presented in Section 2).

A strategy that is often proposed to enhance the resilience of a stand or forest to climate change is increasing the use of species or even provenance mixtures (Broadmeadow and Ray, 2005). However, this requires that all species in a mixture to have compatible growth rates and are capable of growing to maturity without intensive intervention. While this may often be the case in broadleaved woodlands, experience of conifer-broadleaved mixtures shows that the former tend to out-compete and suppress the latter on most sites throughout upland Britain (Mason, 2006). In conifer forests, it is better to aim for small clumps of single species ('mosaic' mixtures) rather than to try and create stem by stem or line by line mixtures of species or provenances ('intimate' mixtures). Intimate mixtures are most likely to be successful where the site conditions are suboptimal for all the species being considered for planting; in all other situations mosaic mixtures are likely to prove more reliable.

## 6.6 Machine operations and carbon impacts

The majority of forestry operations during forest management in the UK are now mechanised, including road building and maintenance, site cultivation, and thinning and harvesting. Each has a cost in terms of primary energy use, and an associated release of GHG. In addition, each operation involves some soil disturbance and will consequentially lead to a release of GHG. For a given energy input, emission figures can be derived. Carbon emissions arising from the use of diesel fuel in forestry operations can be calculated (Defra, 2007). These are equivalent to 0.071 tC MWh<sup>-1</sup> and are used in calculating the fuel emission values in Table 6.8.

There has been very little investigation into fuel use and resultant GHG emissions of forestry operations in the UK. What information there is predominantly examines

carbon losses, and not production of other GHG. Here, we describe primary energy use and GHG release from each major machine operation, and then attempt to estimate soil carbon loss following each operation based on the volume of soil disturbed.

### 6.6.1 Road building and maintenance

Forest roads in the UK are essentially constructed as 'water bound macadam'. They are classed as 'Type A' for arterial roads that are in regular use, 'Type B' for infrequently used spur roads for access to stands, and 'Type C' for other purposes. Soil disturbance from road building may lead to accelerated loss of soil carbon through decomposition, especially from the higher carbon soils. The production of material for road building involves the release of substantial amounts of GHG from quarrying and preparation, not least of which is the release of N<sub>2</sub>O from use of explosives in a quarry. Road building operations also require heavy machinery that consumes fossil fuel in extracting, preparing, transporting and laying road stone. Forest roads can require around 10 000 tonnes of rock per km (Whittaker 2008, Dickerson pers. comm. 2009). Class A roads require frequent maintenance. There is occasionally a need for reconstruction or upgrading work, but a well-built forest road with a good 'sacrificial' surface layer that is maintained and replenished, should have a good economic life (Dickerson, 1996). Life cycle analysis of UK forest roads has been conducted and the data have been used to estimate UK figures presented in Table 6.7.

Modelling the impacts of erecting turbines on deep peat soils (Nayak *et al.*, 2008), along with forest civil engineering standards, allows calculation of the potential impact of floating road construction. For floating roads developed on a deep peat site the impact is estimated to be approximately 345 tCO<sub>2</sub>e km<sup>-1</sup> (assumed width 3.4 m, depth 0.5 m) for construction at afforestation.

### 6.6.2 Site cultivation

The use of machinery in site preparation will involve

**Table 6.7**  
Estimated Type A and B forest road lengths in UK forests, total primary energy use in their construction and maintenance and associated GHG emissions (CO<sub>2</sub> equivalent), based on a life cycle analysis (Whittaker *et al.*, 2008).

Estimated length of forest roads ('000 km)			Total annual primary energy use (000 GJ year <sup>-1</sup> )	Total GHG emissions (tCO <sub>2</sub> e year <sup>-1</sup> )
Type A forest road	Type B forest road	Total forest road length		
15.2	28.1	43.3	556.5	42 493



Table 6.8

UK operational fuel use figures for standard establishment and harvesting procedures (includes direct and indirect emissions).

Operation	Machinery	Average fuel emissions	Units
Establishment	Excavator	0.6550	tCO <sub>2</sub> e ha <sup>-1</sup>
	Scarifier	0.2382	tCO <sub>2</sub> e ha <sup>-1</sup>
Agricultural conversion	Agricultural plough	0.073	tCO <sub>2</sub> e ha <sup>-1</sup>
Thinning	Harvester	0.0046	tCO <sub>2</sub> e m <sup>-3</sup>
Felling	Harvester	0.0036	tCO <sub>2</sub> e m <sup>-3</sup>
	Forwarder	0.0027	tCO <sub>2</sub> e m <sup>-3</sup>
Stump extraction (70% removal)	Modified excavator	0.0470	tCO <sub>2</sub> e odt <sup>-1</sup>
	Forwarder	0.0186	tCO <sub>2</sub> e odt <sup>-1</sup>
	Shred	0.1240	tCO <sub>2</sub> e odt <sup>-1</sup>

tCO<sub>2</sub>e ha<sup>-1</sup> = tonnes of carbon dioxide equivalent per hectare; odt = oven-dry tonnes.

carbon emissions. The figures in Table 6.8 are based on a preliminary survey of UK contractors working in forest establishment. The figures are higher than those from other European studies. For site preparation in Finland, Karjalainen and Asikainen (1996) reported an average carbon cost of 0.35 tCO<sub>2</sub>e ha<sup>-1</sup> for fuel emissions in scarification, ditch clearing and remedial drainage. Similar figures were obtained in Sweden where standard site preparation practice had a carbon cost equating to ~0.6 tCO<sub>2</sub>e ha<sup>-1</sup> (Berg and Lindholm, 2005).

### 6.6.3 Thinning and harvesting

UK derived 'on-site' fuel use is calculated as full life cycle analysis (LCA) carbon equivalent costs of forest harvesting operations (Table 6.8). Note that while it is possible to estimate fuel-derived emissions for some operations (e.g. harvesting) as C or CO<sub>2</sub>e per timber volume, for other operations (e.g. woody biomass provision from stumps) the appropriate measure is CO<sub>2</sub>e emitted per oven-dry tonne (odt) harvested.

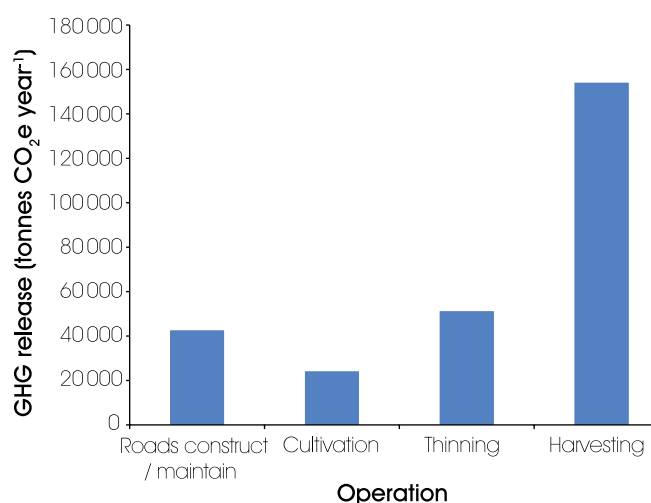
Similar figures have been derived by Greig (2008) for Kielder with calculated harvesting emissions (harvesters and forwarders combined) of 0.00599 tCO<sub>2</sub>e m<sup>-3</sup>. The most directly comparable data on forest operational emissions comes from Scandinavia where Berg and Lindholm (2005) calculated that harvesting caused emissions of 0.0044 tCO<sub>2</sub>e m<sup>-3</sup> and forwarding 0.0036 tCO<sub>2</sub>e m<sup>-3</sup>. Karjalainen and Asikainen (1996) performed a comprehensive assessment of the energy use and resultant GHG emissions in Finnish forestry. They calculated that harvesting caused emissions of 0.0039

tCO<sub>2</sub>e m<sup>-3</sup>, thinning 0.0082 tCO<sub>2</sub>e m<sup>-3</sup> and forwarding 0.0041 tCO<sub>2</sub>e m<sup>-3</sup>. These higher values relative to British estimates may reflect differences in stand structure and operational efficiency.

### 6.6.4 Overall emission estimates

We combined figures from the sections above to provide preliminary estimates of GHG emissions for road construction/maintenance, cultivation, thinning operations, and harvesting in British forests (Figure 6.3). These calculations are based on theoretical yields and management regimes for a Sitka spruce stand of average productivity. These were adjusted for each FMA by appropriate rotation lengths, operations, out-turns and estimated forest area covered by each FMA

Figure 6.3  
Estimated total annual GHG emissions (tCO<sub>2</sub>e year<sup>-1</sup>) from UK forest machine operations.

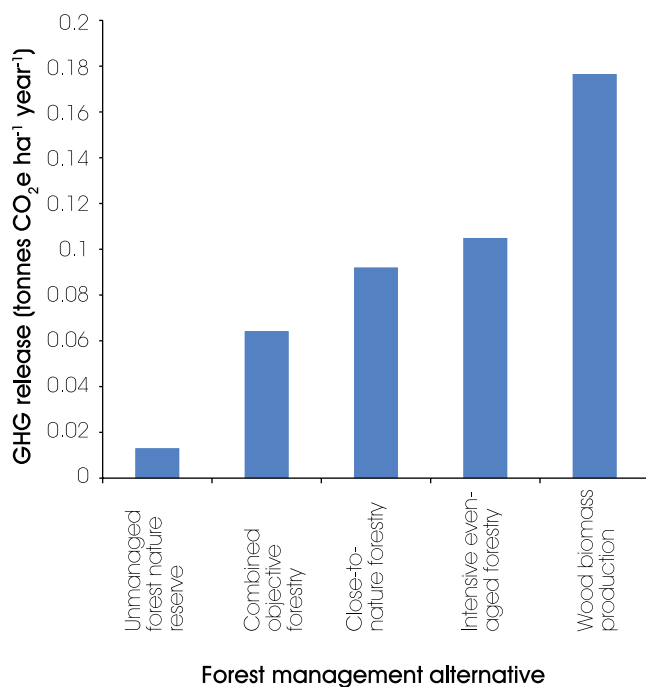


(Table 6.2). The figures do not include timber transport or GHG emissions following soil disturbance associated with these operations. Clearly, GHG emissions are considerably greater from harvesting than from any other forest operation and the total emission associated with forest machine operations in the UK is estimated to be 0.26 MtCO<sub>2</sub>e year<sup>-1</sup> or an overall average of 0.09 tCO<sub>2</sub>e ha<sup>-1</sup> year<sup>-1</sup>. Further work is needed to see how sensitive these results are to different policy scenarios, such as an increase in thinning to produce woodfuel.

The intensity of machine operations varies considerably between forest management alternatives and the yearly GHG emissions would be expected to increase with greater amounts of biomass removal as shown in Figure 6.4. This trend also reflects less use of site cultivation in FMAs which rely upon natural regeneration such as close-to-nature forestry.

A key finding from a recent analysis of the carbon budget for Kielder Forest (Greig, 2008) suggests that the annual carbon emission from all forest machine operations (e.g. harvesting, haulage, cultivation, roading) was around 0.21 tCO<sub>2</sub>e ha<sup>-1</sup>, or nearly 40 times less than the annual sequestration in the above ground tree biomass. The discrepancy between this and the UK average is in part explained by the exclusion of haulage from the UK figures.

**Figure 6.4**  
Estimated GHG emissions per hectare per year from each forest management alternative (FMA).



## 6.7 Incorporating mitigation strategies into forest management

The total UK forest carbon stock in trees is approximately 550 MtCO<sub>2</sub>e over 2.8 Mha with an average stock of approximately 200 tCO<sub>2</sub>e ha<sup>-1</sup>. This includes an allowance for open ground not in production and under-managed stands (Morison *et al.*, 2009). Average soil carbon stocks for woodland soils in the UK vary greatly with soil type (see above), but a UK average (including litter) is approximately 830 tCO<sub>2</sub>e ha<sup>-1</sup> (Morison *et al.*, 2009). Under current trends, the UK forest carbon stock will continue to increase (MCPFE 2007, Nabuurs *et al.*, 2008), while annual growth increment exceeds losses and removals. However, forest carbon sequestration over coming decades will vary, due primarily to the fluctuation in afforestation rates during the last century, and the rates of carbon uptake to UK forests are now declining (see 8.1.1, Chapter 8 and Figure 8.1).

British forest managers are now being challenged to integrate mitigation strategies into forest planning to increase the potential for forestry to sequester atmospheric CO<sub>2</sub> and reduce overall GHG emissions. Assessments of forest management mitigation strategies should also include carbon storage in products and carbon substitution effects (Lindner *et al.*, 2008, see Chapters 7 and 8). Sensitivity analyses of a model-based approach showed that parameters exhibiting the highest influence on carbon sequestration are carbon content, wood density and current annual increment of stems (Nabuurs *et al.*, 2008).

Emissions reduction in all phases of the management cycle need to be identified and quantified in order to maximise the contribution of sustainable forest management to national climate change mitigation strategies. For example, extending rotation length and therefore moving into the understorey reinitiation phase, and perhaps creating old-growth characteristics under a close-to-nature FMA, can diversify habitat structure (Kerr, 1999), while also helping to adapt forests to climate change and favouring long-term carbon sequestration (Liski *et al.*, 2001). The net carbon benefit of transition from even-aged Norway spruce to continuous cover management has been estimated at 1.65–2.75 tCO<sub>2</sub>e ha<sup>-1</sup> year<sup>-1</sup> (Seidl *et al.*, 2008). However, the application of this FMA in the UK is constrained by the risk of windthrow, which limits the number of sites where conditions permit the transformation of existing even-aged stands to more complex structures (Mason and Kerr, 2004). When carbon stocks are compared between

unmanaged and managed forest stands, unmanaged stands typically show higher stocks. However, these results generally exclude the effects of disturbance (Lindner *et al.*, 2008) and also do not take into account the full life cycle analysis including the GHG balance and the benefits of substituting forest products for fossil fuels and other materials. If the primary management objective is the maximisation of forest carbon sequestration rate, more intensive FMAs may be more favourable, as proposed for New Zealand (Turner *et al.*, 2008).

Shorter rotation lengths may decrease the risk of abiotic and biotic damage, while regular thinnings can maintain stand vigour and increase resilience by developing sturdier trees. In stands facing drought stress and reduced growth rates, thinning practices may be adapted to optimise water use and increase vitality and vigour of the remaining trees in the stand (Kellomäki *et al.*, 2005). In highly productive forest stands, altered management practices (e.g. different thinning intensities) may be needed to reflect the increased growth and yield of the forest ecosystem under future climate scenarios (Garcia-Gonzalo *et al.*, 2007). However, as yet few studies have analysed the effects of silvicultural strategies on carbon sequestration, timber production and other forest services and functions at the operational level of the forest management unit (Seidl *et al.*, 2007).

A modelling approach can be helpful to explore the impacts of different FMAs on forest ecosystem carbon balances. For example, the hybrid process-based tree growth model 3PGN<sup>1</sup> (Xenakis *et al.*, 2008) has been calibrated and independently validated using eddy covariance and biometric data from the UK for the

assessment of the carbon sequestration potential of Sitka spruce plantations (Minnuno, 2009). The model is based on tree eco-physiology, but with important statistical components included, such as allometric equations, which increase model robustness and calculate woody biomass (carbon) outputs at the stand level for even-aged forests and coupled carbon and nitrogen balances in the soil. It thus enables a complete ecosystem level analysis of biome fluxes such as NEP (net ecosystem productivity, see Chapter 3). When the model was applied to Sitka spruce under two FMAs and calibrated across soils of different productivity, it showed that carbon sequestration varied with site characters and management (Table 6.9).

The values obtained are similar to those reported elsewhere (see Chapter 3). A Sitka spruce stand of moderate productivity (YC 14, i.e. 14 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup>) on a peaty-gley soil produced a net carbon accumulation during the active growth phase of ca 27 tCO<sub>2</sub>e ha<sup>-1</sup> year<sup>-1</sup>. Total ecosystem carbon, which accounts for changes in both timber and soil carbon stocks suggests that wood biomass production (FMA 5) may achieve greater sequestration than intensive even-aged management (FMA 4) at the most productive (YC 20) site. The differences in total ecosystem carbon between FMA 4 and 5 at YC 20 on mineral soils are not great, but there are major and important differences within each FMA associated with yield class and soil type. However, timber product lifespan was not evaluated in this simulation.

The results illustrate how the series of FMAs can be used to compare the carbon impacts of different silvicultural strategies as part of adaptive forest

**Table 6.9**  
Modelled values of NPP, NEP and total ecosystem carbon uptake (tCO<sub>2</sub>e ha<sup>-1</sup> year<sup>-1</sup>) for Sitka spruce under 'intensive even-aged management' (FMA 4) and 'wood biomass production' (FMA 5) across sites of different productivity (yield class).

Forest management and site details					NPP		NEP		Total ecosystem carbon
FMA Number	Yield Class	Soil type	Thinning	Rotn. length	Number of rotation		Number of rotation		
					1	2	1	2	
4	10	Peat	1	50	37.5	37.5	12.9	8.4	0.53
4	14	Peaty-gley	1	50	47.0	47.0	23.8	16.6	6.55
4	20	Mineral	1	50	60.9	60.9	34.4	25.0	9.65
5	10	Peat	2	40	34.8	34.8	11.9	7.4	-2.79
5	14	Peaty-gley	2	40	44.0	44.0	23.1	16.0	6.32
5	20	Mineral	2	40	57.4	57.4	33.7	24.0	10.47

<sup>1</sup> 3PGN is composed of 3PG (Physiological Principles for Predicting Growth) model (Landsberg and Waring, 1997) and the ICBM/2N (Introductory Carbon Balance Model) model (Andrén and Kätterer, 1997).

management to meet the requirements of sustainable forest management. Evaluation of best choice management alternatives are, however, hampered by considerable uncertainty and difficulty in analysing net carbon balances (Cathcart and Delaney, 2006). The modelling of the forest carbon balance in different FMAs, involving the selection and combination of various treatments and practices to fit specific circumstances, will be most useful (Millar *et al.*, 2007; Pretzsch *et al.*, 2008). Furthermore, this approach recognises that strategies may vary based on the spatial and temporal scales of decision-making: planning at regional scales will often involve acceptance of different levels of uncertainty and risk than is appropriate at local scales (Saxon *et al.*, 2005).

An urgent need is to develop improved methods of forest planning that take climate change into account and which will help managers take actions to increase the resilience of British forests (Forestry Commission, 2009). For instance, the current guidance for Forestry Commission staff on forest design planning contains no reference to climate change. It is critical that this and other relevant operational guidance documents throughout the sector are revised to allow managers to consider how to adapt their silvicultural practices to a changing climate or alter management to maximise forest mitigation potential. This adjustment would comply with the aspirations of the revised UK Forestry Standard (UKFS, see 1.5.4, Chapter 1). The revised guidance needs to be coupled with site-based training that will help foresters identify areas that may be particularly at risk.

The knowledge base for such guidance would use the Ecological Site Classification (Pyatt *et al.*, 2001) approach to integrate species suitability and site characteristics, particularly soil moisture, and would be combined with predictions of climate change to derive a vulnerability ranking for stands and forests in different regions of the country. Stands with higher vulnerability would be those where remedial actions would be concentrated, involving either a change of species or of forest management alternative. Such a methodology would probably need to be developed using a case study approach to see how current knowledge about climate change could be linked to the GIS-based planning systems which underpin contemporary forest management in the UK. Designing, testing and monitoring a process of this type is probably the key to ensuring that forest management practices help adapt British forests to future climate change and maintain the carbon stocks that will help mitigate its impacts.

## 6.8 Research priorities

- Develop methodologies to help forest managers identify sites and stands most vulnerable to climate change;
- Trialling of species that may be suitable for the current and projected British climate.
- Provide more accurate data on the distribution of FMAs in the UK, develop the capability to model carbon impacts of FMAs and validate estimates in representative stands.
- Better understanding of rates of carbon sequestration and stocks in older stands that are retained for landscape or biodiversity reasons.
- Improve knowledge of the role of fast-growing species used in wood biomass production as a means of maintaining carbon sequestration rates in British forests.
- Improve predictions of changes in wind climate and adapt existing wind risk models to predict vulnerability of more varied stand structures.
- Better prediction of the potential impact of extreme climatic effects (storms, drought) upon British forests.
- Development of an accurate inventory and monitoring programme for forest soil carbon stocks.
- Understand the impact of disturbance (such as harvesting and windthrow) on soil carbon stocks.
- Obtain better understanding of forest soil and ecosystem fluxes of nitrogen in addition to greenhouse gases.
- Validation of models developed for intensive even-aged forestry when applied to other FMAs and/or provision of more flexible models.
- Quantification of the impacts of afforestation on site carbon balance, specifically the impact of cultivation on soil carbon.
- More investigation into fuel use and GHG emissions of forestry operations including the role of more traditional methods of extraction (e.g. horse logging).
- Select for tree progenies with higher wood (hence carbon) densities.

## References

- ANDRÉN, O. and KÄTTERER, T. (1997). ICBM: The introductory carbon balance model for exploration of soil carbon balance. *Ecological Applications* 7, 1226–1236.
- BENHAM, S. (2008). *The Environmental Change Network at Alice Holt Research Forest*. Forestry Commission Research Note 001. Forestry Commission, Edinburgh.
- BERG, S. and LINDHOLM, E.-L. (2005). Energy use and environmental impacts of forest operations in Sweden. *Journal of Cleaner Production* 13, 33–42.



- BLACK, K., BYRNE, K., MENCUCCINI, M., TOBIN, B., NIEUWENHUIS, M., REIDY, B., BOLGER, T., SAIZ, G., GREEN, C., FARRELL, E.D. and OSBORNE, B.A. (2009). Carbon stock and stock changes across a Sitka spruce chronosequence on surface water gley soils. *Forestry*. doi:10.1093/forestry/cpp005
- BROADMEADOW, M. and MATTHEWS, R. (2003). *Forests, carbon and climate change: the UK contribution*. Forestry Commission Information Note 48. Forestry Commission, Edinburgh.
- BROADMEADOW, M. and RAY, D. (2005). *Climate change and British woodland*. Forestry Commission Information Note 69. Forestry Commission, Edinburgh.
- BROADMEADOW, M.S.J., RAY, D. and SAMUEL, C.J.A. (2005). The future for broadleaved tree species in Britain. *Forestry* 78, 145–161.
- CANNELL, M.G.R. and MILNE, R. (1995). Carbon pools and sequestration in forest ecosystems in Britain. *Forestry* 68, 361–378.
- CAREY, P.D., WALLIS, S., CHAMBERLAIN, P.M., COOPER, A., EMMETT, B.A., MASKELL, L.C., MCCANN, T., MURPHY, J., NORTON, L.R., REYNOLDS, B., SCOTT, W.A., SIMPSON, I.C., SMART, S.M. and ULLYETT, J.M. (2008). *Countryside Survey: UK Results from 2007*. NERC/Centre for Ecology and Hydrology (CEH Project Number: C03259).
- CATHCART, J. and DELANEY, M. (2006). Carbon accounting: determining offsets from forest products. In: Cloughesy, M. (ed.) *Forests, carbon and climate change: a synthesis of science findings*. Oregon Forest Resources Institute, Portland, Oregon. pp. 157–176.
- CONEN, F., ZERVA, A., ARROUAYS, D., JOLIVET, C., JARVIS, P.G., GRACE, J. and MENCUCCINI, M. (2005). The carbon balance of forest soils: detectability of changes in soil carbon stocks in temperate and boreal forests. In: Griffiths, H. and Jarvis, P.G. (eds) *The carbon balance of forest biomes*. Taylor and Francis, Oxford. pp. 235–249.
- DEFRA. (2007). Guidelines to DEFRA's GHG conversion factors for company reporting. Online at: [www.defra.gov.uk/environment/business/enrp/conversion-factors.htm](http://www.defra.gov.uk/environment/business/enrp/conversion-factors.htm)
- DICKERSON, A. (1996). Resourcing civil engineering works in forestry. Unpublished thesis. Joint Board for Engineering Management.
- DUNCKER, P., SPIECKER, H. and TOJIC, K. (2008). *Definition of forest management alternatives*. Eforwood project PD 2.1.3. Online at: <http://87.192.2.62/eforwood/Home/tabid/36/Default.aspx>
- EDWARDS, P.N. and CHRISTIE, J.M. (1981). *Yield tables for forest management*. Forestry Commission Booklet 48. HMSO, London.
- FOREST RESEARCH. (2009). *Stump harvesting: Interim guidance on site selection and good practice*. Forest Research, Farnham. Online at: [www.forestresearch.gov.uk/stumpharvesting](http://www.forestresearch.gov.uk/stumpharvesting)
- FORESTRY COMMISSION. (2009). *Forests and climate change guidelines*. Consultation draft July 2009. Forestry Commission, Edinburgh.
- GARCIA-GONZALO, J., PELTOLA, H., BRICEÑO-ELIZONDO, E. and KELLOMÄKI, S. (2007). Changed thinning regimes may increase carbon stock under climate change: a case study from a Finnish boreal forest. *Climatic Change* 81, 431–454.
- GARDINER, B., PELTOLA, H. and KELLOMÄKI, S. (2000). Comparison of two models for predicting the critical wind speeds required to damage coniferous trees. *Ecological Modelling* 129, 1–23.
- GREIG, S. (2008). A carbon account for Kielder forest. *Scottish Forestry* 62 (3), 2–8.
- GUO, L.B. and GIFFORD, R.M. (2002). Soil carbon stocks and land use change: a meta analysis. *Global Change Biology* 8, 345–360.
- HARGREAVES, K.J., MILNE, R., and CANNELL, M.G.R. (2003). Carbon balance of afforested peatland in Scotland. *Forestry* 76, 299–317.
- HARRISON, A.F., JONES, H.E., HOWSON, G., GARNETT, J.S. and WOODS, C. (1997). *Long term changes in the carbon balance of afforested peatlands*. Final report to the Department of the Environment, Contract EPG1/1/3.
- HEMERY, G.E. (2008). Forest management and silvicultural responses to projected climate change impacts on European broadleaved trees and forests. *International Forestry Review* 10, 591–607.
- HYVÖNEN, R., ÅGREN, G.I., LINDER, S., PERSSON, T., COTRUFO, M.F., EKBLAD, A., FREEMAN, M., GRELE, A., JANSSENS, J., JARVIS, P.G., KELLOMÄKI, S., LINDROTH, A., LOUSTAU, D., LUNDMARK, T., NORBY, R.J., OREN, R., PILEGAARD, K., RYAN, M.G., SIGURDSSON, B.D., STRÖMGREN, M., VAN OIJEN, M. and WALLIN, G. (2007). The likely impact of elevated [CO<sub>2</sub>], nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: a literature review. *New Phytologist* 173, 463–480.
- JANZEN, H.H. (2004). Carbon cycling in earth systems – a soil science perspective. *Agriculture Ecosystems and Environment* 104, 399–417.
- JARVIS, P.G. and LINDER, S. (2007). Forests remove carbon dioxide from the atmosphere: spruce forest tales! In: Freer-Smith, P.H., Broadmeadow, M.S.J. and Lynch, J.M. (eds) *Forestry and climate change*. CABI, Wallingford. pp. 60–72.
- JOHNSON, D.W. (1992). Effects of forest management on soil carbon storage. *Water, Air and Soil Pollution* 64, 83–120.
- JONES, H.E., GARNETT, J.S., AINSWORTH, G. and

- HARRISON, A.F. (2000). Long-term changes in the carbon balance of afforested peat lands. Final Report. April. *Carbon sequestration in vegetation and soils report*. Section 4, part 1. Report to the Department of the Environment, Transport and the Regions. Centre for Ecology and Hydrology, Edinburgh. pp. 3–14.
- KARJALAINEN, T. and ASIKAINEN, A. (1996). Greenhouse gas emissions from the use of primary energy in forest operations and long-distance transportation of timber in Finland. *Forestry* **69**, 215–228.
- KELLOMÄKI, S., PELTOLA, H., BAUWENS, B., DEKKER, M., MOHREN, F., BADECK, F-W., GRACIA, C., SANCHEZ, A., PLA, E., SABATE, S., LINDNER, M. and PUSSINEN, A. (2005). European mitigation and adaptation potentials: Conclusions and recommendations. In: Kellomäki, S. and Leinonen, S. (eds) *Management of European forests under changing climatic conditions*. Research Notes 163. University of Joensuu, Finland. pp. 401–427
- KERR, G. (1999). The use of silvicultural systems to enhance the biological diversity of plantation forests in Britain. *Forestry* **72**, 191–205.
- LANDSBERG, J.J., WARING, R.H. (1997). A generalised model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *Forest Ecology and Management* **95**, 209–228.
- LAVERS, G.M. (1983). *The strength properties of timber*. 3rd edn. Building Research Establishment Report. HMSO, London.
- LEE, T.R. (2001). *Perceptions, attitudes and preferences in forests and woodland*. Forestry Commission Technical Paper 18. Forestry Commission, Edinburgh.
- LINDNER, M., GREEN, T. WOODALL, C.W.PERRY, C.H., NABUURS, G-J. and SANZ, M.J. (2008). Impacts of forest ecosystem management on greenhouse gas budgets. *Forest Ecology and Management* **256**, 191–193.
- LINDROTH, A., LAGERGREN, F., GRELE, A., KLEMEDTSSON, L., LANGVALL, O., WESLIEN, P. and TUULIK, J. (2009). Storms can cause Europe-wide reduction in forest carbon sink. *Global Change Biology* **15**, 346–355.
- LISKI, J., PUSSINEN, A., PINGOUD, K., MÄKIPÄÄ, R. and KARJALAINEN, T. (2001). Which rotation length is favourable to carbon sequestration? *Canadian Journal of Forest Research* **31**, 2004–2013.
- LUYSSAERT, S., SCHULZE, E-D., BORNER, A., KNOHL, A., HESSENMOLLER, D., LAW, B.E., CIAIS, P. and GRACE, J. (2008). Old growth forests as carbon sinks. *Nature* **455**, 213–215.
- MACDONALD, E. and HUBERT, J. (2002). A review of the effects of silviculture on timber quality of Sitka spruce. *Forestry* **75**, 107–138.
- MASON, W.L. (2006). *Managing mixed stands of conifers and broadleaves in upland forests in Britain*. Forestry Commission Information Note 83. Forestry Commission, Edinburgh.
- MASON, W.L. (2007). Changes in the management of British forests between 1945 and 2000 and possible future trends. *Ibis* **149** (Suppl. 2), 41–52.
- MASON, B. and KERR, G. (2004). *Transforming even-aged conifer stands to continuous cover management*. Forestry Commission Information Note 40. Forestry Commission, Edinburgh.
- MATTHEWS, R.W., ROBERTSON, K., MARLAND, G. and MARLAND, E. (2007). Carbon in wood products and product substitution. In: Freer-Smith, P.H., Broadmeadow, M.S.J. and Lynch, J.M. (eds) *Forestry and climate change*. CABI, Wallingford. pp. 91–104.
- MCKENNEY, D.W., YEMSHANOV, D., FOX, G. and RAMLAL, E. (2004). Cost estimates for carbon sequestration from fast growing poplar plantation in Canada. *Forest Policy and Economics* **6**, 345–358.
- MCPFE (2007). *State of Europe's forests 2007: the MCPFE report on sustainable forest management in Europe*. MCPFE/UNECE/FAO, Warsaw.
- MILLAR, C.I., STEPHENSON, N.L. and STEPHENS, N.L. (2007). Climate change and forests of the future: managing in the face of uncertainty. *Ecological Applications* **17**, 2145–2151.
- MINNUNO, F. (2009). *Parameterisation, validation and application of 3-PGN for Sitka spruce across Scotland: spatial predictions of forest carbon balance using a simplified process based model*. MSc Research, University of Edinburgh.
- MORISON, J., MATTHEWS, R., PERKS, M., RANDLE, T., VANGUELOVA, E., WHITE, M. and YAMULKI, S. (2009). *The carbon and GHG balance of UK forests: a review*. Forestry Commission, Edinburgh.
- MOORE, J.R., MOCHAN, S., BRÜCHERT, F., HAPCA, A.I., RIDLEY-ELLIS, D.J., GARDINER, B.A. and LEE, S.J. (2009). Effects of genetics on the wood properties of Sitka spruce growing in the United Kingdom. Part 1: Bending strength and stiffness of structural timber. *Forestry*. doi:10.1093/forestry/cpp018
- NABUURS, G.J., MASERA, O., ANDRASKO, K., BENITEZ-PONCE, P., BOER, R., DUTSCHKE, M., ELSIDDIG, E., FORD-ROBERTSON, J., FRUMHOFF, P., KARJALAINEN, T., KRANKINA, O., KURZ, W.A., MATSUMOTO, M., OYHANTCABAL, W., RAVINDRANATH, N.H., SANZ SANCHEZ, M.J. and ZHANG, X. (2007). Forestry. In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R. and Meyer L.A. (eds) *Climate change 2007: mitigation*. Contribution of Working Group III to the Fourth Assessment Report of the

- Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. pp. 541–584.
- NABUURS G.J., THURIG E., HEIDEMA N., ARMOLAITIS K., BIBER P., CIENCALA E., KAUFMANN E., MAKIPAA R., NISEN P., PETRISCH R., PRISTOVA T., ROCK J., SCHELHAAS M.J., SIEVANEN, SOMOGYI Z and VALLET P. (2008). Hotspots of the European forests carbon cycle. *Forest Ecology and Management* **256**, 194–200.
- NAYAK D.R., MILLER, D., NOLAN, A., SMITH, P. and SMITH, J. (2008). Calculating carbon savings from wind farms on Scottish peat lands – a new approach. *Final Report*. Rural and Environmental Research and Analysis Directorate of the Scottish Government. Online at: [www.scotland.gov.uk/Publications/2008/06/25114657/0](http://www.scotland.gov.uk/Publications/2008/06/25114657/0)
- NICOLL, B.C., ACHIM, A., MOCHAN, S. and GARDINER, B.A. (2005). Does steep terrain influence tree stability? A field investigation. *Canadian Journal of Forest Research* **35**, 2360–2367.
- OLIVER, C.D. and LARSON, B.R. (1996). *Forest stand dynamics*. McGraw-Hill, New York.
- PATENAUDE, G.L., BRIGGS, B.D.J., MILNE, R., ROWLAND, C.S., DAWSON, T.P. and PRYOR, S.N. (2003). The carbon pool in a British semi-natural woodland. *Forestry* **76**, 109–119.
- PAUL, K.I., POLGLASE, P.J., NYAKUENGAMA, J.G. and KHANNA, P.K. (2002). Change in soil carbon following afforestation. *Forest Ecology and Management* **154**, 395–407.
- POLGLASE, P.J., PAUL, K.I., KHANNA, P.K., NYAKUENGAMA, J.G., O'CONNELL, A.M., GROVE, T.S. and BATTAGLIA, M. (2000). *Change in soil carbon following afforestation or reforestation: review of experimental evidence and development of a conceptual framework*. National Carbon Accounting System Technical Report No. 20. Australian Greenhouse Office, Canberra, ACT, Australia.
- PRETZSCH, H., GROTE, R., REINEKING, B., RÖTZER, T.H. and SEIFERT, S.T. (2008). Models for forest ecosystem management: a European perspective. *Annals of Botany* **101**, 1065–1087.
- PYATT, D.G., RAY, D. and FLETCHER, J. (2001). *An ecological site classification for forestry in Great Britain*. Forestry Commission Bulletin 124. Forestry Commission, Edinburgh.
- QUINE, C.P., COUTTS, M.P., GARDINER, B.A. and PYATT, D.G. (1995). *Forests and wind: management to minimise damage*. Forestry Commission Bulletin 114. HMSO, London.
- RAY, D. (2008). *Impacts of climate change on forestry in Scotland – a synopsis of spatial modelling research*. Forestry Commission Research Note. Forestry Commission Scotland, Edinburgh.
- REYNOLDS, B. (2007). Implications of changing from grazed or semi-natural vegetation to forestry on carbon stores and fluxes in upland organo-mineral soils in the UK. *Hydrology and Earth System Sciences* **10**, 61–76.
- RIBE, R. G. (1989). The aesthetics of forestry – what has empirical preference research taught us. *Environmental Management* **13**, 55–74.
- SAMUEL, C.J.A., FLETCHER, A.M. and LINES R. (2007). *Choice of Sitka spruce origins for use in British forests*. Forestry Commission Bulletin 127. Forestry Commission, Edinburgh.
- SAVILL, P.S., FENNESSY, J. and SAMUEL, C.J.A. (2005). Approaches in Great Britain and Ireland to the genetic improvement of broadleaved trees. *Forestry* **78**, 163–174.
- SAXON, E., BAKER, B., HARGROVE, W., HOFFMAN, F. and ZGANJAR, C. (2005). Mapping environments at risk under different global climate change scenarios. *Ecology Letters* **8**, 53–60.
- SCHELHAAS, M.J., NABUURS, G.J. and SCHUCK, A. (2003). Natural disturbances in the European forests in the 19th and 20th centuries. *Global Change Biology* **9**, 1620–1633.
- SEIDL, R., RAMMER, W., JÄGER, D., CURRIE, W.S. and LEXER, M.J. (2007). Assessing trade-offs between carbon sequestration and timber production within a framework of multi-purpose forestry in Austria. *Forest Ecology and Management* **248**, 64–79.
- SEIDL, R., RAMMER, W., LASCH, P., BADECK, F-W and LEXER, M.J. (2008). Does conversion of even-aged, secondary coniferous forests affect carbon sequestration? A simulation under changing environmental conditions. *Silva Fennica* **42**, 369–386.
- TURNER, J.A., WEST, G. DUNGEY, H., WAKELIN, S., MACLAREN, P., ADAMS, T. and SILCOCK, P. (2008). *Managing New Zealand planted forests for carbon – a review of selected management scenarios and identification of knowledge gaps*. Ministry of Agriculture and Forestry, New Zealand.
- VALLET, P., MEREDIEU, C., SEYNAVE, I., BELOUARD, T. and DHOTE, J-F. (2009). Species substitution for carbon storage: sessile oak versus Corsican pine in France as a case study. *Forest Ecology and Management* **257**, 1314–1323.
- VESTERDAL, L., RITTER, E. and GUNDERSEN, P. (2002). Changes in soil organic carbon following afforestation of former arable land. *Forest Ecology and Management* **169**, 137–147.
- WHITTAKER, C., KILLER, D., ZYBERT, D. and RUSSEL, D. (2008). *Life cycle assessment of construction of forest roads*. (Spreadsheet tool). Imperial College, London.
- WORRELL, R. (1996). *The environmental impacts and effectiveness of different forestry ground preparation*

*practices*. Scottish National Heritage Research, Survey and Monitoring Report No 52. SNH, Battleby.

XENAKIS, G., RAY, D., MENCUCCINI, M. (2008). Sensitivity and uncertainty analysis from a coupled 3-PG and soil organic matter decomposition model. *Ecological Modelling* **219**, 1–16.

ZERVA, A., BALL, T., SMITH, K.A. and MENCUCCINI, M. (2005). Soil carbon dynamics in a Sitka spruce (*Picea sitchensis* (Bong.) Carr.) chronosequence on a peaty gley. *Forest Ecology and Management* **205**, 227–240.

ZERVA, A and MENCUCCINI, M. (2005a) Carbon stock changes in a peaty gley soil profile after afforestation with Sitka spruce (*Picea sitchensis*). *Annals of Forest Science* **62**, 873–880.

ZERVA, A. and MENCUCCINI, M. (2005b) Short-term effects of clearfelling on soil CO<sub>2</sub>, CH<sub>4</sub> and N<sub>2</sub>O fluxes in a Sitka spruce plantation. *Soil Biology and Biochemistry* **37**, 2025–2036.



## POTENTIAL OF FOREST PRODUCTS AND SUBSTITUTION FOR FOSSIL FUELS TO CONTRIBUTE TO MITIGATION

Chapter

7

E. Suttie, G. Taylor, K. Livesey and F. Tickell

### Key Findings

Climate change will fundamentally alter the world market for wood products and energy. Regulation, taxation and other mechanisms will alter the competitiveness of materials and products. Wood products and wood fuel have a significant role to play in substitution to reduce greenhouse gas (GHG) emissions in the UK.

If the wood construction products sector continues to grow as it has for the past 10 years there is potential to store an estimated additional 10 MtC in the UK's new and refurbished homes. Without legislation or incentive it may take 10 years to reach this additional stored amount as the construction sector is slow to change.

Wood fuel has the potential to save between 2 and 4 MtC per year by substituting for fossil fuel in the near future. A complex regulatory framework is currently in place to support the development of new bioenergy projects. More than 17 different incentive schemes were identified by the Biomass Task Force, and yet uptake is still limited. Action is required to ensure these incentives work together in an effective way.

The UK has a significant biomass resource, estimated at an annual 22 million oven-dried tonnes (Modt), although only a fraction of this is effectively captured for energy, currently contributing approximately 3–4% to heat and electricity production in the UK. In the short term, it could be useful for the UK to focus on developing a limited number of bioenergy chains. Biomass for heat provides one of the most cost-effective and environmentally sustainable ways to de-carbonise the UK economy. This should be linked to a joined-up policy and regulatory framework.

Public perception, understanding and acceptance of biotechnological routes to tree improvement may be a key challenge for the deployment of future energy forests. Technological advances may provide the step-change necessary for improved yields and to alter wood quality. Urgent engagement with the public is required to enable further development of this complex area.

Co-firing of power stations with biomass has, to date, largely relied on imports, but new regulations and modifications to the renewable obligation certificates (banded ROCs) will lead to demand for more dedicated energy crops and this may stimulate the UK energy forestry sector; both short rotation forestry and short rotation coppice. Research is required to enable selection of species and genotypes which are correctly adapted to future environments.

Substitution offers an attractive opportunity for tackling climate change by storing carbon in our buildings and reducing fossil fuel consumption. In contrast to alternative materials which release GHG in their production, wood products enable carbon to be stored in buildings. Failure to accept and adopt wood products arises in part from conservatism in the construction industry and outmoded attitudes that need to be robustly challenged.

Adaptation of the built environment to changes in climate will be critical to the future success of all building systems. By 2016, all new homes will need to be zero carbon rated and the UK has the target to cut emissions of CO<sub>2</sub> by 80% of 1990 emissions by 2050. This places huge technical demands on our buildings and the products used to make them. Legislation provides an opportunity to develop tailored wood-based products that will result in the necessary substitutions.

A harmonised approach for the measurement of GHG balances for construction systems, that provides genuine comparability and transparency for all materials would stimulate more use of wood products.

It is likely that the world and UK national markets for wood products and wood-derived energy as a component of bioenergy will be completely altered by the changing climate. Here we consider the opportunities for the UK forestry sector to contribute to tackling climate change by providing wood-derived fuels as alternatives to fossil fuels and wood products in place of other more GHG-intensive materials, most notably for construction and packaging.

Such changes of source materials are referred to as substitution. Below, we consider the potential for wood and wood-derived materials to contribute to UK renewable energy generation. The key advantage of using energy from crops is that the CO<sub>2</sub> released during combustion is recaptured by the growth of subsequent crops. Suitable woody crop systems are short-rotation coppice (SRC, 2–5 year rotations) and short-rotation forestry (SRF, 10–20 year rotations). The chapter then goes on to examine the potential of wood products to replace other materials in construction and packaging. Current construction practice is heavily dependent on use of materials which require large amounts of fossil fuel combustion in their manufacture. In contrast, the use of woody materials captures and stores carbon.

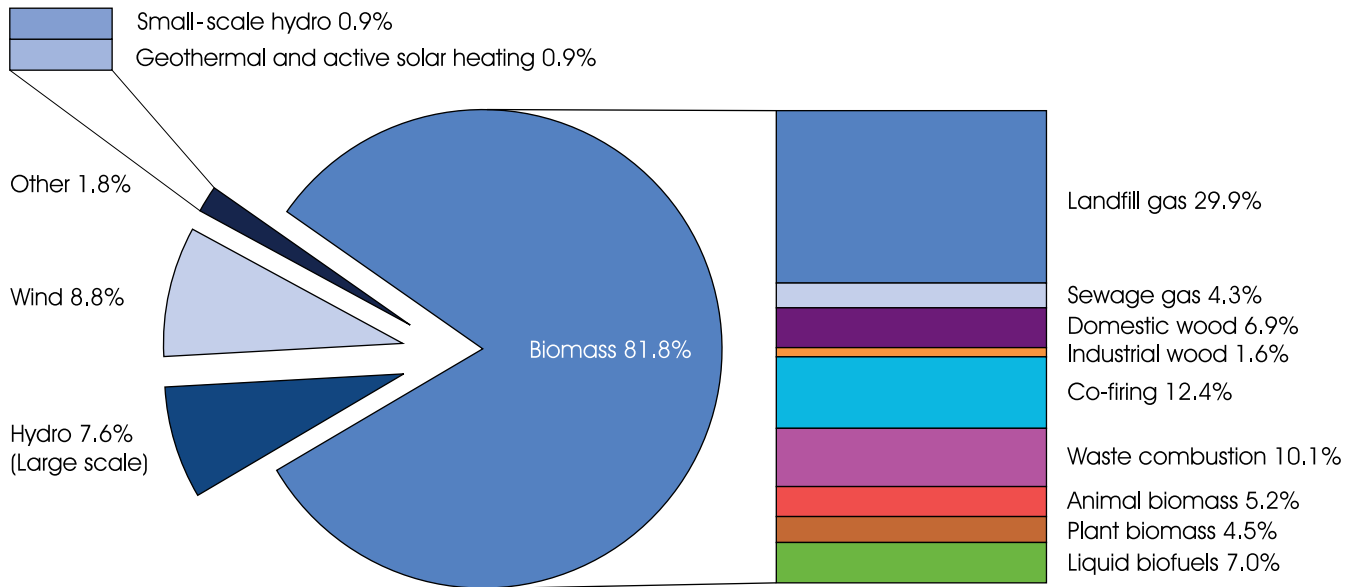
To date, a major barrier to the effective exploitation of wood products and fuels in substitution is a widespread ignorance of the qualities and opportunities offered by these sustainable systems. This problem is exacerbated by a consequent failure, particularly in the construction sector, to develop technologies which will enable more effective use of these materials. Clearly, in addition to the needs for research to plug gaps in our technological knowledge, there is also a significant role for education to bring both the economic and environmental advantages of wood as a substitute for fossil fuels to the attention of a wider public.

### 7.1 Wood for bioenergy – heat, power and liquid transport fuel

Biomass for energy can be defined as any biological mass derived recently from plant or animal matter. This includes material from forests (round wood, cutting residues and other wood brushings), dedicated crop-derived biomass (timber crops, woody short-rotation energy crops such as willow and poplar, grass crops, e.g. *Miscanthus*), dry agricultural residues (straw, poultry litter) and wet waste (slurry, silage), food wastes, industrial and municipal waste (e.g. woody waste from paper manufacture and consumption). Energy derived from these biomass streams, in general, has a lower carbon intensity (ratio of CO<sub>2</sub> released per unit of energy produced) and better energy balance than fossil fuels and biomass to liquid conversions. Although variations exist depending on feedstock, it is generally recognised that perennial woody crops used for heat have one of the best whole life cycle carbon balances of any route for biomass conversion (Royal Society, 2008; Rowe *et al.*, 2009; Environment Agency, 2009). In 2007, renewables contributed approximately 5 million tonnes oil equivalent (Mtoe) to the UK primary supply of energy and of this 81.8% was biomass derived (Figure 7.1). If we assume half of all energy crops and half of co-fired (i.e. mixing of biomass and fossil fuel feedstock) biomass is woody, and that waste combustion is likely to include a significant waste wood component, then we can estimate that woody

Figure 7.1

The contribution of woody biomass to the total biomass (bioenergy) derived from renewable resources used in the generation of UK electricity in 2007, measured in primary input terms. Of the c. 82% contributed by biomass, around 7.5 (6.9+1.6)% are provided by direct combustion of wood, approximately 6.2% (around half of 12.4% – see text) is derived from wood used in co-firing, and approximately half of the energy derived from plant biomass (including energy crops) around 2.25% is wood-derived. Waste combustion is also assumed to contain a significant component of woody material. In total, woody products are calculated to have contributed around 16% or the equivalent of 1–1.2 million tonnes of oil (Mtoe) to the 5.7 Mtoe of renewables used in 2007. (Source DTI Digest of UK Energy Statistics, 2009).



Total renewables used = 5.17 million tonnes of oil equivalent

Source: DTI Digest of UK Energy Statistics, 2009.

biomass resources contributed approximately 1–1.2 Mtoe equivalent to the UK primary energy inputs which is approximately 0.5–1.0% of the primary energy supply to the UK of 236 Mtoe in 2007.

### 7.1.1 Contribution of biomass to the UK energy mix

Wood as a fuel can replace fossil fuels and offers an attractive route to reduction of net GHG emissions. The UK Biomass Strategy (Defra, 2007) called for expansion of wood use for fuel and the Renewable Energy Strategy (DECC, 2009a) also indicates a significant gain yet to be achieved from the use of biomass resources in the UK to produce energy. Woodfuel use for heat, electricity and in the future, transport fuel, are all highlighted in the strategy. However, emerging policy developments, in particular the effectiveness of the proposed renewable heat incentive and the feed-in tariff that allows excess energy to be sold back to the grid, will be key to the more effective exploitation of woodfuel. The implementation plan of the Forestry Commission Woodfuel Strategy (2009) is designed to improve the management of private woodland for energy.

The Biomass Task Force (Defra, 2005) reported that the UK biomass resource is approximately 22 million oven-dried tonnes (odt) annually and, of this, identified 5–6 million odt of wood waste generated per annum as a top priority for recovery and energy use. This is compared to 3 million odt annual production of cereal straw. The overall contribution of forestry to the UK biomass resource is unclear since discrepancies exist due to different assessment criteria and boundaries in the different reports (see 7.1.2 below and Table 7.1). However, the forestry component of the biomass resource remains significant and could contribute up to 7% of the biomass-fired heat market. Recent research depicting a number of UK future energy scenarios using MARKAL modelling (UKERC, 2009) all suggest that renewable heat from biomass will become increasingly important in the UK renewable energy landscape. Currently, only 1% of heat is derived from renewables (DECC, 2009a). The Renewable Energy Strategy has identified biomass to heat as a least-cost way to increase the share of renewable heat with a target of 12% by 2020. Deploying forest resources to achieve these renewable energy targets should be a priority over the coming decade.

Forest biomass can, potentially, be used for heat and electricity, biogas production and also as a liquid fuel, but some of these technologies for woody biomass remain at research scale only. As far as immediate commercial deployment is concerned, it has been suggested that heat, followed by small-scale combined heat and power (CHP), grid-fed electricity and then co-firing in large-scale power stations, represent the priorities for current use in the UK (Forestry Commission, 2007). Combustion technologies may be considered as mature, although their deployment for heat and power is still limited in the UK, despite the fact that they offer good GHG emissions savings, compared to liquid fuel routes. Liquid biofuels provide one of the few options for fossil fuel replacement for transport in the short to medium term. However, in recent months, with rising food prices and reportedly poor energy balances, the validity of their use has been questioned widely at both global (GBEP, 2009) and local levels (RFA, 2008). Current liquid biofuels include bioethanol, biodiesel and other biomass-based products such as biobutanol. Feedstocks are generally non-woody, oil-based crops such as oil seed rape for biodiesel, non-woody sugar and starch based crops such as sugar beet and sugar cane used for bioethanol. However, in future it is more than likely that lignocellulosic woody biomass will be converted to liquid fuels through biological processes (esterification, fermentation) or through thermochemical routes such as pyrolysis (Carroll and Somerville, 2009). Large projects on wood fuel for liquid fuels for transport are currently funded by the DOE in the USA, Genome Canada and by FP7 in Europe. At a national level in the UK there is a current research commitment to investigate SRC willow for

bioethanol production as part of the BBSRC Sustainable Bioenergy Centre, created in 2009.

### 7.1.2 UK forestry biomass for bioenergy

Forest biomass resources for bioenergy in the UK can be defined as primary, secondary or tertiary. Primary forestry biomass resources include forest harvesting residues such as small roundwood logs and branches. Secondary residues are those from sawmills (chips and sawdust), while tertiary residues include paper, construction, recycling and material derived from urban tree and hedgerow maintenance (arboricultural waste). Several attempts to assess the UK forest biomass resource for bioenergy have been made in recent years. These include a joint assessment for the UK by McKay *et al.* (2003), the Defra UK Biomass Strategy (2007), and the Carbon Trust Biomass Sector Review (2004). The findings of these reports, as summarised by Whittaker and Murphy (2009), are given in Table 7.1. The contrasting estimates of forest biomass resource provided by these studies are consistent in revealing waste wood as the largest single source of woody resource which could become available for energy use (Defra, 2007). They include increasing amounts of waste wood that will arise as a consequence of the landfill directive. In future, the projected increase in harvest volumes can be expected to increase wood processing residues from primary and secondary sources over the next few years. The creation of new woodlands and restoration of management in neglected woodland can also be expected to make a significant contribution. Better management of existing woods could supply an

**Table 7.1**  
 Contrasting estimates of the biomass resources available from UK forests for bioenergy – as summarised in Whittaker and Murphy (2009). Data expressed as millions of oven dried tonnes.

Source of data	Total estimated forest biomass resource for bioenergy (Mdt year <sup>1</sup> )	Details of the assessment	Reference
UK assessment	3.1	Primary and secondary sources as well as dedicated SRC	McKay, 2003
The Carbon Trust	11	Extensive overview including forestry (2.24 million odt year <sup>1</sup> ), paper and card industry (2.52 million odt year <sup>1</sup> ), wood packaging waste (970 000 odt year <sup>1</sup> ), paper sludge (800 000 odt year <sup>1</sup> ), and SRC (16 688 odt year <sup>1</sup> )	Carbon Trust, 2004
UK Biomass Strategy	1.3	Only includes sawmill co-products and arboricultural arisings	Defra, UK Biomass Strategy, 2007
UK Biomass report: Mirror to the US's billion ton report	13	Extensive analysis of all forest biomass sources and a forward prediction to suggest that a potential 23 million odt year <sup>1</sup> could be available	Whittaker and Murphy, 2009



additional 1 Mt annually for energy purposes, bringing the annual wood fuel production in England to 2 Mt (Forestry Commission, 2007).

### 7.1.3 UK-sourced vs imported woody biomass

Statistics on imported woody biomass for energy are difficult to verify, since imports for co-firing may be subject to commercial confidentiality. This emphasises the complexity of the UK bioenergy system where there is a mix of home-grown feedstocks as well as those that are imported. In general, approximately half of the utilised feedstocks within the UK are derived from import, which includes approximately 1 Mt of biomass for co-firing. The co-firing market grew by over 100% between 2004 and 2006 and is likely to expand further. This will be driven in part by changes to the renewable obligation certificates (ROCs), that provide better incentives for home-grown biomass as compared to imported supplies.

### 7.1.4 Carbon capture by woody energy crops in the UK

The key advantage of using energy from crops compared to that derived from fossil fuels is that the CO<sub>2</sub> released during combustion of biomass can be recaptured by the growth of subsequent crops. Cannell and Dewar (1995) described a potential carbon saving from the use of wood-derived energy in the range of 5–19 MtC per year by substituting biomass for coal across the UK. These authors assumed that 1 t dry biomass used to generate electricity prevents 0.5 tC being emitted from coal, 0.44 tC from oil and 0.28 tC from natural gas.

Wood fuel use in Scotland in 2008 was recorded as 413 000 odt, of which 62% was virgin fibre (chip), 35% recycled fibre and the remaining 3% pellets. Woodfuel projects in Scotland were estimated to have saved 334 000 tonnes of CO<sub>2</sub> emissions in 2008. If all the projects in planning in Scotland were to go ahead in 2009, then woodfuel use would be around 1 400 000 odt, saving an estimated 1.1 MtCO<sub>2</sub> (0.3 MtC). With an increase in planning agreements, a realistic potential saving from biomass substituting for fossil fuels in the whole of the UK within the next five years could be up to 2 MtC per year. However there is potential to double this if the uptake of woody energy crops was as suggested in the UK Biomass Strategy (Defra, 2007).

A key question for the development of forest energy crops in both SRC and SRF systems is the impact that plantations may have on soil carbon stores and long-term

carbon sequestration (see Chapters 3, 6 and 8). The overall GHG balance of energy forests compared with other land uses such as arable, grassland and upland grazing is only now being quantified. The fertiliser applications required for bioenergy production in intensively managed annual crops are a major source of GHG emissions. Tree crops in contrast do not require annual fertilisation (St. Clair *et al.*, 2008). Although data for N<sub>2</sub>O and methane emissions from soil and crops are limited, when available data are coupled to models, the net positive advantage of woody energy crops is clear. St. Clair *et al.* (2008) showed that replacing arable and grassland with energy SRC had a net positive effect on GHG balance, while replacement of tall forest with SRC had a small negative impact on soil carbon and GHG emissions. These data and information of SRC yields for England and Wales have been used to develop maps assessing the potential for mitigation of GHG emissions (Hillier *et al.*, 2009).

A recent model of the potential for carbon sequestration in SRC willow plantations suggests that within the UK, increases in soil organic carbon (SOC) under SRC alone could contribute around 5% of the emissions mitigation benefits of this crop. A US-based study of poplar plantations (Grigal and Bergson, 1998) similarly suggested that after an initial period of loss, carbon sequestration could be expected to result in gains equivalent to 1–1.6 tC ha<sup>-1</sup> year<sup>-1</sup> over a 10–15-year period. However, other studies provide different results. For example, an investigation on SOC sequestration at three sites in Germany (each with plots of SRC willow, poplar and aspen) reported an increase in SOC at one site of 20% compared to arable land, due mainly to increases in carbon in the top 10 cm of soil (Kahle *et al.*, 2001). However, at the other two sites, no overall increase in SOC was seen, as increases in SOC in the top level of soil were balanced by a decrease in levels below 10 cm. A similar pattern was also seen in the study on SRC willow and poplar by Makerschin *et al.* (1999). This study also included a site on former grassland in which a loss of 15% of original SOC was reported, showing that former land use, and thus initial SOC levels, need to be considered when locating SRC plantations for maximisation of mitigation benefits (see 8.3, Chapter 8). This is certainly an area where further research is needed.

Despite these variations, there is a broad acceptance that while the conversion of arable land to SRC or *Miscanthus* will result in an increase in carbon sequestration in the soil, the conversion of grassland may not be as beneficial (Hillier *et al.*, 2009). It is also important to note that in all cases, soil carbon concentrations will not increase indefinitely, as

eventually a new higher equilibrium SOC will be achieved over some decades (Kahle *et al.*, 2001).

### 7.1.5 Woody bioenergy and climate change – adaptation and mitigation

If SRC and SRF are to be important elements in UK energy generation, then we need to ensure that they are suited for the likely future climate. Predicted changes in climate may have both direct and indirect effects on SRC and forests grown for energy, although again, empirical data in this area are limited. Direct effects include those of rising temperature, altered rainfall, increased CO<sub>2</sub> and tropospheric ozone on tree productivity, chemistry and morphology, while indirect effects include interactions with pests and pathogens and wider ecosystem impacts (see Chapter 3 and Section 2 for more detail). There is some empirical information on the climate impacts on SRC and SRF. In response to an experimentally increased CO<sub>2</sub> concentration to 550 ppm the productivity of stands of loblolly pine, poplar and aspen rose by an average of 23% but in some cases there were increases of up to 60% in total tree biomass (Karnosky *et al.*, 2007). Interactions with tree age, nutrition, climate and pests all influence this effect. In the UK climate, all evidence suggests that in future, yields of SRC are likely to increase as CO<sub>2</sub> concentrations continue to rise, this despite the fact that water may become limited (Oliver *et al.*, 2009). However, yield enhancement may eventually become limited by soil nutrient availability in these rotation systems.

### 7.1.6 Sustainability of woody-based bioenergy systems in the UK

The delivery of enhanced ecosystem services to the UK landscape (including carbon management, water and biodiversity preservation and amenity provision) will gain increasing importance in the UK, alongside the pressures to develop a low carbon society (DECC 2009b) and an 80% reduction in CO<sub>2</sub> emissions, as part of the legal requirements contained in the Climate Change Act. For dedicated woody energy crops such as fast-growing willow and poplar, there is now clear evidence from UK trials showing enhanced farm-scale biodiversity compared to arable land use, including increased small mammal breeding and bird populations (Rowe *et al.*, 2009). Some remaining questions exist regarding catchment-scale water resources but on-going research within the TSEC-BIOSYS and RELU research projects will answer the question of seasonal water use in SRC bioenergy cropping systems. All reported evidence suggests positive rather

than negative impacts on water quality. The large unknown in many UK woody systems is the contribution of below-ground rhizosphere and soil processes to GHG balance.

Currently, liquid biofuel supply to the UK is regulated by the Renewable Fuel Agency. Minimum standards of reporting on GHG mitigation are required but there are no restrictions on land use or crop types, although this may change in the future. More than 70% of the current 2.5% by volume liquid transport fuel from biological sources is supplied from imported sources (RFA, 2008). The sustainability of this supply is largely unregulated, although bioethanol from Brazilian sugar cane is known to have one of the best energy balances of any bioenergy system. Both the UK and EU will address the issue of sustainability in the near future, with sustainability criteria emerging (EU, 2008). Future directives for liquid fuel are likely to include a minimum standard for GHG mitigation relative to fossil fuel, a consideration of prior land use and a ban on the use of pristine high carbon soils and ecosystems with high biodiversity. These changes are likely to encourage a move away from food crops for fuel and could favour the development of the woody biomass energy industry in the UK, since they will restrict feedstocks to those showing at least a 35% improvement in GHG balance relative to fossil fuels. Issues concerning the sustainability of biomass supply have been considered recently (Royal Society 2008).

To achieve sustainability standards for bioenergy supply, there is a requirement for comparison of contrasting and often complex bioenergy chains, including feedstock type, processing and end use. Life Cycle Analysis (LCA) assesses the complete GHG balance of the material or system under consideration and enables more valid comparisons (see Chapter 8). Several detailed studies now confirm that bioenergy chain efficiencies vary dramatically but that in general, woody biomass provides one of the least carbon intensive bioenergy chains, particularly when used for heat (Royal Society, 2008). Better tools are required for this type of LCA comparative analysis and considerable global research effort is on-going to develop these tools, particularly within the Global Bioenergy Partnership ([www.globalbioenergy.org](http://www.globalbioenergy.org)).

### 7.1.7 Drivers supporting the development of bioenergy in the UK

The Renewable Energy Strategy (DECC, 2009a) suggests that bioenergy can make an important contribution to the Government's energy and environment objectives, including energy security and the reduction of GHG

emissions, relative to current practices. It particularly identified biomass heat as a cost-effective mechanism for decarbonisation of the energy sector. Scenarios presented for renewable energy (DECC, 2009a) confirm that bioenergy is likely to play an increasingly important role in contributing to renewable targets for heat, power and liquid fuel (Figure 7.2a). The Recent EU policy developments include the '20-20-20' policy that demands a 20% renewables deployment by 2020. Approximately 6% of all gross domestic energy requirements across Europe are provided by renewables, and bioenergy accounts for the largest share of this, providing about two-thirds of the supply. The European Environment Agency (EEA, 2006) identified the UK, Spain, Italy and France as having high potential for increased use of forests for bioenergy production. Currently, forestry contributes half of the European biomass supply. Despite this, attempts by the UK Government to stimulate the bioenergy sector in the UK have so far had limited success. Recently, however this market has seen increasing activity in micro CHP developments. Also the use of biomass to co-fire power stations such as Drax will be favoured by new 'banding' of the renewable obligations certificates leading to the use of UK-grown dedicated crops for co-firing.

Croft in southern Scotland is one of the first large-scale (44 MW) dedicated biomass power stations in the UK, currently running exclusively on woody feedstocks with a requirement of over 400 000 tonnes each year. It provides energy for up to 70 000 homes. Several other dedicated biomass power stations are under consideration across the UK.

The report of the Royal Commission on Environmental Pollution (2004) on bioenergy and that of the Biomass Task Force (Defra 2005) report attribute the general lack of progress in the uptake of biomass energy crops to a focus on promoting specific technologies without full consideration of the wider market. There is also a lack of integration of biomass supply with its utilisation, and there are issues of public perception and planning, i.e. a whole-systems approach is needed requiring policy incentives and investment from several Government departments.

The European Commission has introduced the Biofuels directive to which the UK is committed. Thus the UK is moving towards development of transport biofuels with a target of 5.75% volume replacement of petroleum-based fuels by 2010 (EU, 2008) with a 2008 commitment of 2.5%, and a commitment to move towards 10% by 2020, regulated by the new Renewable Fuels Agency

Commercial interest in bioenergy is growing. Steven's

**Figure 7.2a**  
The possible relative contributions of different forms of renewable energy to the achievement of a proposed UK Government Target of 15% of total energy being derived from renewables by 2020. Wood fuel will be expected to make significant contributions to the major energy consumers in the electricity (blue labels), transport (green label) and heat generating (red labels) sectors. Data from DECC (2009a).

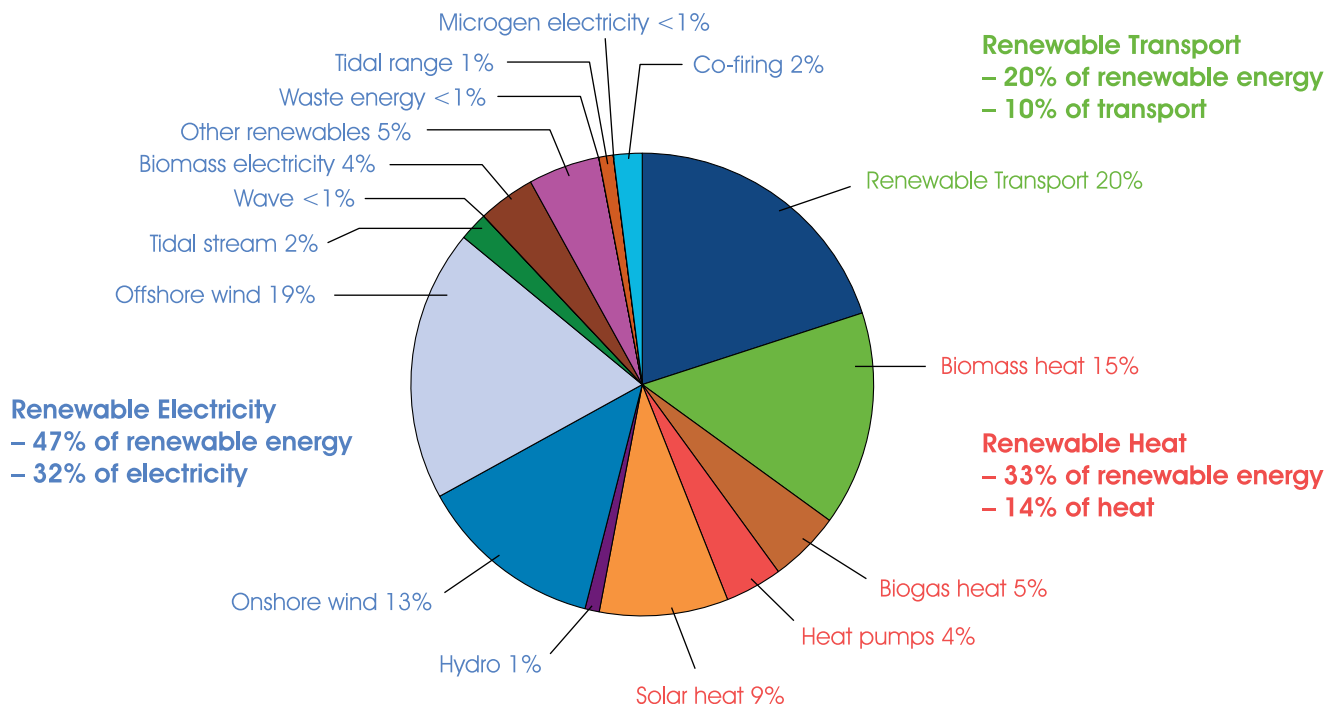
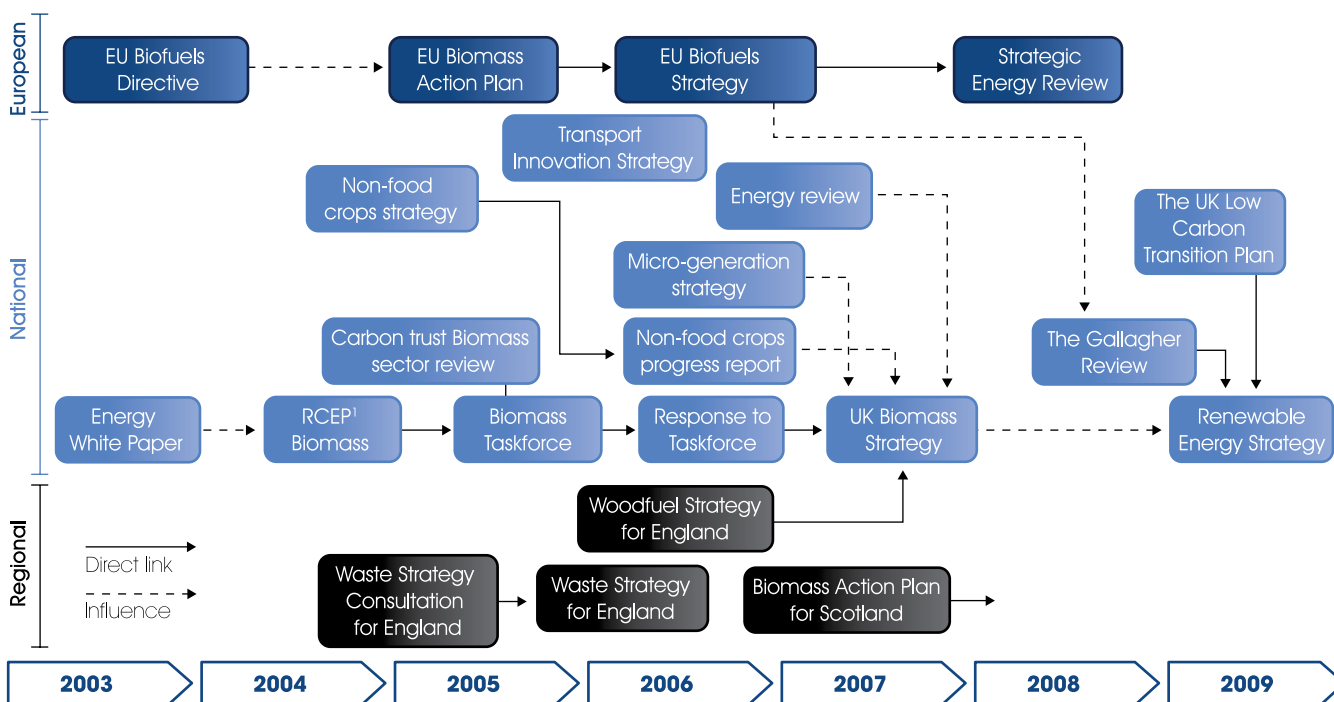


Figure 7.2b

Schematic flow diagram showing the development, over time, of European (dark blue) UK national (light blue) and UK regional (black) policy initiatives directed towards deployment of bioenergy at a range of scales. Solid connecting arrows indicate a direct link to emerging policy documents and broken arrows an emerging influence. Since 2003 these initiatives have contributed to the current Renewable Energy Strategy which places the target of 15% (see a. above) for the overall contribution of renewables to total energy demand by 2020. In the UK context, both the Energy White Paper (2003) and the Royal Commission on Environmental Pollution (2004) emphasised our failure to make use of bioenergy sources. In an attempt to rectify this situation the Biomass Task Force and later the UK Biomass Strategy, Woodfuel Strategy for England and Biomass Action Plans for Scotland were established. Modified from Slade *et al.* (2009).



<sup>1</sup> Royal Commission on Environmental Pollution

(2008). It has been estimated that liquid fuel demand in the UK in 2010 will be 44.5 Mt, which will therefore require approximately 2.56 Mt of biofuel, providing a carbon saving of approximately 2 MtC.

Other drivers to support the deployment of bioenergy systems in the UK include capital grant support provided for infrastructure development, the ‘banding’ of the renewable obligations certificates and a new heat incentive, which is likely to be confirmed in late 2009. The Energy Crops Scheme, Woodland Grant Scheme and other regional support schemes are also available and are detailed in The Biomass Energy Centre website ([www.biomassenergycentre.org.uk](http://www.biomassenergycentre.org.uk)).

### 7.1.8 Barriers to the deployment of woody biomass for bioenergy

There is a plethora of incentives and schemes introduced to enable ambitious targets for bioenergy to be met in the UK and more widely across Europe (Figure 7.2b). More

than 17 different schemes were identified by the Biomass Task Force, and yet uptake is still limited. The effectiveness of these policies in delivering against bioenergy targets as defined by the Biomass Task Force and Biomass Strategy (summarised by Slade *et al.*, 2009), is questionable since the contribution of bioenergy to UK energy supply remains stubbornly low. Public perception of bioenergy schemes can often be negative with concerns over air pollution, the siting of major infrastructural changes and also changes to the landscape, all being noted as reasons for public rejection. Action is required to ensure these incentives work together in an effective way. Barriers to uptake are not only financial, although long lead-in times for perennial crops and contractual obligations between growers and energy producers remain a problem. In the long term, the European emissions trading scheme should help to give bioenergy a considerable boost.

Limited land area and the lack of planning to enable future management of UK land to deliver multiple benefits also inhibits widescale deployment of forest energy



systems. A foresight activity on land use change and management is currently underway to address this issue and the 'Land Based Renewables' research initiative will be determining how ecosystems services might be valued in such a changing landscape. A second project will quantify the likely carbon benefits from increased bioenergy systems and a third will consider how the UK wind resource may be best utilised in a forested landscape alongside the deployment of other energy sources in areas of the UK, particularly Scotland. The UK land-based resource for farming and forestry deployment is modest at approximately 17–20 million ha. Since 2008, the steep rise in food prices has placed a new burden on the UK to deliver food crops and the possibility of any additional use of land to deliver liquid biofuels crops (e.g. from oil seed rape and sugar beet) as well as bioenergy heat and CHP (from forest and grass crops) remains open to speculation. Certainly the uptake of SRC and SRF by farmers and foresters as estimated from the Energy Crops Scheme, has remained sluggish, with only 5000–6000 ha of current plantations. In a series of farm-based surveys (Sherrington *et al.*, 2008), the reasons given include unwillingness to commit to contracts with power stations over several years and a general caution in growing a perennial crop that limits farm flexibility. There are major barriers to be overcome for any large scale forestry energy crop deployment. They require further Government incentives and farm-scale demonstration.

Varying amounts of land have been suggested for biomass feedstock production from the 20 million ha of UK agricultural and forest land available (Rowe *et al.*, 2009). For example, the Biomass Task Force (Defra 2005) suggested that approximately 1 million ha of bioenergy crops in the future could provide 8 million odt of energy crop annually, while the Biomass Strategy (Defra, 2007) proposed 350 000 ha of dedicated energy crops by 2020. There is no coherent current strategy for land deployment between food and energy crops. There will be large-scale changes in the landscape in the UK if specialist bioenergy crops are widely planted. If food prices remain high, there will be competition between these land uses. Perennial crops, such as trees, have a better energy ratio and are more effective at mitigation of GHG emissions than annual crops, and yet farming practice is such that this land use may be slow to develop (see Section 5). Co-firing of power stations is a market for biomass use that has developed since 2002 (growing by 150% between 2004 and 2006 and utilising 1.4 million odt of biomass) and could in future utilise a very large amount of dedicated biomass resource from energy crop supplies. At least half of the current

supply is sourced from outside the UK, with implications for sustainability.

Another barrier to be overcome is the current centralisation of power generation which leads to less favourable economics and a poorer GHG balance for biomass due to transport requirements. The development of microgeneration (small CHP units serving individual homes, businesses or communities) will alleviate the need to transport biomass from point of production to large regional power stations. Microgeneration is currently a small contributor to the UK energy economy but, with careful development, could become a very major one by 2030. In addition, no clear strategy currently exists in the UK to capture bioenergy from biomass 'waste' including municipal solid waste, and agricultural and forestry waste, and this should be an important future priority and is likely to be achieved through increase in the deployment of anaerobic digestion, given the maturity of this technology.

The expertise in woodfuel infrastructure is not well-developed in the UK compared with elsewhere in Europe. However, as wood fuel supply grows, spin-off growth in UK boiler manufacture, installation, maintenance and training is likely to occur.

### 7.1.9 Outstanding issues and research needs

A clear strategy for UK land management is required, since there are many competing land uses. This finite resource must be managed effectively.

There is considerable enthusiasm over the possibility in the future of new bioscience technologies (DoE, 2006) harnessed to improve photosynthetic gains for bioenergy, including the use of synthetic biology. Purpose-designed energy forestry could be an important part of a 'biorefinery' (a refinery using biomass for the production of liquid fuels), contributing energy streams linked to high quality chemical and other biofuel outputs. In future, biotechnology could deliver important improvements to current forest traits for energy, including:

- higher yielding forest energy crops that require minimal inputs (optimised not maximised), thus improving efficiency further;
- forest energy crops with different qualities – increased lignin for calorific combustion, or improved oils, starches and sugars for liquid biofuels;
- forest energy crops with improved resistance to biotic and abiotic stresses that are likely to occur in future.

The model bioenergy tree is poplar (for which the DNA sequence and genomic resources are already available). This is an important resource for future accelerated science advances but the UK has limited scientific investment in this model, in contrast to the USA, China, Canada and the rest of Europe. A strategic view on utilisation of the model tree for energy forestry should be established.

Second generation biotechnologies (molecular breeding in the absence of genetic modification), the use of genetically-modified trees with enhanced traits for carbon sequestration and energy production should be on the agenda for future research, in line with current efforts in Canada, USA, India and China. Trials of exotic species and new silvicultural practices designed to select systems best suited to emerging climate scenarios should be undertaken (see Section 2 and Chapter 8).

Development of new gasification technologies and other advances linked to the biorefinery concept and new technologies for conversion of biomass to fuel are likely to develop to commercial scale by 2020.

By 2020 and beyond, gasification and other technologies may be deployed to improve the efficiency with which wood-based energy supplies are processed and delivered. Advanced technologies for heat and power generation from green and woody plants may be possible at commercial scale using biological rather than thermochemical conversion pathways. Wood waste should be developed as an energy source.

## 7.2 Wood products

Climate change will almost certainly change world markets for the systems and products used in construction. It is likely that in some regions incentives will be developed to promote and support wood product integration in buildings in place of more energy intensive materials. The increasing emphasis on reducing the environmental impact of building has led to the development of so-called 'green' building specifications. These reflect the positive contribution of wood products. Increases in the volume of wood products used in construction by more timber-rich buildings combined with extended service life of wood products will contribute to reducing GHG emissions. However, such increased use of wood is not considered under Article 3.4 of the Kyoto protocol to the UNFCCC, and thus does not apparently contribute to the achievement of Kyoto Protocol targets, nor will improvements be reported in GHG

inventories. The scale of the contribution that substitution of wood products can make to tackling climate change is not clearly understood in the research and technical community because the measurement parameters vary from study to study as do the findings. A result is that the benefits of wood products have not been communicated in a meaningful way to the public.

The pathway of carbon flow from atmosphere into forests and through the different components to wood products that is the focus of this section, is shown in Figure 7.3. The GHG balance of different types of constructions is a highly complex issue. There are relatively few studies and estimates based on buildings, and the boundaries and assumptions in estimates are not always clearly stated and uniform. The variation in wood products industries across the world, and the differing building regulations and practices is a further layer of complexity.

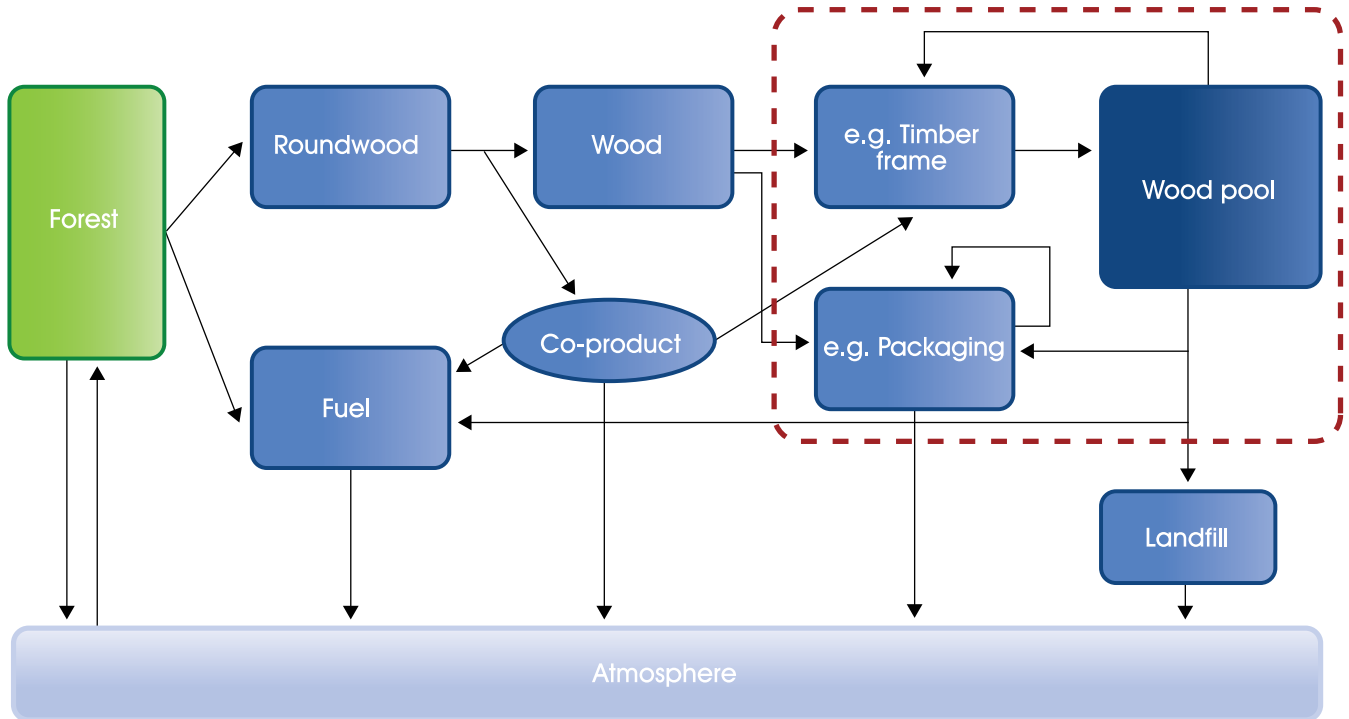
Gustavsson (2008) presented a Scandinavian Carbon balance case study comparing a wood frame apartment building with a concrete framed apartment building that had similar costs to build. The study included primary energy used to produce the buildings, the electricity from fossil fuels and the CO<sub>2</sub> balance in cement reactions. It was concluded that production of materials for the wood frame building used less primary energy, reduced the net CO<sub>2</sub> emission and recovered more biomass residue to replace fossil fuels. The wood frame building gave a net CO<sub>2</sub> emission of -40 tC compared with the concrete framed building net CO<sub>2</sub> emission of approximately +25 tC over a 100-year life cycle. With such estimates it is essential to understand that there are considerable uncertainties regarding the amounts of materials used which will vary from country to country and design to design. In addition, the primary energy used to produce materials will vary with technology, time and country.

A significant complexity in assessing the contributions of wood products arises from the method of accounting for imported and exported material. For example, the accounting of carbon sequestered in the harvested tree could be credited in the country of growth or passed on to the country where the wood product is used. Similarly the decomposition or energy recovery of wood in one country may be credited to that country where the activity happens as an emission or passed back to the country where the tree was grown.

Further complexity is added by differing approaches to the key issue of how to dispose of the products, including:

Figure 7.3

The full life cycle pathways of carbon contained in trees and wood products showing their connections to the atmosphere. The wood products components of the pathway considered here are enclosed within the dashed red line. The consideration of long lasting wood-based construction products in carbon life cycle analyses is of fundamental importance for estimation of national carbon budgets.



- recycling to extend the stored life of the carbon in the wood products;
- energy recovery for immediate release of carbon but displacement of fossil fuel;
- disposal in landfill where the decay rates are variable;
- accounting that considers short-term storage in, e.g. packaging and also long-term storage in the frame of a timber building or a panel product.

### 7.2.1 Wood and other materials in construction and packaging

The energy consumed in producing a construction material, from the extraction of raw material to its transport and manufacture, leads to associated CO<sub>2</sub> emissions which are known as the ‘embodied CO<sub>2</sub>’ of the materials. For example, an estimated 5% of the total annual anthropogenic CO<sub>2</sub> emissions are associated with world concrete production. In addition, the way we extract, produce and transport our construction materials has huge impacts on the amount of embodied CO<sub>2</sub>. By identifying and selecting low embodied CO<sub>2</sub> materials, we can therefore substantially reduce overall CO<sub>2</sub> emissions (Lazarus, 2005).

Of the 678 Mt of materials consumed in the UK annually, 420 Mt is in construction. A relatively small fraction, estimated to be 4% by weight, is wood and wood-based products (e.g. panel products). This fraction is growing. The construction of UK homes accounts for some 3% of our annual CO<sub>2</sub> emissions, because of the embodied CO<sub>2</sub> in the material used (Table 7.2).

Table 7.2

Showing the quantities of CO<sub>2</sub> contained (embodied) in a typical semi-detached house (as used in volume house building) normalised for a typical occupancy and over a 60 year working life. The values are calculated for house area (top row) and per person per year (second row). The total UK CO<sub>2</sub> equivalent emissions per person per year are shown in row three, so that the percentage of individual CO<sub>2</sub> emissions which are embodied by house building can be calculated (bottom row).

Embodied CO <sub>2</sub> for volume house builders	600–800 kg m <sup>-2</sup>
Embodied CO <sub>2</sub> per person per year	286–381 kg
UK Total CO <sub>2</sub> equivalent emissions per person per year	12300 kg
Embodied CO <sub>2</sub> of volume domestic dwellings as % of total CO <sub>2</sub> emissions	2.3–3.1%

In addition, approximately 70 Mt of waste is produced from construction and demolition every year in the UK. A large proportion (75%) of this is recycled, with only 25% going to landfill. But the recycling is generally as low-grade products such as crushed aggregate hardcore. For all products, the focus should be on a cascade down the hierarchy of reuse, recycle and energy recovery.

Construction in a low-carbon economy will need to be highly efficient, it should shift to use of materials that have low embodied CO<sub>2</sub> and use designs that reduce whole building life operational energy. At present, the operational energy used to heat space during the building's lifetime dominates over the buildings embodied energy. As our buildings are designed to more passive heating standards, with high air-tightness and low to zero energy input, then the embodied energy of the construction materials may begin to dominate.

The most promising opportunity for wood products to contribute to carbon storage in the UK is in buildings. FAO statistics from 2003 show that 20% of all wood consumption is used in construction, 30% as panel products and the remainder in packaging and communication. Of the 25 million m<sup>3</sup> of timber consumed in the UK per year about half is used in construction with 85% of the total being imported. In the construction of buildings, wood is a versatile material that can be used as:

- structure (frame, roof);
- engineered panels (sub-floors, joists, wall panels, SIP (structural insulated panel));
- thermal and acoustic insulation (wood wool or recycled paper insulation);
- high aesthetic items (floors, joinery, furniture, cladding);
- biomass boiler fuel.

Wood products can replace more energy intensive construction materials such as concrete and steel, which can result in carbon savings in embodied energy and also increase the carbon storage in buildings. However, a sound evidence base for the construction industry is far from established. Data is presented in fragments and the sector would benefit from robust data gathering to provide a summary of trends in wood product markets for construction and packaging, including the balance of imported and exported raw material and products. The growth in timber frame is well reported by the UKTFA from 7% (1997) of new build to 22% (2008), representing a growth of 300 000 new timber frame houses in 10 years. This amounts to an estimated 1.6 MtC stored.

For the purposes of this chapter, wood products include solid wood, wood-based panels, paper and board. Construction products include permanent and temporary works, public and private buildings and infrastructure. Broadly, this category has products of longer design life needs up to 100 years, which opens up an opportunity for long-term carbon storage and low life cycle impact in the majority of applications.

Packaging includes paper and board and typically is used in short life span applications of up to one year. It has inherent value as a recycled resource. Wood-based products such as cardboard and paper have been compared with glass, PVC, PET, steel and aluminium for packaging (Reid *et al.*, 2004). Cardboard and glass represent the lowest GHG contribution per kilogram of packaging. Savings from using virgin card in gCO<sub>2</sub>e kg<sup>-1</sup> material are for glass (1100), PET (2950), PVC (2850), steel (2910) and aluminium (4040). For cardboard the net GHG emissions were negative (−0.4 kgCO<sub>2</sub>e kg<sup>-1</sup> material) due to energy recovery in one life cycle path.

Wood-based products represent sinks of carbon, whereas the uses of all other common construction materials are net sources of CO<sub>2</sub> (Figure 7.4). This accounting of emissions and storage is important. It is also important to note that these relative performance figures are changing as sectors seek to reduce the carbon footprint of their products and materials.

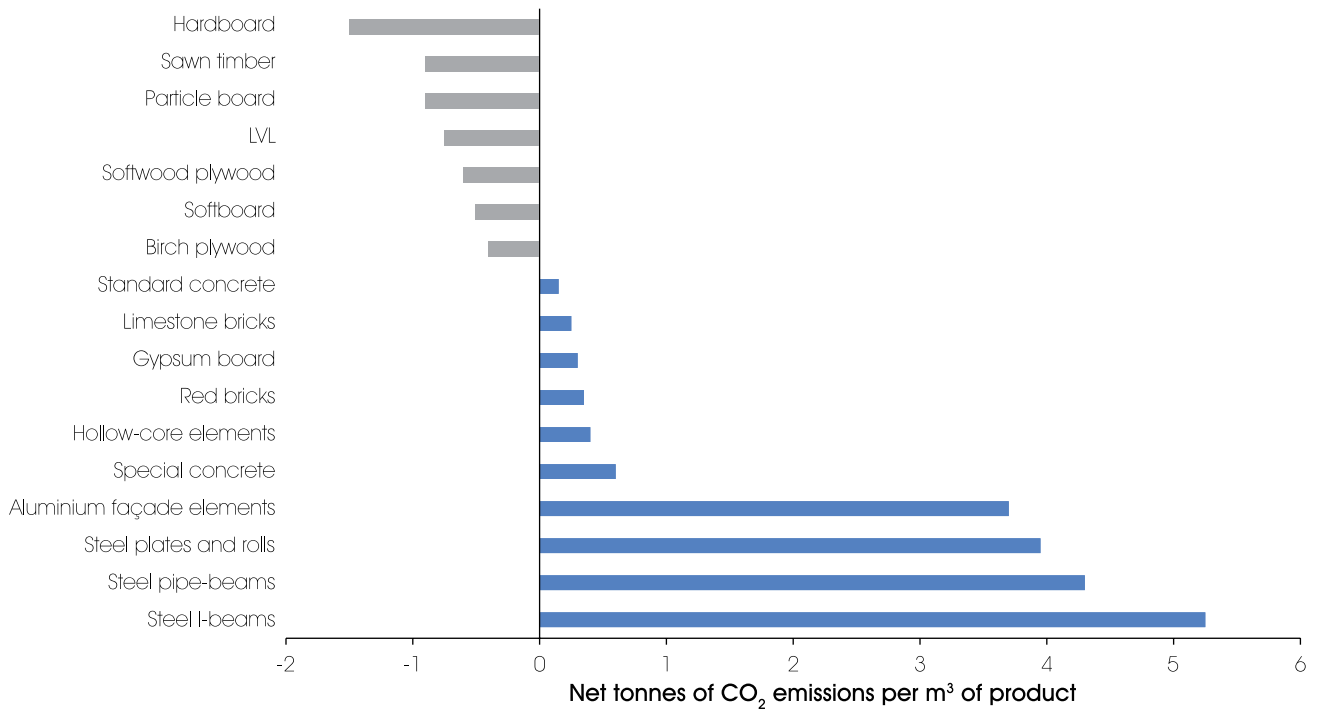
It is important to account for carbon in the whole life cycle from the raw material extraction to the end of life of the product. A 1 m<sup>3</sup> of steel I-beam does a very different job to 1 m<sup>3</sup> of sawn timber in all respects including structural span, service life and end-of-life use. The major complexity here is the need to capture the whole picture by considering material as part of functional units. A negative CO<sub>2</sub> emission for wood products is an excellent platform for increasing the use of wood-based products in construction providing the regulatory framework demands low carbon technologies. In addition, products must perform as predicted up until the end of the design life to avoid wasteful resource use and subsequent imbalance through premature failure and early replacement.

Wood products used in construction are stored and there is a degree of turnover as they are replaced. The wood products pool in the UK is estimated to be 80 MtC stored and growing at 0.44 MtC per year (Broadmeadow and Matthews, 2003). Wood products have favourable net negative CO<sub>2</sub> emissions as more carbon is stored



Figure 7.4

The net CO<sub>2</sub> emissions of the major products used in the construction industry. All non-woody components are seen to constitute net sources of CO<sub>2</sub> while all wood-based components are net sinks. LVL = laminated veneer lumber.



(Reproduced from WRI Trees in the Greenhouse Report using RTS data of 1998–2001 Aulisi A, Saucer A and Wellington F. World Resources Institute 'Trees in the Greenhouse')

than produced in manufacture. Whether the product is in packaging or construction, other materials are improving their position as they reduce impacts, strive for low energy processing, become resource efficient and apply new technologies through innovation and the application of life cycle analytical research. To keep pace, wood products also need to conduct this important work and continue to lead in low impact solutions for packaging and construction.

### 7.2.2 Challenges facing the increased use of wood-based products

Awareness of carbon storage potential in wood products is limited but improving. There remain, however, considerable challenges in realising a major shift towards increasing wood products in construction in the UK.

Lack of know-how and inexperience of use in the hands of engineers and construction professionals in the UK presents a primary barrier for widespread use of wood products. Traditional UK building practices have not extensively used wood as they do in Germany, Scandinavia and Austria, for example. Timber presents challenges to

use in UK markets as designers, architects, engineers and specifiers are not broadly as familiar with the material and its use as with steel and concrete. This knowledge gap is evident in architectural and engineering higher education. Limited know-how is overcome in part by publications and training but these are fragmented and new initiatives risk limited or low impact. Technical performance and capabilities need to be in appropriate formats for ease of use – design packages, software, systems not individual products – and to provide an easy route to meet building regulations and approvals bodies' requirements. Wood products need to work hard in a conservative construction industry. The mortgage lending and insurance sector trusts traditional construction because of its track record in delivery of service life of brick and block technology. New technologies and timber frame systems initially were hindered by lack of understanding of the robustness of the systems to deliver long-life buildings. These perceptions still persist, despite the substantial independent research evidence and the wide range of existing successful buildings.

Uncertainties about wood product service life exist as there are not systems widely available for its prediction

in construction as there are for concrete and steel. Testing of new and existing wood products needs to be robust to enable prediction of service life against defined performance criteria. Maintenance systems need to be fully adopted, integrated and accompanied by training packages for all wood systems to extend service life in use.

The myths surrounding the use of wood, wood products and timber construction need to be challenged by effective communication of research findings and by the use of projects to pass on learning. Reid *et al.* (2004) record some of the misconceptions about wood. They note that the perception that wood use is non-sustainable arises because it is associated with felling and not with the replanting and regeneration of forests. Concerns around overheating, low thermal mass and durability of wood, together with fire safety and complex specification of fire safety issues, are sometimes overemphasised in the competition of different materials for market share in domestic housing. There is a need for example construction projects using wood and for the research findings about construction with wood to be centrally promoted. There are only a few mechanisms to enable such promotion. Among these are the 'Wood for Good', 'Wood for Gold' and some Forestry Commission activities. Independent research should be used to present the case for wood products.

There are skills shortages and gaps in training concerning the use of wood in the construction industry. Since there are so few data on wood product use in construction, so data gathering and analysis should be a priority to improve this and to monitor change.

The construction industry is relatively conservative and product substitution occurs slowly. Early adoption of new products is determined by perceived practicality, fashion and modernity (Reid *et al.*, 2004). The markets are often mature and rooted in traditional practice and products. Substitution of existing products by wood is more likely to be driven by product quality (e.g. straightness, freedom from defect), availability, price and ease of use or maintenance, than by innovation and considerations of environmental sustainability *per se*.

Furthermore, the forest industries are characterised by many small-to-medium enterprises (less than 250 employees), a large number of very small businesses (20 employees) and a large number of trade associations and representative bodies. Gaining a focus to national

research has been a challenge which has been somewhat alleviated by the UK's National Research Agenda (FTP, 2009). Overall, the approach to innovation and R&D leads to a focus on small step changes and immediate problem-solving. Focus on medium- to longer-term benefits is more difficult to achieve. The fragmented nature of the industry results in difficulties in reaching consensus as well as causing weak communication of opportunities.

### 7.2.3 Drivers supporting the specification of wood-based products

The key strengths of wood-based products need to be emphasised to get maximum penetration in major markets such as timber frame, and massive timber construction using cross-laminated timber. Offsite manufacture offers opportunity for wood-based construction systems to capture the efficiency and sustainability benefits that include fast build programmes, less disruption, reduced site waste and more cost-efficient processes. It is also important to communicate the additional functionality benefits of wood such as its thermal insulation and thus its savings in emissions through reduced space heating.

There are significant market drivers that support the promotion and use of wood and wood products in construction. Some of these are based in direct Government directives and codes and others are less formally driven.

The Green Guide for Specification (GGS) (BRE, 2009) is a tool which compares different building elements at a functional unit level for their environmental impacts. The GGS is based on full life cycle analysis (LCA) and yields an overall rating on a scale from A+ to E for any functional unit to be employed in a given construction. For timber, the extent of carbon sequestration over the growth period of the raw material is included as part of the rating. Without exception, wood and wood-based products contained in other functional units achieve either A or A+ ratings in the GGS system. In England, the Code for Sustainable Homes (CLG, 2006) is pushing for a step change in the delivery of sustainable new-build housing. This is underpinned by the Green Guide for Specification and is setting a framework in which all new-build housing will be zero carbon rated by 2016. At this time it remains unclear as to the impact of the economic downturn on our ability to innovate and meet these targets. House building has slowed to a level of less than a quarter of that predicted before the credit crunch unfolded.

Building regulations and codes can support the development and integration of long service life and durable wood and timber products into construction, but these must be facilitated by standards development. The smooth integration and transition to the latest European standards, among which Eurocode 5 covers the use of timber in buildings and civil engineering structures, will be critical for the future growth of the structural use of timber.

### 7.2.4 Potential for substitution and the scale of opportunity

The science of carbon accounting across the whole life cycle of wood products is still developing. However, life cycle assessments (LCA) such as those that underpin the Green Guide to Specification and which consider all stages of a product's life, consistently place wood products in low environmental impact categories. As LCAs develop, further competitive advantages can be expected to be for wood products in a low carbon economy.

The UK is starting from a varied baseline of wood product types which vary in their ability to penetrate, establish and sustain a presence in the various markets. Some are established and mature such as fencing and others where growth is anticipated, such as cladding, are very small.

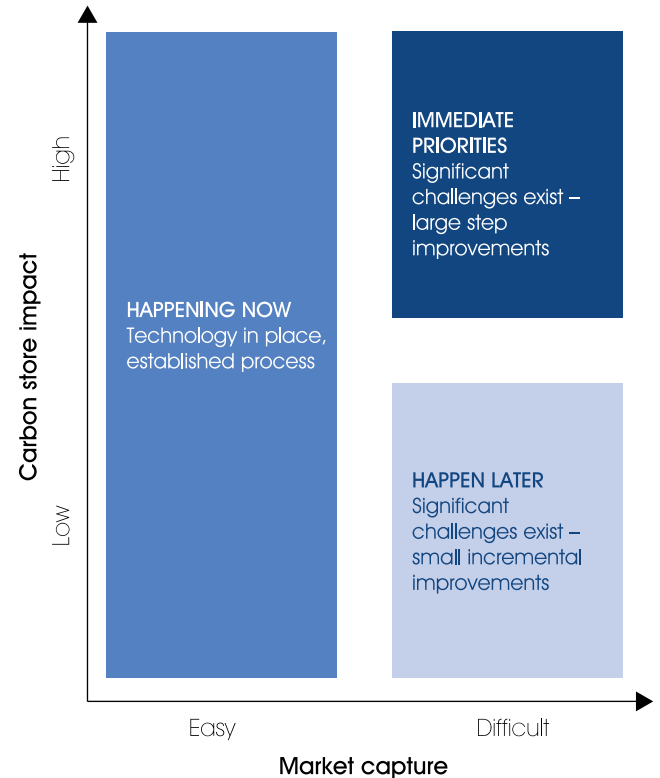
Table 7.3 lists many wood products currently employed in the UK and provides estimates of their current carbon storage, service life and the extent of their use. The current level of demand, market prospects for the next 10 years and the issues faced in expanding their market share are also indicated. There are likely to be good prospects for growth of wood products in timber frame, walls, exterior cladding, floors and joinery. These will have a major role in storing carbon.

The markets for wood products that can be most readily captured should be identified with the impacts they will have on carbon storage and substitution. Options should be analysed and placed in the context of impact of carbon storage and ease of market capture and a scheme for achieving this is shown in Figure 7.5.

A traditional brick and block built, three bedroom, semi-detached house is estimated to contain wood products that store 4.4 tCO<sub>2</sub> equivalent in the roof, tiling battens, floors and studs (Davies, 2009). This figure can be as high as 15.0 tCO<sub>2</sub> stored in a timber frame dwelling. For traditional brick-built housing, the value scales up to approximately 92 MtCO<sub>2</sub> stored (25 MtC) in existing UK

**Figure 7.5**

A scheme to allow the identification of markets which would maximise the carbon store in buildings and thus which should be targeted for market development.



homes. This value can be compared with the total UK CO<sub>2</sub> emitted 150 MtC per year by burning fossil fuels alone (Cannell, 2003). The magnitude of this carbon store in buildings is made more impressive when combined with the carbon displaced by replacing more fossil fuel intensive products which is estimated to be between 15 t and 40 tCO<sub>2</sub> for a single dwelling.

Prior to the economic downturn, the UK had an ambitious target of building 250 000 new homes per year in which an estimated 1.6 MtCO<sub>2</sub> (or 0.44 MtC) would be stored. Recent predictions are that about 80 000 new homes were to be built in 2009 (Construction News, 2009) which could represent storage of 0.5 MtCO<sub>2</sub> (0.14 MtC), if an assumed 20% market share (UKTFA, 2009) is selected for timber frame construction.

There has been much debate about the carbon savings to be gained by substituting timber for brick and cement. A much quoted statistic is that 1 t of CO<sub>2</sub> is saved if 1 t of brick or concrete is replaced with timber. However, the assumptions in deriving this comparison can be challenged because the materials have considerably

## Section 3: Mitigation

Table 7.3

Representation of different wood products, their market demands, minimum service life, market prospects and estimated carbon stored in 2009.

Use for wood product	Market demands for product	Minimum service life (years)	Market prospect for next 10 years	Estimation of CO <sub>2</sub> stored (number of homes or wood products x convert wood to CO <sub>2</sub> x volume in typical home or wood product )
<b>WOOD PRODUCTS IN THE CONSTRUCTION OF HOMES</b>				
Timber frame	Improving acoustic and thermal insulation	60	↑	$2\,000\,000 \times 0.9 \times 6 = 10.8 \text{ MtCO}_2$
Walls	Improving acoustic and thermal insulation	60	↑	$5\,000\,000 \times 0.9 \times 2 = 9.0 \text{ MtCO}_2$
Structural floors and floor cassettes	Improving acoustic and thermal insulation	60	↑	$5\,000\,000 \times 0.9 \times 2 = 9.0 \text{ MtCO}_2$
Floor covering	High aesthetic, affordability, long lasting and wear resistant	15	↑	$5\,000\,000 \times 0.9 \times 0.36 = 1.6 \text{ MtCO}_2$
Trussed rafters	New designs utilising UK timber	60	→	$12\,600\,000 \times 0.9 \times 2.58 = 29.3 \text{ MtCO}_2$
Exterior cladding	High aesthetic, extending maintenance intervals	30	↑	$2\,000\,000 \times 0.9 \times 0.33 = 0.6 \text{ MtCO}_2$
Tiling battens	Improving treatment quality	60	→	$12\,600\,000 \times 0.9 \times 0.457 = 5.2 \text{ MtCO}_2$
Exterior joinery (doors and windows)	Improving thermal performance and extending maintenance intervals	30	→	$8\,400\,000 \times 0.9 \times 0.26 = 2.0 \text{ MtCO}_2$
Interior joinery	High aesthetic, affordability, long lasting and wear resistant	30	↑	$15\,000\,000 \times 0.9 \times 0.13 = 1.8 \text{ MtCO}_2$
Wood wool insulation	Long lasting thermal performance	60	↑	$5\,000 \times 0.9 \times 1.5 = <0.01 \text{ MtCO}_2$
			<b>TOTAL</b>	<b>69.2 MtCO<sub>2</sub> = 18.87 MtC</b>
<b>ADDITIONAL WOOD PRODUCTS</b>				
Fencing	Reliability, improving treatment quality, end of life options	15	→	$10\,000\,000 \times 0.9 \times 0.33 = 3.0 \text{ MtCO}_2$
Furniture (indoor)	High aesthetic, affordability, long lasting and wear resistant, end of life options	15-30	→	$21\,000\,000 \times 0.9 \times 0.11 = 2.1 \text{ MtCO}_2$
Furniture (outdoor)	High aesthetic, affordability, low maintenance	10	→	$10\,000\,000 \times 0.9 \times 0.04 = 0.4 \text{ MtCO}_2$
Landscaping timber	Reliability, improving treatment quality, end of life options	15	→	$10\,000\,000 \times 0.9 \times 0.11 = 1.0 \text{ MtCO}_2$
Foundations	Long service life	60-100	→	Not quantified
Scaffold boards	Maintaining preferred choice status	10	→	Not quantified
Transmission poles	Maintaining preferred choice status, serviceability, working at height, end of life	60-100	→	$14\,000\,000 \times 0.9 \times 0.7 = 8.8 \text{ MtCO}_2$
			<b>TOTAL</b>	<b>15.2 MtCO<sub>2</sub> = 4.15 MtC</b>
<b>PACKAGING</b>				
Pallets, boxes, crates	Maintaining preferred choice status, improving hygiene	3	→	$20\,000\,000 \times 0.9 \times 0.02 = 0.4 \text{ MtCO}_2$
Product packaging	Innovative form and function	0.1	↑	Estimated 20.0 MtCO <sub>2</sub>
			<b>TOTAL</b>	<b>20.4 MtCO<sub>2</sub> = 5.55MtC</b>

Note: the conversion factor used is 900 kg CO<sub>2</sub> stored per m<sup>3</sup> of wood.



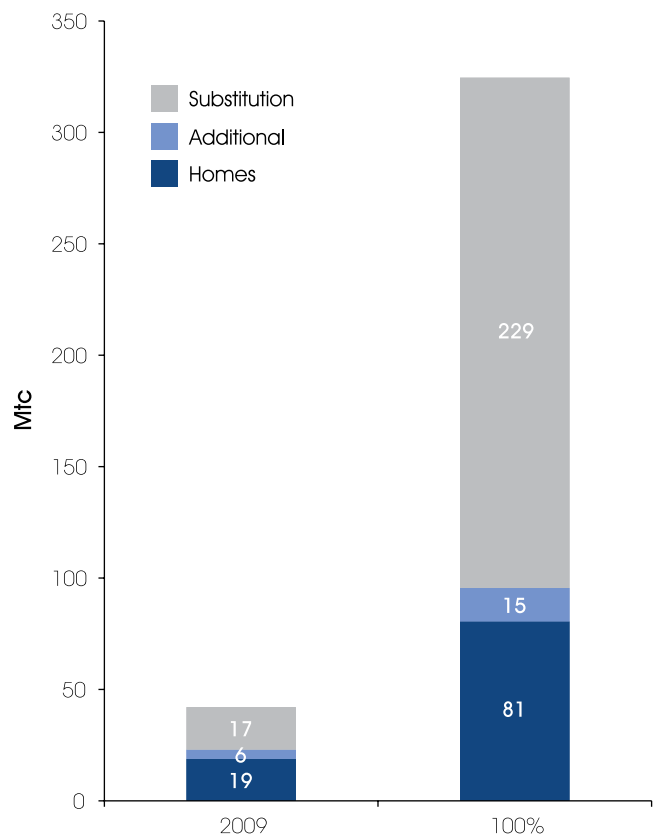
different properties, varying service lives (10–100+ years) and different roles in buildings. The amount of carbon associated with a defined functional unit is an important concept to ensure an appropriate comparison is made between products (Table 7.3). Work is needed here to gather better data of this nature.

Estimates of the annual carbon sequestration in the wood products pool (sawnwood, roundwood, panels, paper, board) for the UK over the period 1990–99 range from 2.4 to 4.9 MtC (Hashimoto, 2002). The estimates published for other Kyoto Protocol Annex I countries are approximately 4MtC per country. By adding the carbon stored in all wood products used in the construction process (based upon carbon storage values for products derived from Table 7.3), it is estimated that the total carbon stored in UK homes in 2009 is 19 MtC (Figure 7.6, left hand blue column). This is comparable with the figure 25 MtC estimated earlier, based on Davies (2009). Applying a scenario where wood products gain wider acceptance and there are increases in the percentage of the housing stock that will be timber rich (i.e. timber framed, clad, floors, wood wool insulation) shows potential significant impacts on carbon stored and carbon saved through substitution. Using the displacement of between 15 t and 40 t of CO<sub>2</sub> for a single dwelling for all UK homes this yields an estimated 43 MtC (for an estimated 50% of UK housing stock) displaced in 2009 and a theoretical 229 MtC maximum displaced in all housing. Figure 7.6 shows the theoretical maximum if all UK homes were timber rich. Somewhere between these two bars is realistically where we are targeting. If the wood construction products sector continues to grow as it has in the past 10 years there is potential to store as estimated additional 10 MtC in the UK's new and refurbished homes. This would save a further estimated 20 MtC as the substitution effect of displacing more carbon intensive materials. Without legislation or incentive it may take 10 years to reach this additional stored amount as the construction sector is slow to change.

One of the principle challenges is to upgrade the existing housing stock for a low carbon economy. This could be achieved through refurbishment to enrich timber contents. However, it must be recognised that the extent to which such upgrading can be achieved will be restricted by planning and conservation issues, plus the longevity of existing stock. On the positive side, the imposition of more exacting energy efficiency standards will increase incentives to employ wood products in the ongoing process of regeneration.

**Figure 7.6**

Estimates of the total carbon stored in wooden construction products in all UK homes standing in 2009 (left-hand column) and the theoretical maximum achievable carbon storage if the industry converted to construction of 100% timber-rich buildings (right-hand column). The values in each column are subdivided to show construction products themselves (dark blue) additional wood products (light blue) and the carbon saved by substitution effects of displacing more carbon-intensive materials using wood (grey). The carbon content of each product is derived from values shown in Table 7.3.



As new timber-rich buildings are constructed and existing buildings are refurbished in the UK, the total wood product pool in the housing stock can be expected to increase progressively. In addition, an extended service life will hold the wood products in the pool for longer before they pass to landfill and subsequently decompose or are recovered and recycled into new products. The end-of-life issues for construction products are of key importance. Wood needs to deliver products that can maximise reuse and recycling and not provide future problems. The recycling infrastructure needs to be developed and recovery opportunities maximised.

### 7.2.5 Climate change and the built environment

Climate change will affect the type and quality of products which are delivered from UK forests. As the regulatory frameworks which drive changes to buildings respond to climate change, the markets for construction materials will also change – increasingly buildings will be required to deliver flood resilience and provide in-built passive cooling. The service life of construction products may be altered by changed environmental weathering factors. Wood products will need to be well placed to deliver into new construction systems providing tailored solutions in composites and will also have the advantage of carbon storage which will become increasingly important.

### 7.2.6 Product life times, sustainability and future scope

Materials with long service life store carbon for longer, and wood products often have the additional advantage of reuse (second life) opportunities either as new wood products (chipped and integrated into panel products) or for displacement of fossil fuel (energy recovery). New technologies are emerging to extend the service life of wood products and, along with improved maintenance and the potential for reuse, this will further improve the carbon benefits of wood products. Examples are paints containing low or no volatile organic compounds for external use, which reduce the environmental impact of paint and require less energy in their manufacture.

Sustainable and ethical production are keys to the continued success of wood products in construction. The forest industries have led the way with sustainably sourced raw materials, and well recognised certified schemes such as the Forest Stewardship Council (FSC) and Programme for the Endorsement of Forest Certification (PEFC) marks have become established. Confirmation of sourcing from sustainably-managed forests (chain of custody) is a requisite for public procurement and will filter through to mainstream private construction in the next five years.

Economic instruments to reduce CO<sub>2</sub> emissions are likely to be in place soon which will influence the choice of materials for construction. A carbon tax would change the market for building materials and reduce competitiveness of materials produced by processes which result in high GHG emissions and are energy inefficient. As a result of the energy efficiency and low GHG emissions associated with their production, forest products may have

considerable opportunity in provision of feedstock for other sectors.

### 7.2.7 Research challenges and gaps

The UK has pockets of research and innovation talent focussing on forest products which provides small incremental improvements in our knowledge and understanding of the likely environmental benefits of wood products. A compelling case to use wood in construction is hampered by the evidence being incomplete and fragmented. Initiatives have yet to provide the step change needed to enable UK grown forest products to take a greater contribution to construction. The research proposed in the UK National Research Agenda (FTP, 2009) should be undertaken as a platform for taking forward commercially relevant studies designed to bring down the barriers to the use of home grown timber.

Wood products in construction can certainly contribute to the delivery of zero carbon homes in the UK, but more research is needed to determine the extent achievable. A clear timetable and process is required to change the building regulations so that standards are in place to achieve the zero carbon 2016 target for all new-build homes.

## 7.3 Conclusions

Substitution of wood and wood products for other construction materials and for non-renewable energy sources offers a major opportunity for tackling climate change by storing carbon in our buildings and reducing fossil fuel consumption. Greenhouse gas emissions from the production and use of wood products are lower than those from other materials commonly in use in construction. Provided the challenges can be met, substitution of wood for fossil fuels and for those materials used in construction which require high GHG emissions in their production presents an attractive solution for industry.

## 7.4 Research priorities

- Development of scenarios describing projected consumption of biomass energy and sustainable wood products are needed to determine how much more forest is required.
- In order to compare wood and other construction materials, GHG balances and energy efficiencies

for different construction systems using consistent assessment methods are required.

- Life cycle analyses of wood products and an understanding of the turn-over of carbon in different wood product pools are required.
- The built environment will need to adapt to climate change and the impacts of such adaptation on the use of wood products should be determined.
- Research on the optimal adaptation of our woodlands and forests should take into account the need for increased supplies of sustainable wood products and woodfuel.

## References

- AULISI, A., SAUER, A. and WELLINGTON, F. (2008). *Trees in the greenhouse: why climate change is transforming the forest products business*. World Resources Institute, Washington.
- BIOTECHNOLOGY AND BIOLOGICAL SCIENCES RESEARCH COUNCIL (2006). *Review on bioenergy research*. Online at: [www.bbsrc.ac.uk/organisation/policies/reviews/scientific\\_areas/0603\\_bioenergy.html](http://www.bbsrc.ac.uk/organisation/policies/reviews/scientific_areas/0603_bioenergy.html) (accessed April 2008).
- BRE (2009). *The green guide for specification*. 4th edn. Wiley-Blackwell, Oxford. Online at: [www.thegreenguide.org.uk](http://www.thegreenguide.org.uk)
- BROADMEADOW, M. and MATTHEWS, R. (2003). *Forests, carbon and climate change; the UK contribution*. Forestry Commission Information Note 48. Forestry Commission, Edinburgh.
- CANNELL, M.G.R. (2003). Carbon sequestration and biomass energy. *Biomass and Bioenergy* **24**, 97–116
- CANNELL, M.G.R. and DEWAR, R.C. (1995). The carbon sink provided by plantation forests and their products in Britain. *Forestry* **68**, 35–48.
- CARROLL, A. and SOMERVILLE, C.R. (2009). Cellulosic biofuels. *Annual Review of Plant Biology* **160**, 165–182.
- CLG (2006). The code for sustainable homes. Online at: [www.planningportal.gov.uk/uploads/code\\_for\\_sust\\_homes.pdf](http://www.planningportal.gov.uk/uploads/code_for_sust_homes.pdf)
- CONSTRUCTION NEWS (2009). Online at: [www.cnplus.co.uk](http://www.cnplus.co.uk) (accessed February 2009).
- DAVIES, I. (2009). *Sustainable construction timber*. Forestry Commission Scotland.
- DEFRA (2005). *Biomass Task Force Report*. Department for Environment, Food and Rural Affairs, London. Online at: [www.defra.gov.uk/farm/crops/industrial/energy/biomass-taskforce/index.htm](http://www.defra.gov.uk/farm/crops/industrial/energy/biomass-taskforce/index.htm) (accessed 3 August 2009).
- DEFRA (2007). *UK biomass strategy*. Department for Environment, Food and Rural Affairs, London. Online at: [www.defra.gov.uk/Environment/climatechange/uk/energy/renewablefuel/pdf/ukbiomassstrategy-0507.pdf](http://www.defra.gov.uk/Environment/climatechange/uk/energy/renewablefuel/pdf/ukbiomassstrategy-0507.pdf) (accessed 3 August 2009).
- DEFRA (2008). *Strategy for waste to energy*. Department for Environment, Food and Rural Affairs, London. Online at: [www.defra.gov.uk/environment/waste/strategy/factsheets/energy.htm](http://www.defra.gov.uk/environment/waste/strategy/factsheets/energy.htm)
- DEPARTMENT OF ENERGY (2006). *Breaking the biological barriers to cellulosic ethanol: a research roadmap from biomass to biofuels workshop*. Department of Energy, London.
- DEPARTMENT OF ENERGY AND CLIMATE CHANGE (2009a). *The UK renewable energy strategy*. Cm. 7686. The Stationery Office, London. Online at: [www.decc.gov.uk/en/content/cms/what\\_we\\_do/uk\\_supply/energy\\_mix/renewable/res/res.asp](http://www.decc.gov.uk/en/content/cms/what_we_do/uk_supply/energy_mix/renewable/res/res.asp) (accessed 3 August 2009).
- DEPARTMENT OF ENERGY AND CLIMATE CHANGE (2009b). *The UK low carbon transition plan*. The Stationery Office, London. Online at: [www.decc.gov.uk/en/content/cms/publications/lc\\_trans\\_plan/lc\\_trans\\_plan.aspx](http://www.decc.gov.uk/en/content/cms/publications/lc_trans_plan/lc_trans_plan.aspx) (accessed 3 August 2009).
- DEPARTMENT OF TRADE AND INDUSTRY (2007). *Digest of UK energy statistics*. Online at: [http://stats.berr.gov.uk/energystats/dukes07\\_c7.pdf](http://stats.berr.gov.uk/energystats/dukes07_c7.pdf) (accessed April 2008).
- ENVIRONMENT AGENCY (2009). Biomass - Carbon sink or carbon sinner? Online at: [www.environment-agency.gov.uk/business/sectors/32595.aspx](http://www.environment-agency.gov.uk/business/sectors/32595.aspx) (accessed August 3 2009).
- EUROPEAN ENVIRONMENT AGENCY (2006). *How much biomass can Europe use without harming the environment*. EEA Report No. 7. Online at: [www.eea.europa.eu/publications/eea\\_report\\_2006\\_7](http://www.eea.europa.eu/publications/eea_report_2006_7) (accessed 3 August 2009).
- EUROPEAN UNION (2008). *EU sustainability criteria for biofuels*. Online at: [www.foeeurope.org/agrofuels/documents/Proposal\\_sustainability\\_criteria\\_biofuels\\_27Mar08.pdf](http://www.foeeurope.org/agrofuels/documents/Proposal_sustainability_criteria_biofuels_27Mar08.pdf) (accessed 8 June 2008).
- FOREST-BASED SECTOR TECHNOLOGY PLATFORM (2009). *A national research agenda for the UK forest-based industries*. Online at: [www.forestplatform.org](http://www.forestplatform.org)
- FORESTRY COMMISSION (2007). *A woodfuel strategy for England*. Online at: [www.forestry.gov.uk](http://www.forestry.gov.uk)
- FORESTRY COMMISSION SCOTLAND (2009). *Woodfuel: demand and usage in Scotland*. Update report, 2008. Online at: [www.forestry.gov.uk](http://www.forestry.gov.uk)
- FTP (2009). The Forest Technology Platform National Research Agenda. Online at: [www.forestplatform.org](http://www.forestplatform.org)
- GLOBAL BIOENERGY PARTNERSHIP (2009). Online at: [www.globalbioenergy.org/](http://www.globalbioenergy.org/) (accessed 3 August 2009).
- GRIGAL, D.F. and BERGSON, W.D. (1998). Soil carbon changes associated with short rotation systems. *Biomass and Bioenergy* **14**, 371–377.

- GUSTAVSSON, L. (2008). Substitution effects of wood-based construction materials. Harvested wood products in the context of climate change, Palais des Nations, Geneva. IEA Bioenergy: T38: 2005: 05. Online at: [www.ieabioenergy-task38.org/projects/task38casesstudies/finswe-brochure.pdf](http://www.ieabioenergy-task38.org/projects/task38casesstudies/finswe-brochure.pdf)
- HASHIMOTO, S., NOSE, M., OBARA, T. and MORIGUCHI, Y. (2002). Wood products: potential carbon sequestration and impact on net carbon emissions of industrialized countries. *Environmental Science and Policy* 5, 183–193.
- HILLIER, J., DAILEY, G., AYLOTT, M.J., WHITTAKER, C.J., RICHTER, G., RICHE, A., MURPHY, R., TAYLOR, G. and SMITH, P. (2009). Greenhouse gas emissions from four bioenergy crops in England and Wales: Integrating spatial estimates of yield and soil carbon balance in life cycle analyses. *Global Change Biology Bioenergy* 1, 267–281.
- KAHLE, P., BEUCH, S., BOELCKE, B., LEINWEBER, P. and SCHULTEN, H.R. (2001). Cropping of *Miscanthus* in Central Europe: biomass production and influence on nutrients and soil organic matter. *European Journal of Agronomy* 15, 171–184.
- KARNOSKY, D.F., TALLIS, M.J., DARBAH, J. and TAYLOR, G. (2007). Direct effects of elevated carbon dioxide on forest tree productivity. In: Freer-Smith, P.H., Broadmeadow, M.S.J. and Lynch, J.M. (eds) *Forestry and climate change*. CABI, Wallingford. pp. 136–144.
- LAZARUS, N. (2005) BedZED Construction materials report. Online at: [www.massbalance.org/downloads/projectfiles/1640-00195.pdf](http://www.massbalance.org/downloads/projectfiles/1640-00195.pdf)
- MCKAY, H., BIJLSMA, A., BULL, G., COPPOCK, R., DUCKWORTH, R., HALSALL, L., HUDSON, J.B., HUDSON, R.J., JOHNSON, D., JONES, B., LIGHTFOOT, M., MACKIE, E., MASON, A., MATTHEWS, R., PURDY, N., SENDROS, M., SMITH, S. and WARD, S. (2003). *Woodfuel resources in Britain*. Final Report. Forestry Commission.
- MAKERSCHIN, F. (1999). Short rotation forestry in central and northern Europe. *Forest Ecology and Management* 121, 1–7.
- OLIVER, R., FINCH, J. and TAYLOR, G. (2009). Second generation bioenergy crops and climate change: Effects of elevated CO<sub>2</sub> on water use and yield. *Global Change Biology Bioenergy* 1, 97–114.
- RENEWABLE FUELS AGENCY (2008). *The Gallagher Review of the indirect effects of biofuels*. Renewable Fuels Agency UK. Online at: [www.dft.gov.uk/rfa/reportsandpublications/reviewoftheindirecteffectsofbiofuels.cfm](http://www.dft.gov.uk/rfa/reportsandpublications/reviewoftheindirecteffectsofbiofuels.cfm) (accessed 3 August 2009).
- REID, H., HUQ, S., INKINEN, A., MACGREGOR, J., MACQUEEN, D., MAYERS, J., MURRAY, L. and TIPPER, R. (2004). *Using wood products to mitigate climate change: a review of evidence and key issues for sustainable development*. Online at: [www.iied.org/pubs/display.php?o=10001IIED](http://www.iied.org/pubs/display.php?o=10001IIED)
- ROYAL COMMISSION ON ENVIRONMENTAL POLLUTION (2004). *Biomass as a renewable energy source*. Online at: <http://www.rcep.org.uk/bioreport.htm> (accessed October 2006).
- ROYAL SOCIETY (2008). *Sustainable biofuels: prospects and challenges*. Royal Society, London.
- ROWE, R.L., STREET, N.R. and TAYLOR, G. (2009). Identifying potential environmental impacts of large-scale deployment of dedicated bioenergy crops in the UK. *Renewable and Sustainable Energy Reviews* 13, 271–290.
- SLADE, R., PANOUTSOU, C. and BAUEN, A. (2009). Reconciling bio-energy policy and delivery in the UK: will UK policy initiatives lead to increased deployment? *Biomass and Bioenergy* 33, 679–688.
- SHERRINGTON, C., BARTLEY, J. and MORAN, D. (2008). Farm-level constraints on the domestic supply of perennial energy crops in the UK. *Energy Policy* 36, 2504–2512.
- ST. CLAIR, S., HILLIER, J. and SMITH, P. (2008). Estimating the pre-harvest greenhouse gas costs of energy crop production. *Biomass and Bioenergy* 32, 442–452.
- THE CARBON TRUST (2004). *Biomass sector review*. Online at: [www.carbontrust.co.uk/Publications/publicationdetail.htm?productid=CTC512](http://www.carbontrust.co.uk/Publications/publicationdetail.htm?productid=CTC512) (accessed 3 August 2009).
- UKERC (2009). *Making the transition to a secure and low-carbon energy system*. Synthesis report, The UKERC Energy 2050 Project.
- UK TIMBER FRAME ASSOCIATION (2009). *Statistics*. Online at: [www.timber-frame.org.uk](http://www.timber-frame.org.uk)
- WHITTAKER, C. and MURPHY, R. (2009). *Assessment of UK Biomass Resource*. A mirror report to the US ‘Billion Ton Report’. AtlannTic Alliance (personal communication).

## THE POTENTIAL OF UK FORESTRY TO CONTRIBUTE TO GOVERNMENT'S EMISSIONS REDUCTION COMMITMENTS

Chapter

8

R. W. Matthews and M. S. J. Broadmeadow

### Key Findings

Significant opportunities exist for the forestry sector in the UK to deliver GHG emissions abatement from woodlands planted since 1990, potentially amounting to 15 MtCO<sub>2</sub> per year by the 2050s and equivalent to 10% of the UK's total GHG emissions if current emissions reduction targets are achieved. The abatement that could be delivered is highly sensitive to the level and timing of woodland creation.

Within forestry, woodland creation is the most effective approach to GHG abatement in the medium to long term, but can deliver relatively little in the UK Government's first three carbon budgets (to 2022). However, by 2050, a 25 000 ha per year programme of woodland creation between now and 2025 could deliver 130 MtCO<sub>2</sub> abatement through sequestration in growing biomass, or total abatement (including fossil fuel and product substitution) of 200 MtCO<sub>2</sub>.

There is limited scope for changes in forest management alone to deliver significant levels of emission abatement, implying that woodland creation should be the initial focus of activity. Optimising timber production in appropriate stands offers the largest opportunities for abatement through new approaches to forest management. Measures that focus solely on increasing forest carbon stocks are likely to limit the abatement potential because of lost opportunities for fossil fuel and product substitution.

If the forestry sector is to deliver the abatement that it can potentially provide its full contribution must be recognised including both carbon storage in forest biomass and abatement through wood and timber products substituting for fossil fuels directly and indirectly.

Currently, the UK's land use, land use change and forestry (LULUCF) GHG inventory does not adequately reflect emissions from, and uptake by, existing woodlands. Furthermore, the lack of attribution to the forestry sector of emissions abatement contributed by forestry products used by other sectors, e.g. energy and construction may limit the development of abatement strategies in the forestry sector.

Woodland creation (and subsequent management) in the UK can be a cost-effective approach to combating climate change; for a number of woodland creation scenarios, net social costs of abatement are negative, but rise to £70 per tonne CO<sub>2</sub> for the least cost-effective options. Production conifer plantations represent particularly cost-effective abatement, although if ancillary benefits were also included in the analysis, the cost-effectiveness of broadleaf and native woodland options, in particular, would increase.

Woodland creation provides a range of co-benefits (social, economic and environmental) that many other approaches to emissions abatement do not provide; if these co-benefits were included in the net cost calculations, abatement through woodland creation would appear even more cost-effective, particularly for those woodland creation options with lower revenue from sales of timber or woodfuel.

A significant woodland creation programme would require the existing regulatory requirements and standards to be maintained; it would also require a spatial planning framework to be established to identify where woodland creation could contribute most to other objectives.



Forest growth results in removal of CO<sub>2</sub> from the atmosphere into the carbon stock of the forest, and the provision of woodfuel and wood products that can be used to substitute for fossil-fuel derived energy sources and materials. At a global level, the potential of the forestry sector to reduce net GHG emissions (i.e. provide 'abatement' of GHG emissions) has been evaluated by the IPCC as a total of 6.7 GtCO<sub>2</sub> per annum in 2030 (Nabuurs *et al.*, 2007).

Approximately half of this amount would be achieved by substituting timber and wood products both directly and indirectly for fossil fuel use. The remaining 3.2 GtCO<sub>2</sub> of abatement was assessed to be evenly distributed between reduced deforestation and afforestation. The abatement potential for Europe has been estimated as 295 MtCO<sub>2</sub> per year in 2030 (Nabuurs *et al.*, 2007).

The concept of accounting for the fossil fuel substitution benefits associated with forest management and woodland creation was reviewed by Matthews (1996). However, in such analyses an over-emphasis on the carbon stored in forest biomass often hides the cross-sectoral contribution that can be made through forest management. Given the current policy focus on carbon budgets, both nationally and globally, it is therefore timely to reconsider the wider potential of forestry within the UK to provide carbon abatement. This chapter therefore provides an holistic assessment of the total GHG emissions abatement potential of the forestry sector in the UK at two scales: national and stand-scale. The contribution of those forest management practices that result in the largest changes in the carbon stocks of forest biomass (as discussed in Chapter 6) are estimated. The roles of harvested wood products, and the fossil fuel emissions that are avoided through utilisation of wood and timber products (see Chapter 7) are taken into account. Importantly, the long-term GHG emissions abatement potentials through to 2100 of a range of woodland creation options are presented. The cost-effectiveness of woodland creation is then evaluated in comparison with other abatement options available across other sectors of the economy.

### 8.1 Carbon abatement through forestry: UK and international perspectives

The UK Government has set an extremely challenging and legally binding emissions target of an 80% reduction on 1990 emissions by 2050 – meaning that current UK

annual emissions (as for 2007) of 611 MtCO<sub>2</sub>e need to fall to 155 MtCO<sub>2</sub>e. This target was set on the advice of the Committee on Climate Change. It represents the necessary contribution of the UK to restricting the global increase in temperature to 2°C, taking 'burden-sharing' between developed and developing countries into account. Interim targets have been set for the first three five-year budget periods that are required to be in place under the terms of the Climate Change Act (GB Parliament, 2008). The target for 2020 (2018–2022) is for a 34% reduction on 1990 GHG emissions, a figure that may rise to 42% if a comprehensive global agreement on emissions reduction is reached through UNFCCC negotiations (CCC, 2008; HMT, 2009).

An assessment has been made of the abatement that each sector (e.g. transport, energy, agriculture and forestry) could deliver (CCC, 2008) and, in the UK Low Carbon Transition Plan (DECC, 2009b), the UK Government announced how the emissions reductions committed to in the first three budget periods would be met. Although abatement resulting from woodland creation was not identified as contributing significantly in the first three budget periods, its long-term role in helping to achieve the ultimate target of an 80% reduction in emissions was outlined, and a programme of new woodland creation was recognised as having the potential to contribute to this target. In this chapter we explore the aspiration expressed in the Low Carbon Transition Plan by providing quantification of the extent to which forests, under a range of different scenarios, could indeed provide a significant contribution to the UK mitigation strategy.

The potential for decarbonisation of energy supply was explored in the UK Renewable Energy Strategy (DECC, 2009c). This included an assessment indicating that renewables could contribute 15% of energy requirements by 2020. Biomass was assessed as delivering 33% of the renewables target, with woodfuel making a significant contribution. Annual production of 2 million tonnes woodfuel from English woodlands is included in the assessment of the Woodfuel Strategy for England (FC,

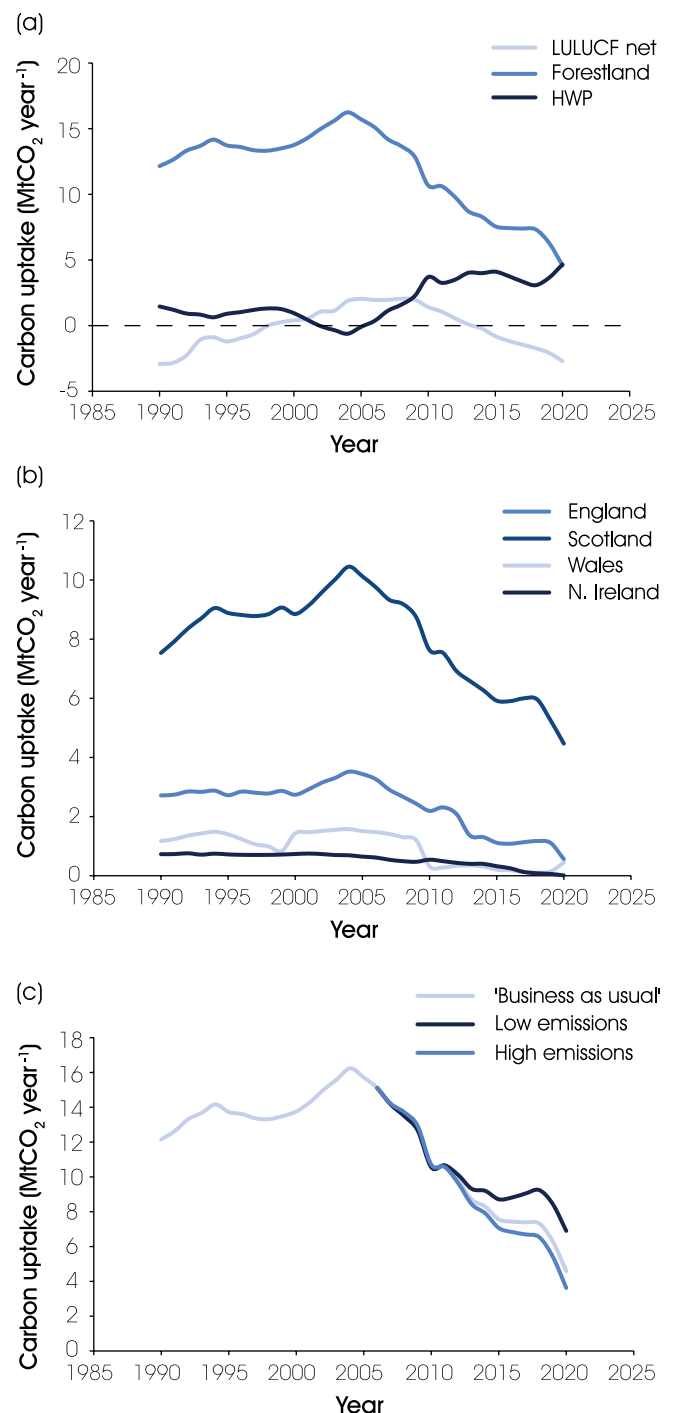
2007), while the Scottish Forestry Strategy (Scottish Executive, 2006) has committed to delivering 1 MtCO<sub>2</sub> emissions abatement through renewable energy production by 2020 (see 1.5.1, Chapter 1; 7.1.3 and 7.1.4, Chapter 7).

### 8.1.1 The forestry contribution to the UK's GHG inventory: projections to 2020

In the UK, the greenhouse gas (GHG) balance of the forestry sector is reported as a component of the Land Use, Land Use Change and Forestry (LULUCF) GHG inventory using methodologies compatible with the Good Practice Guidelines published by the Intergovernmental Panel on Climate Change (IPCC, 2006), as described in Chapter 1. The GHG balance of UK woodland (using the UK definition of woodland: see Chapter 1) is reported under the terms of the United Nations Framework Convention on Climate Change (UNFCCC). For pragmatic reasons, the forestry GHG inventory is currently restricted to woodlands planted after 1919 because good data records are available for these woodlands. It is assumed that woodlands planted before this date are at equilibrium in terms of GHG balance. The inventory projections of net carbon uptake rates by forests are prepared using the C-FLOW carbon accounting model (Dewar, 1991; Dewar and Cannell, 1992; see Thomson, 2009 for the current formulation and parameterisation of the model). Annual carbon uptake/removals in tree biomass, soil carbon and harvested wood products are modelled on the basis of year of planting and assuming that the woodlands are managed conventionally, according to published forest growth and yield models (Edwards and Christie, 1981). Broadleaved woodland is modelled as Yield Class (YC) 6 beech (see Glossary for definition of Yield Class). Modelling of conifer woodland assumes YC 12 Sitka spruce (but YC 14 in Northern Ireland). The projections (Figure 8.1 a,b) assume that annual rates of woodland creation (8360 ha year<sup>-1</sup>) and removal (1128 ha year<sup>-1</sup>) continue as reported for 2006 (although the rate of woodland removal is assumed to decline in the future). This is described as the 'business-as-usual' (BAU) scenario.

The dynamics of the current and projected UK forest carbon sink are thus largely determined by historic planting patterns involving large scale afforestation schemes operating through the 1950s to the 1980s. As a result of these, the estimated strength of the UK forest carbon sink increased from 12 MtCO<sub>2</sub> year<sup>-1</sup> in 1990 to a peak of 16 MtCO<sub>2</sub> year<sup>-1</sup> in 2004 (Figure 8.1c). However, because of the marked decline in new planting since the 30 000 ha per year in the late-1980s (see Figure 1 in 1.4, Chapter 1),

**Figure 8.1** Values of net GHG (CO<sub>2</sub> equivalents) uptake for the UK GHG inventory projected to 2020. Values for: (a) forest land, harvested wood products (HWP), and the net change from the whole LULUCF sector (LULUCFnet); (b) net CO<sub>2</sub> uptake by forests in the four countries of the UK, including changes in stocks of harvested wood products; (c) forest net uptake assuming 'business-as-usual' (BAU) (as in forestland (a) above), high emissions scenario (no new afforestation) and low emissions scenario (increased afforestation). (See text for description of scenarios. All data as reported to UNFCCC; Thomson, 2009.)



the estimated forest carbon sink has subsequently fallen to little more than 12 MtCO<sub>2</sub> year<sup>-1</sup> in 2009. A further dramatic decline is projected to 4.6 MtCO<sub>2</sub> year<sup>-1</sup> in 2020 (Figure 8.1c). This decline in the strength of the forest carbon sink has serious implications for the UK's GHG inventory, particularly in the light of the challenging targets for emissions reductions outlined first in the Climate Change Act (2008) and, subsequently, in the UK Low Carbon Transition Plan (DECC, 2009b). It is, however, important to recognise that despite the falling CO<sub>2</sub> uptake rates, UK woodlands remain a carbon sink, albeit at a much reduced level, through to 2020.

Largely because of the pattern of previous large scale planting, followed by reductions in the extent of woodland creation experienced in the UK over the last decade, there will be a rapid decline in the extent of abatement provided by forest land up to 2020 (Figure 8.1a). The decline in new planting contributes significantly to the LULUCF GHG inventory becoming negative by 2020, i.e. it becomes a net source of carbon (Figure 8.1a). The pattern is broadly the same for all of the devolved administrations but the decline appears to be particularly marked in Scotland as a result of the relatively large proportion of new planting during the 1950s to 1980s in that country (Figure 8.1b). The UK GHG inventory has explored the impacts of two alternatives to the BAU scenario on the projected forest carbon sink (Figure 8.1c). A low emissions scenario considers the impact of increasing woodland creation between 2007 and 2020 to 25 000 ha year<sup>-1</sup> (compared with the BAU assumption of 8360 ha year<sup>-1</sup>), with the assumption that broadleaf and conifer species are planted in the same ratio as at present. A high emissions scenario considers the impact of no new woodland creation between 2007 and 2020. As illustrated in the three projections in Figure 8.1c, for the low emissions scenario involving enhanced woodland creation, the decline in abatement is reduced relative to the BAU and high emissions (no woodland creation) scenarios.

The decline in the forest carbon sink evident in the projections to 2020 can only be modified a little by increases or decreases in new woodland planting. This is clearly demonstrated by the relatively small difference between the low and high emissions scenarios (Figure 8.1c) compared to the decline in the strength of the overall sink. However, a subsequent significant level of abatement would be provided by a sustained increase in woodland creation starting at the present as demonstrated in 8.2 and 8.3 below.

### 8.1.2 Forestry contribution to UK Kyoto protocol-reporting

The reporting of the GHG balance of forests under the terms of the UNFCCC's Kyoto Protocol is restricted to CO<sub>2</sub> emissions and uptake (i.e. removal from the atmosphere) associated with afforestation, deforestation and reforestation (ARD) that has taken place since 1990. This provides a much better indication of the potential contribution of the forestry sector through changes to rates of woodland creation and removal because the effects of the high planting rates in the 1950s to 1980s that dominate the inventory projections shown in Figure 8.1 are not included. Business-as-usual (BAU) projections for UK forests (assuming woodland creation and removal continue at 2006 levels) indicate that CO<sub>2</sub> uptake associated with the 'Kyoto forest' (i.e. new woodlands planted since 1990 and accounting for woodland removal) will rise to 2.5 MtCO<sub>2</sub> per year in 2012. Although meeting commitments made under the Kyoto Protocol is clearly a high policy priority at present, it is uncertain how LULUCF reporting, particularly for forestry, will be taken forward. It is important to recognise that unlike the GHG inventory reported to the UNFCCC, emissions and uptakes associated with ARD that are reported under the terms of the Kyoto Protocol do not include carbon stocks associated with harvested wood products.

### 8.1.3 The role of forestry in meeting the UK's GHG reduction commitments

Further development of the UK's LULUCF GHG inventory that is currently in progress (Thomson, 2009), coupled with the results being delivered by the National Forest Inventory (see Chapter 1), will improve its precision and enable the impacts of changes in forest management to be better reflected in the values reported. However, accounting methodologies mean that although the carbon stocks in harvested wood products may be allocated to the LULUCF/forestry sector, emissions reduction that result from wood substituting for fossil fuels are not. This includes both direct substitution in the form of woodfuel and indirect substitution (product displacement) through timber products replacing high energy materials such as concrete and steel. This approach to emissions accounting can result in the conclusion (see Chapter 6) that to maximise the forestry sector's contribution to emissions reduction, carbon stocks in forest biomass should be maximised and harvesting minimised (Forster and Levy, 2008). However, as demonstrated by Nabuurs (1996), Tipper *et al.* (2004) and Nabuurs *et al.* (2007) such

a conclusion can be over-simplistic, with total abatement in the longer term maximised by maintaining high growth rates through managing woodlands and utilising the resulting timber products effectively. The need to supply a future low carbon society with sustainably produced wood products should also be recognised. Furthermore, the sustainable management of woodlands in the UK also has a potential role in reducing unsustainable harvesting of old growth forests and subsequent land use change elsewhere in the world.

A further complication in GHG accounting relates to GHG emissions abated through direct fossil fuel substitution (see above) when woodfuel is used to generate electricity. Emissions from electricity production are capped under the EU Emissions Trading Scheme (EU-ETS) – and are part of the so-called 'traded sector'. As such, emissions reductions in this sector would not be considered as abatement because a reduction in traded-sector emissions in the UK would (theoretically) result in higher emissions elsewhere in the EU. It would only be considered as abatement if such actions directly brought about a reduction in the cap (DECC, 2009a). However, we believe that it is important to acknowledge the contribution of the forestry sector to reducing emissions within the UK as a part of the global response to climate change. Emissions reduction through substituting directly for fossil fuels in electricity generation are included in the abatement potential reported in 8.2 and 8.3 below. However, for consistency with wider cross-sector studies they are not included in the subsequent evaluation of cost-effectiveness (see 8.4 below).

## 8.2 National level forest management scenarios

The way in which existing woodlands are managed has a significant impact on their carbon stocks (see 3.4 and 3.5, Chapter 3 and Chapter 6) and, consequently, on their ability to deliver emissions abatement. Although the current UK GHG inventory would not reflect any changes made in forest management, planned improvements to the forestry sector inventory may allow the impacts of any actions to be reflected in the future. The objective of this chapter is to evaluate the effect of forest management options at national scale on the GHG inventory, incorporating a limited number of country specific measures. The scenarios presented here are purely illustrative and do not reflect what is planned or might be achievable; they are intended to demonstrate the level to which the GHG inventory could

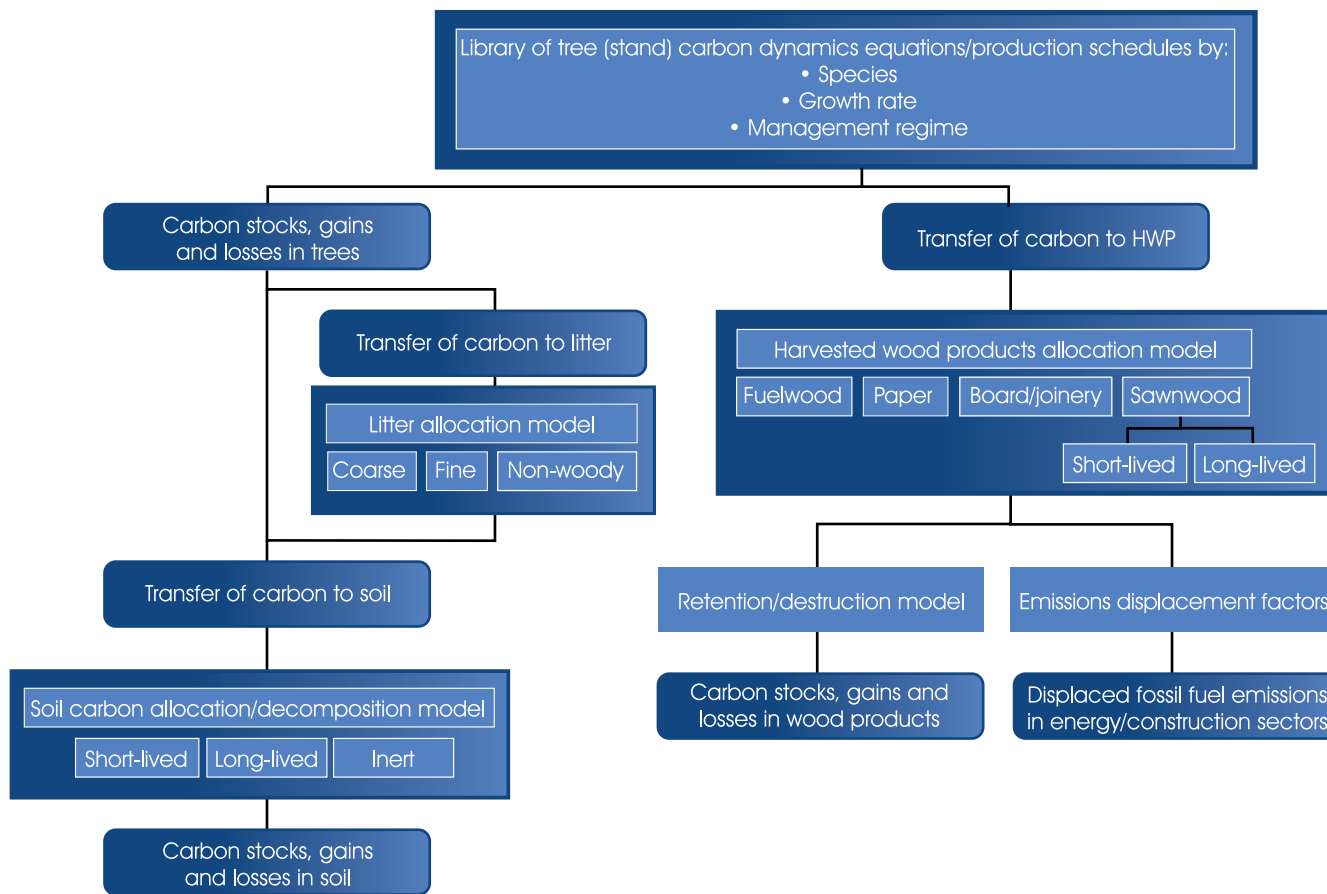
be affected by changes in forest management and to identify those measures that warrant further exploration.

### 8.2.1 The CARBINE carbon accounting tool

The following discussion describes simulations of GHG balances in the forest sector (as well as interactions with the energy and construction sectors) with the main objective of capturing indicative changes in emissions abatement under a number of different management scenarios and woodland creation options. The simulations have been undertaken using the Forest Research CARBINE model. CARBINE was the world's first forest carbon accounting model to be developed (Thompson and Matthews, 1989a,b) and has common features of structure and functionality with other forest carbon models such as C-FLOW (Dewar, 1990, 1991; Dewar and Cannell, 1992), CO<sub>2</sub>fix (Mohren and Klein Goldewijk, 1990; Nabuurs, 1996; Mohren *et al.*, 1999) and CBM-CFS3 (Kurz *et al.*, 2009). From the outset, links between the forest sector and harvested wood products (HWP) were recognised to be important and are represented within the CARBINE model structure. The model was also one of the first to be applied to understanding impacts across the forest, energy and construction sectors (Matthews, 1994). Subsequently, CARBINE has been further developed into a national-scale scenario analysis tool and has been used to assess the impacts of current and alternative forestry practices on GHG balances in Great Britain (Matthews, 1996). The modelling system is based on conventional yield models (e.g. Edwards and Christie, 1981), coupled to models of carbon content, decomposition, soil carbon exchange, product utilisation and empirical data on the GHG balance of forestry operations, timber transport and timber processing.

The forest biomass and management components incorporated in CARBINE are shown in Figure 8.2. The modelling involves a sequential approach in which an appropriate yield model is selected and used to estimate biomass of various tree components employing the BSORT model (Matthews and Duckworth, 2005). Wood density (Lavers, 1983) is used within BSORT in order to convert wood volumes to dry weight, 50% of which is assumed to be carbon (Matthews, 1993). The biomass components are roots, stump, roundwood, sawlog, tips, branches and foliage. The biomass of the different compartments are considered either as standing (living) biomass, in-forest debris, or extracted material to be processed. Finally, the modelling system provides estimates of direct fossil fuel substitution (i.e. using woody

Figure 8.2  
Schematic representation of the structure and components of the CARBINE forestry carbon accounting model.



biomass for energy generation), and product substitution where, for example in construction, a wood product may replace other building materials with higher associated fossil fuel emissions (see Chapter 7).

Alongside growth and product estimations, the impacts on soil carbon and operational fossil fuel use involved in establishing, maintaining and harvesting trees, and processing extracted material of the forest are all considered. Model estimates have been produced for a number of species and site conditions broadly representative of existing and potential scenarios across the UK. While site conditions and species are key determinants of C stocks and sequestration potential of woodland, stand management (notably thinning, application of silvicultural systems and rotation length) also has profound impacts (Chapter 6). In this series of simulations, the GHG balance of the non-forest understorey is not considered.

The comprehensive analysis associated with the CARBINE

modelling system represents a marked departure from many previous attempts to evaluate abatement potential, which, like C-FLOW, have concentrated on forest carbon stocks and/or carbon stocks in harvested products (e.g. Forster and Levy, 2008). The inadequacies of many previous studies were highlighted by Matthews (1996), who reviewed the studies of the impacts of forest management (including woodland creation) on carbon balance available at that time. Of the 43 studies evaluated, only three considered all forest carbon pools and the contribution from both direct and indirect fossil fuel substitution. Matthews (1996) concluded that the inconsistencies and differing viewpoints evident in the studies were the result of the differing carbon-budgeting methodologies used in the studies – and that ‘a clear and correct picture of the extent to which forest management can be modified to enhance C sequestration by forests’ can only emerge when conventions for the modelling and reporting of carbon budgets for forests and their management are agreed. The analysis presented here therefore provides clarity over the contribution of each



component to total emissions abatement, enabling an holistic assessment of the contribution of forest management and woodland creation to carbon abatement to be made.

## 8.2.2 Forest management scenarios

The forest management scenarios detailed below evaluate a range of measures that affect forest carbon stocks or the ability of forest products to deliver emissions abatement by substituting for fossil fuels, either directly or indirectly. A comparison of CARBINE simulations with those produced by the C-FLOW model used to produce the GHG inventory for the forestry sector is provided by Robertson *et al.* (2003) and Matthews *et al.* (2007).

### Enhanced afforestation scenario (EAS)

This scenario explores the abatement potential that could be achieved in the four countries of the UK by means of enhanced levels of woodland creation over the period 2010 to 2050. It is based on published targets, aspirations and case studies produced by the respective countries (e.g. FC, 2009; DECC, 2009b), coupled in some cases with expert judgement of desirable and achievable rates of woodland creation. The nature of the woodland created differs between countries (Table 8.1), its composition in the simulations having been determined following discussions with policy representatives in each country. A total of four distinct woodland types are included for England, designated as: high yielding short rotation forestry, managed broadleaf woodland (Sycamore-Ash-Birch), unmanaged native broadleaf woodland (Native), and conventionally managed Douglas fir. For Scotland, Wales and Northern Ireland, managed broadleaf (Sycamore-Ash-Birch) and unmanaged native woodland categories are assessed, while Sitka spruce replaces Douglas fir as the modelled conifer crop species (but mixed Sitka spruce and Douglas fir in Wales). The combined total of new planting for the four countries is assumed to be 23 200 hectares year<sup>-1</sup> for the period 2010–2050, representing an enhancement of 14 840 hectares year<sup>-1</sup> over the baseline projection of new planting assumed in the UK inventory of 8360 hectares year<sup>-1</sup> (see 8.1.1 above). The recent rate of deforestation (1128 ha year<sup>-1</sup> for the UK) is assumed to continue, maintaining consistency in terms of woodland area with the UK's 'low emissions scenario' GHG inventory projections described in 8.1.1 above. For consistency with reporting conventions under the Kyoto Protocol, results for the EAS scenario include the contributions due to existing new planting between 1990 and 2009 as well

as the proposed new planting from 2010. The abatement potentials of a broader range of woodland creation options and species are considered later.

### Carbon stock enhancement scenario (FMS-A)

FMS-A recognises that forest carbon stocks can be enhanced by: (1) ceasing the management (i.e. harvesting and/or thinning) of existing woodland, effectively creating 'carbon reserves' or (2) deferring harvesting by 20 years or 25% of the rotation length, whichever is the greater. Here, both approaches are included in the analysis and applied to half the managed forest area in each country (calculated from timber production statistics). The relative contributions of each of the enhancement components assumed in the analysis differs between countries (Table 8.1).

### Enhanced management scenario (FMS-B)

FMS-B assumes increasing the level of management (e.g. thinning and harvesting) will reduce the carbon stocks in the standing biomass. If the timber products are used in substitution (either as woodfuel to substitute for fossil fuels or as wood products to substitute indirectly), the abatement that may be achieved could more than compensate for the lower forest carbon stocks, particularly in the longer term. This scenario assumes that in all four countries, 50% of the existing managed woodland (as calculated from timber production statistics) is managed closer to optimum rotation length for timber production (Table 8.1).

### Improved productivity scenario (FMS-C)

FMS-C considers the impact of increasing productivity at restocking, based upon the apparently logical assumption that increases of productivity (i.e. yield class) will enhance both rates of sequestration in biomass and, to a larger extent, the abatement potential through fossil fuel substitution. Increased productivity could be achieved through species/provenance selection (including suitability for the projected impacts of climate change, see Sections 2 and 4) or through the continued development of improved planting stock. It is assumed that YC is increased by 2 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup> on 50% of sites at restocking by using Douglas fir to replace Corsican pine; Japanese larch to replace Scots pine; and Western red cedar to replace Sitka spruce (Table 8.1). Improved productivity is thus assumed to be implemented across 11% of woodlands in England, 30% in Scotland and 18% in Wales, based on species breakdown recorded in the National Inventory of Woodland and Trees

(Forestry Commission, 2001a,b, 2002). FMS-C supplements either FMS-A or FMS-B to give two scenarios: FMS-C(A) and FMS-C(B).

### Reinstating management scenario (FMS-D)

FMS-D considers the impact on abatement of bringing a proportion of woodlands that are currently unmanaged, or under-managed, back into productive management through re-instatement of regular thinning and harvesting (and re-planting as necessary). As in scenario FMS-B, the reduction in carbon stocks needs to be set against the increased abatement that could be delivered through direct and indirect fossil fuel substitution. This scenario assumes that 50% of unmanaged woodland (calculated from timber production statistics) in each of the countries is brought back into management (Table 8.1).

### 8.2.3 Illustration of the contribution of different components to total abatement potential from forestry

In order to understand the differences in projected emissions abatement potential of the various forest management scenarios, it is helpful first, to illustrate the way the individual components contribute to total emissions abatement. A number of components constitute the total carbon balance for the forestry sector: trees, litter and soils, harvested wood products, direct fossil

fuel substitution ('fuel'), indirect fossil fuel substitution ('materials') and emissions arising from woodland removal ('deforestation') (Figures 8.3a and b). The dynamics of each of these components can affect the overall abatement potential as outlined for one of the forest management scenarios, C-stock enhancement (FM-A), in Figure 8.3b. Up to 2020, the analysis presented in Figure 8.3a for the business-as-usual (BAU) scenario is similar to the LULUCF GHG inventory projections presented in 8.1.1 above, but additionally considers abatement through fossil fuel substitution and within forest uptake and emissions in greater detail. The BAU assumes that UK afforestation and woodland removal rates continue into the future at 2006 rates (8360 ha year<sup>-1</sup> and 1128 ha year<sup>-1</sup>, respectively). Figure 8.3b estimates the forest sector GHG inventory, additionally assuming the implementation of forest management scenario FMS-A. The results demonstrate:

- the relative contributions of each component of forest carbon to overall abatement;
- the changes over time in the relative contribution from sequestration and substitution to abatement;
- the relative impact of implementing FMS-A compared with the carbon balance of the forest sector assuming current (BAU) approaches to woodland management and levels of afforestation and deforestation;
- the details of the five forest management scenarios are given in Table 8.1.

Table 8.1

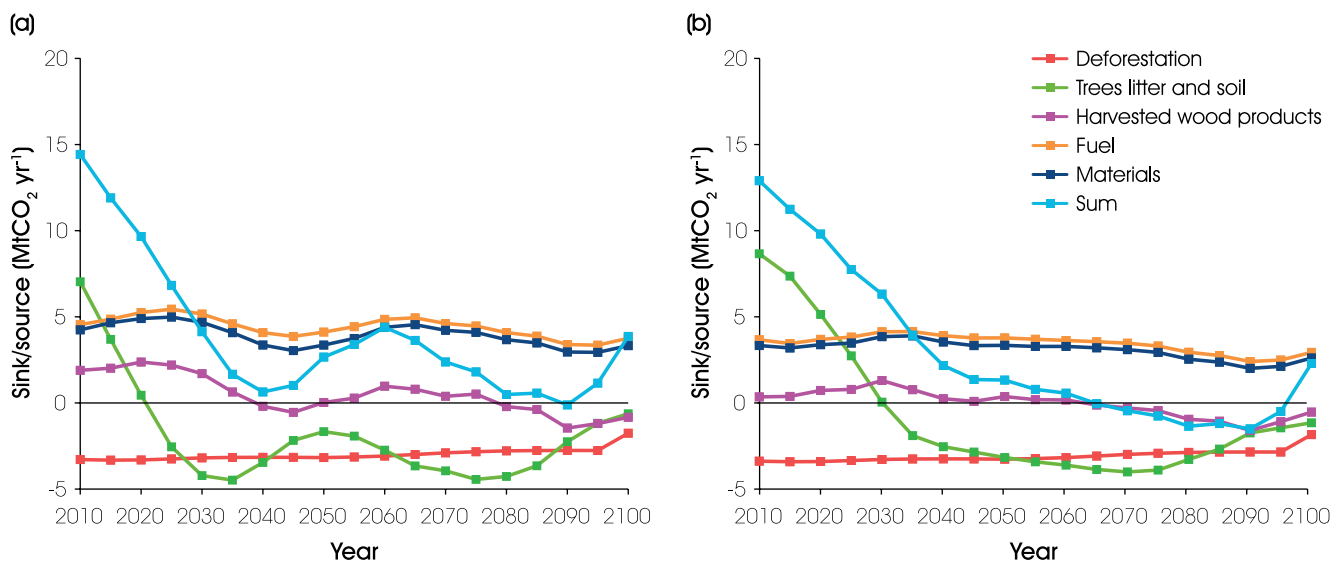
Assumed changes to forest management in England, Scotland, Wales and Northern Ireland for the five scenarios used to project changes in CO<sub>2</sub> uptake values reported in Figures 8.3 and 8.4. Enhanced afforestation – areas are annual rates of new planting. Combined total new planting for UK is 23 200 ha year<sup>-1</sup> (14 840 ha year<sup>-1</sup> additional to 8360 ha year<sup>-1</sup> assumed under BAU).

Country	EAS: Enhanced afforestation	FMS-A: C-stock enhancement	FMS-B: Enhanced management	FMS-C: Improved productivity	FMS-D: Reinstating management
England	SRF: 1500 ha SAB: 2000 ha Native: 5000 ha DF: 1500 ha	30% of managed forest to carbon reserves 20% deferred fell	50% of managed forest to optimum rotation length	FMS-A or FMS-B plus: 50% CP to DF 50% SP to JL 50% SS to WRC	50% of unmanaged woodland brought into production
Scotland	Native: 2000 ha SAB: 2500 ha SS: 5500 ha	20% of managed forest to carbon reserves 30% deferred fell	50% of managed forest to optimum rotation length	FMS-A or FMS-B plus: 50% SS to WRC	50% of unmanaged woodland brought into production
Wales	Native: 500 ha SAB: 1000 ha DF/SS: 1000 ha	10% of managed forest to carbon reserves 40% deferred fell	50% of managed forest to optimum rotation length	FMS-A or FMS-B plus: 50% SS to DF 100% SP to JL	50% of unmanaged woodland brought into production
Northern Ireland	Native: 100 ha SAB: 300 ha SS: 300 ha	10% of managed forest to carbon reserves 40% deferred fell	50% of managed forest to optimum rotation length	FMS-A or FMS-B plus: 50% SS to WRC	50% of unmanaged woodland brought into production

SRF, short rotation forestry; SAB, sycamore-ash-birch mixture; Native, native woodland species (as appropriate for country) managed with amenity as main priority; SS, Sitka spruce, DF, Douglas fir, SS/DF, Douglas fir and Sitka spruce in mixture; CP, Corsican pine; SP, Scots pine; JL, Japanese larch; WRC, Western red cedar.

Figure 8.3

Comparison of the net carbon uptake by the components (see key) UK forests (sink = positive values; source = negative values) for (a) 'Business-as-usual' GHG inventory projections for the forestry sector with (b) projections that assume that the C-stock enhancement scenario (FMS-A) is implemented.



A comparison of Figure 8.3a with Figure 8.3b shows that the FMS-A scenario gives a change in the projected year that the trees, litter and soil component becomes a net source of CO<sub>2</sub> (i.e. becomes negative) from 2020 to 2030. The strength of the trees, litter and soil sink is enhanced by FMS-A relative to the BAU in the near term because of reduced levels of harvesting. However, between 2030 and 2100, forest biomass and soils become a larger source if FMS-A is implemented, due to the decline in growth rate in mature over-stocked stands. Furthermore, when the contribution to emissions reductions in other sectors is also considered (HWP and fuel), it is evident that as a result of reduced abatement through fossil fuel substitution and product displacement, the abatement potential of forestry in its entirety ('sum') is reduced by implementation of FMS-A. This is particularly the case for the period between 2040 and 2080, during which there is a rise in total abatement ('sum') in the BAU scenario, but not FMS-A. Importantly, in 2050, the point at which emissions reduction commitments are most challenging, implementing FMS-A is projected to result in a reduction in total abatement of 1.3 MtCO<sub>2</sub>. Drawing conclusions on the optimum approach to achieving maximum emissions abatement without considering the contribution outside the forest therefore risks defining management prescriptions that reduce rather than optimise abatement. It should be noted that the decline in the projected strength of the tree, litter and soil sink is, as discussed in 8.1.1 above, primarily a result of the age structure of British woodlands,

particularly the high levels of woodland creation in the 1950s to 1980s. A further point to recognise is that this FMS-A scenario applies to only 50% of managed woodland in the UK, of which only 10–30% are managed as carbon reserves. The impacts on emissions abatement could be significantly larger under different assumptions for FMS-A.

#### 8.2.4 Evaluation of the abatement potentials of different forest management scenarios

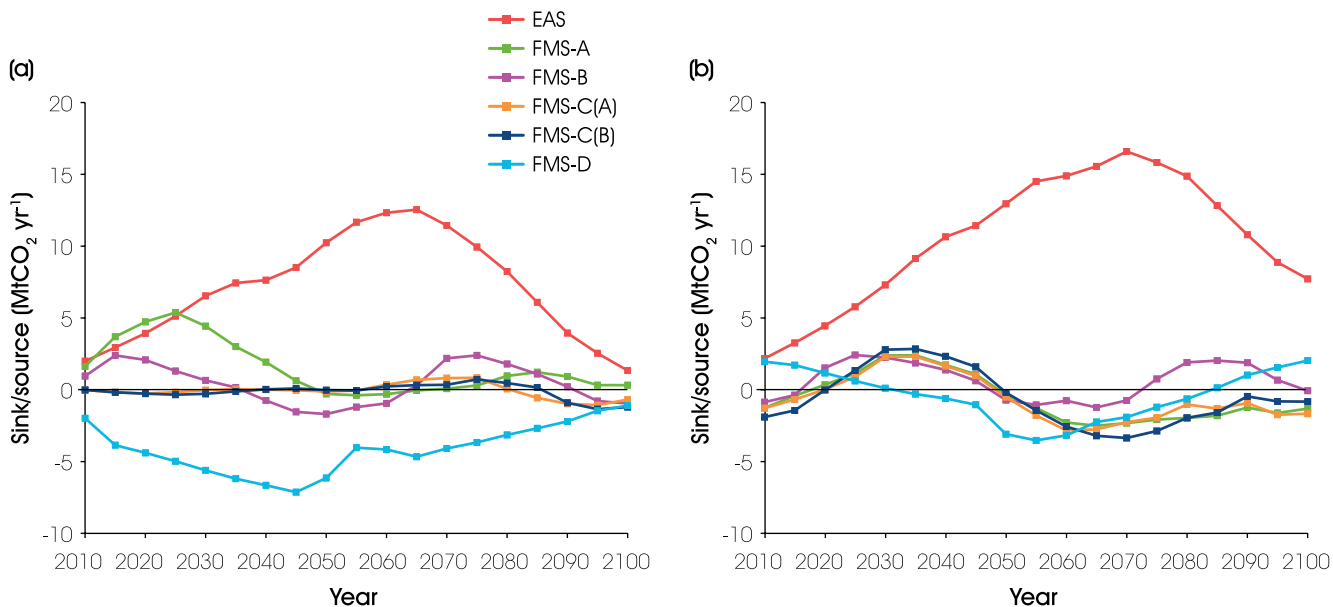
For comparative purposes, the contribution of trees, litter and soil as net CO<sub>2</sub> sinks or sources for each of the forest management scenarios expressed as differences in net CO<sub>2</sub> uptake from the business as usual scenario (Figure 8.3) are shown in Figure 8.4a alongside the total abatement including by fossil-fuel and forest product substitution in Figure 8.4b. The quantitative significance of trees, litter and soil as contributions to the overall abatement is evident. Longer projections for each of the scenarios over different time periods are quantified as average abatement potentials and are presented in Table 8.2.

#### EAS: enhanced afforestation

The clearest conclusion from the comparison of afforestation and forest management scenarios presented in Figure 8.4 is that the enhanced afforestation scenario provides, by far, the greatest potential for additional

Figure 8.4

Impacts of each of the forest management scenarios (see key) on projected CO<sub>2</sub> uptake compared to the BAU scenario in Figure 8.3 (sink = positive values; source = negative values). (a) Net CO<sub>2</sub> emissions associated with trees, litter and soils; (b) total abatement also including carbon stored in harvested wood products, fossil fuel substitution and product substitution.



abatement, particularly in the longer term and when abatement through substitution is also considered. The enhanced afforestation scenario results in the total emissions abatement by all woodland created since 1990, rising to more than 17 MtCO<sub>2</sub> in 2070 (Figure 8.4b). During the 2050s (by which time the UK aims to achieve an 80% reduction in GHG emissions) the total abatement reaches 15 MtCO<sub>2</sub> year<sup>-1</sup>, equivalent to 10% of the UK's total emissions if current reduction targets are achieved. This assumes a total of 23 200 ha year<sup>-1</sup> is planted between 2010 and 2050, representing 14 840 ha year<sup>-1</sup> over and above the BAU assumption that afforestation continues at 8360 ha year<sup>-1</sup> (the area of woodland created in 2006). This large level of abatement is primarily the result of the increase in the forest biomass and soil sink strength, but carbon stored in harvested wood products, fossil fuel substitution and product displacement also make a contribution, particularly towards the end of the simulation period.

#### FMS-A: carbon stock enhancement

Of the forest management scenarios, FMS-A (carbon stock enhancement) appears in Figure 8.4a to provide a consistent and significant additional abatement potential by the uptake of CO<sub>2</sub> into trees, litter and soil over the period 2025 to 2050. This is particularly the case when the FMS-A scenario is combined with FMS-C (improved

productivity). However, as discussed in 8.2.3 above, when total abatement is considered (Figure 8.4b) the benefits of FMS-A are smaller and, even when combined with FMS-C lead to significant emissions relative to the BAU scenario in the longer term (see below for explanation).

#### FMS-B: enhanced management

In contrast to the FMS-A scenario, FMS-B (enhanced management) appears to contribute little to additional abatement when only forest biomass and soil carbon stocks are considered. However, the contribution of enhanced management to abatement through substitution results in additional abatement of up to 2.5 MtCO<sub>2</sub> year<sup>-1</sup> between 2020 and 2040, and 2075 and 2095. The additional abatement is further enhanced between 2020 and 2050 by combining FMS-B with FMS-C, but the opposite result is apparent towards the end of the simulation. Furthermore, FMS-B is the only forest management scenario that delivers net abatement over all time periods presented in Table 8.2, even when the assessment of abatement is restricted to forest biomass and soils components. Optimising rotation length therefore appears to offer real opportunities for abatement, although the level of abatement is limited, largely because forests in the UK that are managed for production are often already close to optimum rotation length.

## FMS-C: improved productivity

In this analysis, FMS-C is assumed to be implemented in combination with either FMS-A or FMS-B. When combined with FMS-A, FMS-C appears to lead to a significant reduction in the uptake into forest biomass and soils (Figure 8.4a), although the impact on total abatement is reduced when substitution and storage in harvested wood products is also considered. When combined with FMS-B, FMS-C appears to reduce fluctuations in the uptake into forest biomass and soils with little impact when averaged over the long term (Table 8.2). However, when abatement through substitution is also considered, there is a marked reduction after 2050. In both cases, the impacts of FMS-C can be largely attributed to complex changes in patterns of production, including rotation lengths and consequent changes to the dynamics of forest carbon stocks that are assumed for more productive stands.

## FMS-D: reinstating management

Bringing unmanaged woodlands back into management (FMS-D) leads to significant net emissions (up to 5.5 MtCO<sub>2</sub> year<sup>-1</sup>) from forest biomass and soils relative to the BAU scenario. However, this impact is reduced when total abatement is considered, with the result that over the full course of the simulation to 2150 (Table 8.2), FMS-D provides a small amount of additional abatement (0.3 MtCO<sub>2</sub> year<sup>-1</sup>). An important point to recognise is that the majority of unmanaged woodland is slow-growing, broadleaved woodland for which both levels of production (and therefore substitution) and rates of recovery in carbon stocks following harvesting are smaller than for faster growing conifer species. The age and current growth rate of a stand brought back into management will also have a profound effect on the balance between substitution benefits and recovery of carbon stocks, requiring more detailed knowledge than available as input to this national scale evaluation.

Table 8.2

Comparison of the impact of enhanced afforestation and forest management scenarios on emissions abatement (compared to the business-as-usual scenario) over different time periods and for the different countries of the UK (sink = positive values; source = negative values). (See 8.2.2 above for definition of forest management scenarios.)

Average impact of scenario on BAU emissions abatement potential over different periods (MtCO <sub>2</sub> year <sup>-1</sup> )										
	England		Scotland		Wales		N. Ireland		UK	
	Forest	Total	Forest	Total	Forest	Total	Forest	Total	Forest	Total
<b>2010 to 2050</b>										
EAS	2.3	2.6	3.0	4.2	0.4	0.5	0.2	0.3	6.0	7.7
FMS-A	0.7	0.2	2.0	0.5	0.3	0.0	0.1	0.0	3.1	0.7
FMS-B	0.0	0.1	0.4	0.7	0.0	0.0	0.0	0.0	0.5	0.9
FMS-C(A)	0.0	0.2	-0.1	0.4	0.0	0.0	0.0	0.0	-0.1	0.6
FMS-C(B)	0.0	0.2	-0.1	0.6	0.0	0.0	0.0	0.0	-0.1	0.8
FMS-D	-3.3	0.2	-1.5	-0.1	-0.7	0.0	-0.1	0.0	-5.5	0.1
<b>2010 to 2100</b>										
EAS	3.7	4.7	2.9	5.3	0.6	0.9	0.2	0.4	7.3	11.2
FMS-A	0.4	0.0	0.9	-0.6	0.1	-0.2	0.1	-0.1	1.6	-0.9
FMS-B	0.1	0.1	0.3	0.4	0.0	0.0	0.0	0.0	0.4	0.4
FMS-C(A)	0.0	0.0	0.0	-0.7	0.0	-0.2	0.0	-0.1	-0.1	-0.9
FMS-C(B)	0.0	0.0	-0.1	-0.6	0.0	-0.2	0.0	-0.1	-0.1	-0.9
FMS-D	-2.6	-0.4	-1.1	-0.3	-0.5	0.0	-0.1	0.0	-4.3	-0.7
<b>2010 to 2150</b>										
EAS	2.5	3.5	2.0	4.5	0.4	0.8	0.1	0.3	5.0	9.1
FMS-A	0.3	-0.1	0.6	-1.0	0.1	-0.2	0.0	-0.1	1.1	-1.4
FMS-B	0.1	0.0	0.2	0.2	0.0	0.0	0.0	0.0	0.2	0.3
FMS-C(A)	0.0	-0.1	0.0	-0.9	0.0	-0.2	0.0	-0.1	0.0	-1.4
FMS-C(B)	0.0	-0.2	0.0	-0.9	0.0	-0.2	0.0	-0.1	0.0	-1.4
FMS-D	-1.8	0.2	-0.8	0.0	-0.3	0.1	0.0	0.0	-2.9	0.3



### Optimising forest management

These calculations provide a suitable framework for determining which forest management options deliver abatement in both the longer and shorter term, and thus which of them should be prioritised. When only the tree, litter and soil component is considered, only forest management scenarios enhanced afforestation (EAS) and FMS-A lead to substantial emissions abatement relative to BAU (Table 8.2). However, of these two scenarios, only EAS continues to provide significant abatement over the longer term.

Even more importantly, when total abatement in the forestry sector including fossil fuel substitution is calculated, the potential abatement increases significantly only in the enhanced afforestation case, with implementation of FMS-A resulting in reduced abatement relative to BAU in the longer term. FMS-B (enhanced management) is the only forest management scenario that results in increased emissions abatement (relative to BAU) over all three periods considered for both the forest component alone and total abatement, although at a much lower level than for EAS. Enhanced afforestation (EAS) is thus the only scenario that can deliver high levels of emissions reduction, whether only the forest component or total abatement are considered. These same conclusions can be drawn at individual country level, particularly that the largest level of abatement can be achieved through woodland creation.

Earlier analysis of emissions abatement by UK forests over

a 50-year period by Matthews (1996) are presented in Table 8.3. The conclusions were broadly consistent with those from the forest management scenarios analysed above, however, Matthews (1996) also considered a longer, 500-year period which provided clarity over the long-term implications of changing approaches to forest management. Over this longer period, the impact of stopping all harvesting activity was particularly stark (a reduction in abatement of 23 MtCO<sub>2</sub> year<sup>-1</sup>), while an increase in UK forest area of 20% (500 000 ha) was projected to increase average abatement by 8 MtCO<sub>2</sub> year<sup>-1</sup> over this same 500-year timeframe. In both cases, these estimates of changes to potential abatement included substitution benefits ('whole forestry sector'); if sequestration in the forest only, was considered ('forest only'), ceasing harvesting activity resulted in annual abatement falling by 5.5 MtCO<sub>2</sub> year<sup>-1</sup> and the additional abatement potential of the increased forest area falling to 4 MtCO<sub>2</sub> year<sup>-1</sup>.

### 8.3 Emissions abatement potential of different woodland creation options

The above text established that, across the various forest management scenarios examined, enhanced afforestation is the only option that could greatly increase the emissions abatement potential of the forestry sector. This discussion therefore explores the abatement potential for a range of different woodland creation options and provides an evaluation of the cost-effectiveness of each, based on the

**Table 8.3**  
Evaluation of forest policy or management options for enhancing emissions abatement potential of British forests, through comparison of two alternative calculation methods (sink = positive; source = negative). Modified after Matthews (1996).

Example management option	Change in annual abatement by British forests compared to the business-as-usual scenario (MtCO <sub>2</sub> year <sup>-1</sup> )			
	Forest only (excluding substitution)		Whole forestry sector (including substitution)	
	Over 50 years	Over 500 years	Over 50 years	Over 500 years
Shorter rotations (-20 years)	-4.4	-0.7	-4.8	-2.9
Longer rotations (+20 years)	2.2	0.4	-2.2	-2.9
Utilise unmanaged forests	0.0	0.0	0.4	1.1
Improve timber quality	-1.1	0.4	-0.4	0.4
Stop all harvesting and felling	19.8	2.6	-5.5	-23.5
Increase forest area by 20%:				
with conifers	2.6	0.4	4.0	8.1
with broadleaves	1.8	0.4	4.0	8.1
Business as usual absolute rates	-0.7	-1.1	28.2	27.9

analysis of Crabtree *et al.* (2009). An illustrative example is then provided of how different options incorporated into a woodland creation programme could contribute to the UK's GHG emissions reduction commitments.

While the growth rate and nature of the woodland created is clearly important, the emissions abatement associated with harvested wood products is crucial to the total abatement potential and its delivery. It should be noted that, at this stage, differences in abatement that would result from the different woodland creation options and abatement delivered through fossil fuel substitution would not be registered in the UK's GHG inventory for the LULUCF sector. This is likely to remain the case for fossil fuel substitution (although the abatement would be registered indirectly in other sectors as described in the introduction to this chapter).

### 8.3.1 Woodland creation options

New woodlands can be planted to deliver three principal objectives:

- 1. Energy forestry:** production of biomass primarily for use in energy generation.
- 2. Productive conifer/mixed forestry:** primarily for timber and other harvested wood products.
- 3. Low impact/multi-purpose forestry, including native woodland:** for conservation, amenity and landscape.

Each of these objectives could be achieved by a range of planting and management options, and would only be appropriate on particular sites. We have chosen a number of possible options in each of the three above categories.

**Table 8.4**

Details of the modelled woodland creation options, for which emissions abatement potentials are shown in Table 8.5.

Option	Soil	Trees				
		Species	Spacing (m)	Yield class (m <sup>3</sup> ha <sup>-1</sup> year <sup>-1</sup> )	Management regime	Rotation (years)
B1	Sand	Eucalyptus	2.0	36	No thinning (short rotation forestry)	7
B2	Gley	Eucalyptus	2.0	20	No thinning (short rotation forestry)	7
C1	Loam	SAB	1.5	6	Standard thinning	80
C2	Loam	SAB	1.5	8	Standard thinning	80
D1	Gley	SAB	1.5	4	No thinning	No felling
D2	Gley	SP	3.0	4	No thinning	No felling
E1	Loam	SS/DF mix	2.0	16	Standard thinning (synchronised for 2 species)	50
E2	Loam	DF	2.0	20	Standard thinning	50
F	Loam	OK/SAB/DF/JL mix	1.5	4/4/14/10	ACF (selection)	No final clearfell
G	Loam	SS/DF mix	1.7	12	Standard thinning (synchronised for 2 species)	60
H	Loam	Sitka spruce	2.0	12	ACF (shelterwood)	Final removal of over-storey at 60 years
I	Loam	SS/DF mix	2.0	12	ACF (selection, synchronised for 2 species)	No final clearfell
J	Peaty-gley	Willow	1.0	20	No thinning (short rotation coppice)	6 (harvesting) 24 (re-planting)
K	Peaty-gley	SAB	1.5	12	No thinning (short rotation forestry)	15
L	Peaty-gley	Eucalyptus	2.0	16	No thinning (short rotation forestry)	12

SAB, combined sycamore, ash, birch yield model; SS, Sitka spruce; DF, Douglas fir; OK, oak; JL, Japanese larch; SP, Scots pine; ACF, alternative to clearfell.

'Selection' is defined as the harvesting of individual trees or groups of trees within a regime of continuous cover; shelterwood is defined as the felling and re-planting of small blocks or stories of trees.

These are (Table 8.4):

- Energy forestry: options B, J, K, L
- Productive conifer/mixed forestry: options E, G, H
- Low impact/multi-purpose forestry: options C, D, F, I.

The options evaluated here are not intended to be exhaustive or to represent the likely results of a woodland creation programme; rather, they are intended to indicate the range of options that might be appropriate across the UK. It is important that these options are viewed alongside the information on possible climate change adaptation requirements in Section 4. For example, among the species included in the simulation for illustrative purposes is *Eucalyptus nitens*, which is just one of the possible exotic species listed in Table 6.5 (see 6.6, Chapter 6).

A number of approaches to low impact silviculture – continuous cover forestry (CCF) or alternative to clearfell (ACF) – are included within the options to reflect changing approaches to management, in part, as a response to climate change (options F, H, I). The GHG balance modelling of these options is less well understood than conventional rotational silvicultural systems. A detailed account of this aspect of the calculations is given in Morison *et al.* (2009). The three short rotation forestry (Eucalyptus) options (B1, B2, L) provide an initial evaluation of what may represent a new focus for forestry in the near future. The extent to which energy forestry will develop is uncertain, as are the levels of productivity that may be achieved. There is evidence (mostly anecdotal) that yield classes of up to 50 m<sup>3</sup> ha<sup>-1</sup> year<sup>-1</sup> can be achieved for *Eucalyptus nitens* grown on a seven-year rotation, but the risk of frost damage is still considered as significant. The potential for short rotation forestry in the UK, including the use of native species such as ash and birch (option K) has been further explored by Hardcastle (2006).

The native woodland creation options (options D1 and D2) assume that the woodlands will be managed for biodiversity objectives and that there will be no abatement through fossil fuel substitution. This may well underestimate potential abatement in the longer term, particularly for option D1 (YC 4 native broadleaf woodland), as a future low carbon economy may place increasing emphasis on productive land covers that also deliver biodiversity benefits. This will certainly be the case if the woodfuel sector develops as outlined, for example, in England's Woodfuel Strategy, Scottish Forestry Strategy (SE, 2006), the UK Low Carbon Transition Plan (DECC, 2009b) and the UK Renewable Energy Strategy (DECC, 2009c).

For all options, abatement potential will be dependent on productivity (i.e. yield class) and, therefore, is subject to site conditions. The analysis presented here is thus not appropriate for application to specific projects for estimating abatement potential. It is also important to consider, as outlined by Broadmeadow and Matthews (2003) and in Chapter 6 of this report, that lower yielding sites are generally more suitable for developing woodland carbon reserves, particularly if located far from end-users or timber processing facilities. In contrast, higher yielding sites have the greatest abatement potential, whether through energy forestry or conventional approaches to management.

### 8.3.2 Abatement potential of different woodland creation options

The estimated abatement potential for each of the woodland creation options outlined in Table 8.4 is given in Table 8.5. For each option, potential abatement is presented as cumulative abatement that could be delivered in 2020, 2030, 2050 and 2100 (i.e. 10, 20, 40 and 90 years after first planting) for each hectare of woodland, assuming planting occurs in 2010. The breakdown between abatement through sequestration in trees, litter and soils and through fossil fuel substitution (both direct and indirect) is also given, although the split between the traded and non-traded sector (see 8.1.3 above and 8.4.2 below) is not shown. For clarity, the estimate of abatement potentials up to 2050 of different woodland creation options representative of the three principal objectives (see above), i.e. energy forestry, productive conifer/mixed forestry and low impact/multipurpose forestry is presented in Figure 8.5. It is clear that energy forestry options achieve their large cumulative abatement potential through the substitution benefits, while multi-purpose forestry achieves considerable abatement mainly through sequestration. Productive conifer/mixed forestry achieves abatement largely through sequestration in trees and soil, but substitution contributes significantly in all options.

Table 8.6 repeats Table 8.5 for total abatement, but excludes changes in soil carbon levels, as there is considerable uncertainty in the modelling of soil carbon, as outlined in 8.2 above.

It is clear from Table 8.5 that, in the short term (to 2020 and 2030) the energy forestry options represent the largest abatement potential, delivering up to 648 tCO<sub>2</sub> ha<sup>-1</sup> by 2030 (for YC 36 Eucalyptus: option B1). It should be noted that in common with other options that involve clearfell,

Table 8.5

Emissions abatement potential of different woodland creation options assumed to be planted in 2010. Sequestration: abatement through sequestration in biomass and soil carbon; substitution: abatement through direct and indirect fossil fuel substitution, with no distinction made between traded and non-traded sectors.

Option	Description	Source of abatement	Cumulative abatement potential (tCO <sub>2</sub> ha <sup>-1</sup> )			
			2020	2030	2050	2100
B1	YC 36 Eucalyptus	Sequestration <sup>1</sup>	94	180	-31	-29
		Substitution	234	468	1170	2575
		<b>Total</b>	<b>328</b>	<b>648</b>	<b>1140</b>	<b>2546</b>
B2	YC 20 Eucalyptus	Sequestration	86	167	84	130
		Substitution	130	260	650	1431
		<b>Total</b>	<b>216</b>	<b>427</b>	<b>734</b>	<b>1561</b>
C1	YC 6 broadleaf farm woodland	Sequestration	5	131	390	93
		Substitution	0	0	89	405
		<b>Total</b>	<b>5</b>	<b>131</b>	<b>480</b>	<b>498</b>
C2	YC 8 broadleaf farm woodland	Sequestration	5	143	477	143
		Substitution	0	0	115	542
		<b>Total</b>	<b>5</b>	<b>143</b>	<b>592</b>	<b>685</b>
D1	YC 4 native broadleaf woodland	Sequestration	32	180	517	854
		Substitution	0	0	0	0
		<b>Total</b>	<b>32</b>	<b>180</b>	<b>517</b>	<b>854</b>
D2	YC 4 native pine woodland	Sequestration	-4	30	144	543
		Substitution	0	0	0	0
		<b>Total</b>	<b>-4</b>	<b>30</b>	<b>144</b>	<b>543</b>
E1	YC 16 Douglas fir and Sitka spruce	Sequestration	75	254	487	336
		Substitution	0	0	160	698
		<b>Total</b>	<b>75</b>	<b>254</b>	<b>647</b>	<b>1034</b>
E2	YC 20 Douglas fir	Sequestration	73	276	573	388
		Substitution	0	87	284	1042
		<b>Total</b>	<b>73</b>	<b>364</b>	<b>858</b>	<b>1430</b>
F	YC 4/10/14 mixed woodland; ACF (selection)	Sequestration	56	194	343	337
		Substitution	0	16	133	417
		<b>Total</b>	<b>56</b>	<b>210</b>	<b>476</b>	<b>753</b>
G	YC 12 Sitka spruce and Douglas fir	Sequestration	67	244	477	373
		Substitution	0	0	123	525
		<b>Total</b>	<b>67</b>	<b>244</b>	<b>600</b>	<b>899</b>
H	YC 12 Sitka spruce; ACF (shelterwood)	Sequestration	13	131	324	273
		Substitution	0	0	122	454
		<b>Total</b>	<b>13</b>	<b>131</b>	<b>446</b>	<b>728</b>
I	YC 12 Sitka spruce/Douglas fir; ACF (selection)	Sequestration	46	191	316	207
		Substitution	0	0	152	511
		<b>Total</b>	<b>46</b>	<b>191</b>	<b>468</b>	<b>718</b>
J	YC 20 Short rotation willow coppice	Sequestration	47	17	-15	-25
		Substitution	59	177	353	766
		<b>Total</b>	<b>106</b>	<b>193</b>	<b>338</b>	<b>740</b>
K	YC 12 short rotation native species	Sequestration	92	49	56	45
		Substitution	0	141	281	704
		<b>Total</b>	<b>92</b>	<b>189</b>	<b>338</b>	<b>749</b>
L	YC 16 Eucalyptus (12-year rotation)	Sequestration	222	125	-68	-128
		Substitution	0	223	669	1561
		<b>Total</b>	<b>222</b>	<b>348</b>	<b>601</b>	<b>1432</b>

<sup>1</sup> Sequestration is the total additional carbon stored in biomass and soils in the year considered, less cumulative fossil fuel emissions resulting from management activity. Sequestration can therefore appear as negative in cases where the year considered immediately follows harvesting.

Table 8.6

Total abatement for the woodland creation options given in Table 8.5, but excluding emissions/sequestration in forest soils.

Option	Description	Cumulative abatement potential (tCO <sub>2</sub> ha <sup>-1</sup> )			
		2020	2030	2050	2100
B1	YC 36 Eucalyptus	318	626	1119	2519
B2	YC 20 Eucalyptus	184	359	628	1403
C1	YC 6 broadleaf farm woodland	13	129	446	526
C2	YC 8 broadleaf farm woodland	14	142	560	746
D1	YC 4 native broadleaf woodland	14	123	393	609
D2	YC 4 native pine woodland	-1	7	68	384
E1	YC 16 Douglas fir and Sitka spruce	74	243	632	1246
E2	YC 20 Douglas fir	71	334	882	1799
F	YC 4/10/14 mixed woodland; ACF (selection)	60	201	445	817
G	YC 12 Sitka spruce and Douglas fir	39	179	488	902
H	YC 12 Sitka spruce; ACF (shelterwood)	16	127	448	878
I	YC 12 Sitka spruce/Douglas fir; ACF (selection)	46	181	469	898
J	YC 20 Short rotation willow coppice	137	233	456	787
K	YC 12 short rotation native species	135	220	353	743
L	YC 16 Eucalyptus (12-year rotation)	257	401	675	1766

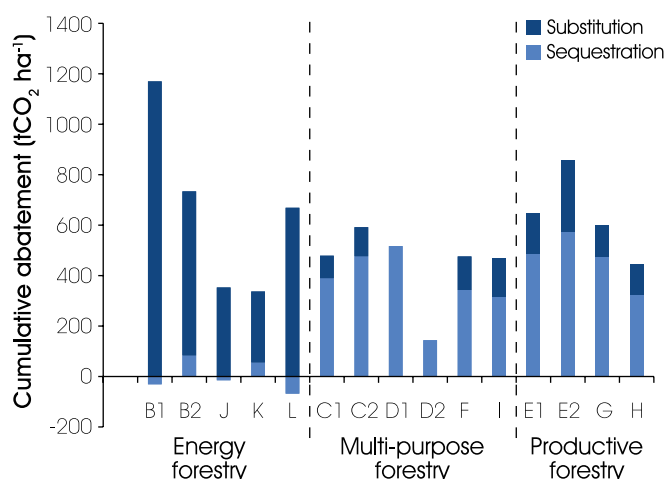
See Table 8.4 for key to abbreviations.

the energy forestry options can appear as negative sequestration abatement (i.e. net GHG emissions) if the time of reporting coincides with harvesting. This is because there has been no increase in biomass carbon stocks (with the exception of soil), but emissions associated with forest management have been accounted for. Other options deliver minimal abatement by 2020, even if

instigated immediately. However, by 2030 and, particularly 2050 (Figure 8.5), the majority of options could provide significant abatement. The one exception is option D2, native pine woodland, which delivers minimal abatement up to 2050 because of the low yield class and low stocking density, reflecting that the principal objective of management is conservation of biodiversity.

Figure 8.5

Projected cumulative emissions abatement from 2010 to 2050 for different woodland creation options grouped by three objectives, showing the contribution from sequestration in the forest biomass and soil carbon components and from substitution by woodfuel and wood products for fossil fuel use and energy-intensive materials. Data from Table 8.5; woodland creation options are detailed in Table 8.4.



### 8.3.3 Case study of the potential abatement achieved by a 15-year woodland creation programme

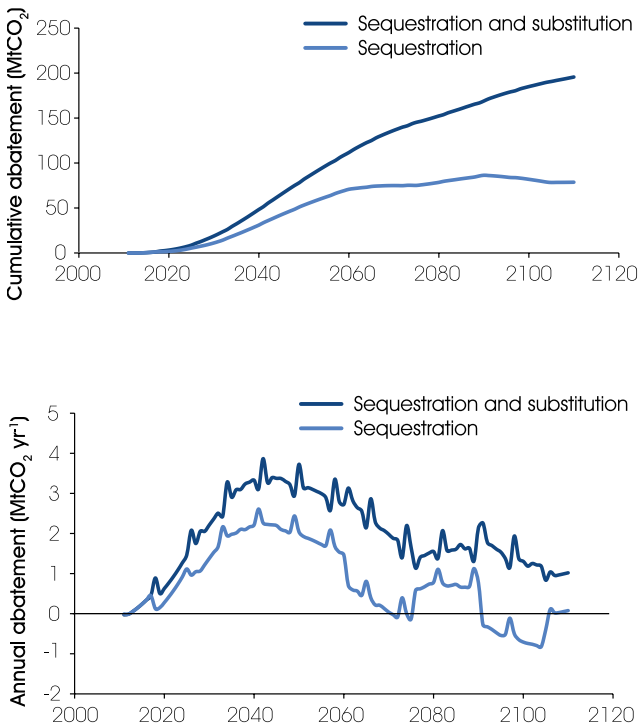
The following case study illustrates the abatement potential that a 15-year, 10000 ha per year woodland creation programme could deliver and provides a comparison with abatement in other sectors and the possible contribution to national emissions reduction targets. The programme considers a narrow range of options, but inclusive of a broad range of forestry objectives:

- 1500 ha year<sup>-1</sup> YC 36 Eucalyptus
- 1500 ha year<sup>-1</sup> YC 20 Douglas fir
- 2000 ha year<sup>-1</sup> YC 8 farm woodland
- 5000 ha year<sup>-1</sup> YC 4 native broadleaf woodland.

Such a programme would provide a minimal contribution to emissions abatement by 2020 (Figure 8.6). This demonstrates that such programmes would not contribute significantly to the first three carbon budgets (and



**Figure 8.6**  
Potential emissions abatement achievable by a woodland creation programme of 10 000 ha per year for 15 years. Time course of (a) cumulative and (b) annual carbon sequestration in woodland biomass and soils (light blue line) and the total abatement including emissions reductions through fossil fuel substitution (dark blue line).



associated emissions reductions) outlined in the Climate Change Act (GB Parliament, 2008) and the UK's low carbon transition plan (DECC, 2009b). However, by the time that an 80% reduction in the UK's GHG emissions is required (i.e. 2050), such a woodland creation programme could have made a significant contribution (53 MtCO<sub>2</sub> cumulative abatement through sequestration alone). Moreover, if abatement through fossil fuel substitution is considered, this rises to 82 MtCO<sub>2</sub> with abatement of 3.7 MtCO<sub>2</sub> delivered in 2050 (Figure 8.6b). This is equivalent to over 2% of target UK emissions in 2050 (155 MtCO<sub>2</sub> per year: see 8.1 above). If this example based on a planting programme of 10 000 ha year<sup>-1</sup> is scaled up to 25 000 ha year<sup>-1</sup> (consistent with assumptions in the UK GHG inventory low emissions scenario (see 8.1.1 above)), the potential cumulative abatement by 2050 is 130 MtCO<sub>2</sub> through sequestration with a total abatement of 200 MtCO<sub>2</sub> when substitution benefits are included. It is therefore possible that, across the UK, woodland creation (and subsequent utilisation of wood products) could deliver additional emissions abatement equivalent to 5–10% of the UK's GHG emissions in the 2050s. The woodland created

would also represent an on-going source of renewable energy and sustainable timber products for future generations, continuing to contribute to a low carbon economy.

The selected options are optimistic in terms of productivity for both the energy forestry and conifer plantation options, assuming that site/species selection and silviculture will be appropriate. If a more conservative scenario is adopted with reduced yields (YC 20 Eucalyptus; YC 6 broadleaf farm woodland; YC 16 Douglas fir), abatement through sequestration in biomass and soil is only reduced to a small extent: from 11 to 10 MtCO<sub>2</sub> by 2030 and 53 to 50 MtCO<sub>2</sub> by 2050. However, the impact on total abatement (i.e. including substitution) is far more significant, with cumulative abatement falling from 82 to 67 MtCO<sub>2</sub> by 2050. The difference is even starker in the longer term, with cumulative abatement by 2100 falling from 185 to 144 MtCO<sub>2</sub> under the more conservative scenario. This again highlights that a greater contribution to emissions reduction can be achieved by focusing more intensive management on the more productive sites, and that lower yielding sites may be better managed as carbon (and biodiversity) reserves.

## 8.4 Cost-effectiveness of woodland creation

The cost-effectiveness of different abatement measures is clearly an important consideration. In establishing the capacity for abatement to be delivered by all sectors, the first report of the Committee on Climate Change (CCC, 2008) published a series of Marginal Abatement Cost (MAC) curves for the UK. For all sectors, abatement costing less than £100 per tonne CO<sub>2</sub> was considered as potentially cost-effective. As a contribution to the CCC's report, Moran *et al.* (2008) developed a marginal abatement cost curve for the agriculture, forestry and land management sector (AFLM). The abatement potential of two forestry options were considered in the analysis, both focussing on Sitka Spruce. This discussion expands on this MAC function for UK forestry, presenting a range of woodland creation options and including a breakdown of abatement in both traded and non-traded sectors. The analysis follows the majority of woodland creation options presented in 8.3 above, and is based on Crabtree *et al.* (2009). However, improvements to the CARBINE modelling system since the work of Crabtree concluded means that the analyses and results in 8.3 and 8.4 are not directly compatible.

### 8.4.1 Marginal abatement cost curves for forestry

A single afforestation option was considered Moran *et al.* (2008) focussing on YC 16 Sitka Spruce managed on a 49-year rotation. This afforestation measure resulted in an average rate of carbon sequestration in timber, soil and dead organic matter of 5 tC ha<sup>-1</sup> year<sup>-1</sup>. When lifetime cost-effectiveness (CE: expressed as a social metric) was considered, the measure was assessed as highly cost-effective (minus £7.12 to minus £1.82 per tonne CO<sub>2</sub>), whether or not abatement through direct and indirect fossil fuel substitution was considered. The cost-effectiveness (for sequestration alone) was derived from a net present value (NPV) assessment of net costs of minus £6405 ha<sup>-1</sup> divided by a lifetime abatement of 899 tCO<sub>2</sub> ha<sup>-1</sup> (18.3 tCO<sub>2</sub> ha<sup>-1</sup> year<sup>-1</sup> for 49 years). The negative sign for CE indicates that the present value of timber revenue exceeded that of the costs and implies this type of forestry planting more than achieves the 3.5% social rate of return from timber output alone and thus has no net social cost. However, it should be noted that the analysis did not consider on-going management costs or guidance on declining discount rates after year 30 (HMT, 2008).

The approach of Moran *et al.* (2008) considered the extent of implementation of the afforestation measure through the adoption of two area-based thresholds: Maximum technical potential (MTP) is 'the absolute upper limit that might result from the highest technically feasible level of adoption or measure implementation', while the central feasible potential (CFP) was defined as the 'adoption level most likely to emerge in the time scales and policy contexts under consideration'. CFP assumed a value of 50% of the MTP of 21 500 ha per year additional to recent levels of woodland creation (8500 in 2006), based on a maximum level of woodland creation of 30 000 ha per year. The abatement (CFP) from 10 750 ha planting per year (starting in 2009) in 2022 was estimated at 0.98 MtCO<sub>2</sub>, while the maximum abatement (MTP) that could be delivered by planting 21 500 ha per year was 1.96 MtCO<sub>2</sub> in 2022. Moran *et al.* (2008) noted that the MTP (and consequently CFP) was a conservative estimate constrained by current policies.

As outlined above, the afforestation measure included a consideration of abatement arising from wood and timber products substituting for fossil fuels, both directly and indirectly. However, concerns over double counting resulted in the forestry option not being included in the CCC's MAC curve for the agriculture and land

management sector. The difficulties associated with accounting for direct and indirect fossil fuel substitution in both the traded and non-traded sectors are further explored in 8.1.3 above.

The analysis of Moran *et al.* (2008) also considered the abatement potential of reducing rotation length from 59 (as in GHG inventory projections: Thomson, 2009) to 49 years (i.e. similar to FMS-B in 8.2.4 above). This measure led to emissions from forest biomass and soil carbon of 0.29 MtCO<sub>2</sub> 2022 (central feasible potential: an additional 7100 ha harvested each year up to 2012 and 4200 ha per year between 2012 and 2022). However, when abatement through direct fossil fuel substitution was also included in the analysis, abatement of 1.1 MtCO<sub>2</sub> in 2022 was calculated at a cost-effectiveness of £12.1 per tCO<sub>2</sub>. However, it was noted that this level of implementation of the measure was unsustainable in the long term. These apparent short-term opportunities for abatement should therefore be considered in the longer timeframe as presented in 8.2.4 above.

### 8.4.2 Costs for a range of woodland creation options

The net social cost of an afforestation option is taken as the sum of the establishment costs and the opportunity cost of the land used (i.e. net income associated with previous land use), less any revenue from wood or other forest product sales. This approximation understates the social cost because no account is taken of additional transaction costs involved in delivering the policy or of any ongoing forest management costs to woodland owners. In other respects, social costs are overstated because establishment costs may include an element of profit while ancillary public benefits (discussed in 8.4.3 below) are neglected in the analysis. It is assumed that policy measures could be designed to deliver the options and that output would not be diverted into other wood markets with different carbon characteristics which would affect cost effectiveness. Cost is derived as the equivalent annual cost (EAC) over one rotation. The EAC is estimated as the annuity equivalent at 3.5% to the net present value of the establishment and management costs plus the opportunity cost of land. It is assumed that subsequent rotations have the same cost structure as the initial rotation. The EAC derived for one rotation can therefore be applied to longer time periods than a rotation. For non-clearfell options, a 100-year life is used, on the assumption that cash flows beyond 100 years are beyond the planning horizon and have minimal present value. The costs used in calculating

EAC are given in Table 8.7, assuming that no stock fencing is used to reflect the nature of the sites considered most likely to be planted.

Revenue from timber sales is calculated as the present value (PV) over 100 years and converted to its equivalent annuity at 3.5% to give an equivalent annual revenue (EAR). This is then subtracted from the EAC (see above) to give a net cost per year. The EAR is derived over 100 years rather than over one rotation to facilitate comparisons between options. This approach also accommodates the likely variation in EAR between rotations that would be expected to result from the changing value of carbon over time. It should also be noted that changes in the value of carbon will influence the carbon substitution benefits of

electricity generation and the cost-effectiveness of relevant options, as discussed below.

Cost-effectiveness (CE) was calculated on a per hectare basis as the net cost per year divided by the abatement achieved on average per year over 100 years (in £ per tCO<sub>2</sub> per year). Thus a net cost of £500 ha<sup>-1</sup> year<sup>-1</sup> divided by an average annual abatement of 15 tCO<sub>2</sub> per ha gives a CE of £36.6 per tCO<sub>2</sub>.

As outlined in 8.1.3 above, emissions reductions that result from fossil fuel substitution in the traded sector (i.e. electricity generation) are not considered as abatement within evaluations of cost-effectiveness that are consistent with wider cross-sector studies. Here, the CO<sub>2</sub> emissions

**Table 8.7**  
Costs assumed for forestry operations.

Option	Description	Establishment/ restocking cost (£/ha)		Establishment and management cost (£ ha <sup>-1</sup> year <sup>-1</sup> )	Agricultural income foregone (£ ha <sup>-1</sup> year <sup>-1</sup> )	PV Agricultural income foregone (£ ha <sup>-1</sup> )	Equivalent annual cost (£ ha <sup>-1</sup> year <sup>-1</sup> ) (EAC)
		With stock fencing	No stock fencing				
B1	SRF YC 36 energy forests	4400	2600	378	350	-2406	728
B2	SRF YC 20 energy forests	4400	2600	378	260	-1787	638
C1	YC 6 broadleaf farm woodland	6700	5400	202	480	-12839	682
D1	YC 4 native broadleaf woodland	5370	4070	147	260	-7190	407
D2	YC 4 native pine woodland	3580	2600	111	50	-1173	161
E1	YC 16 SS/DF	3580	2600	111	260	-6098	371
F	YC 4/10/14 mixed woodland: ACF (selection)	4400	3500	131	190	-5082	321
G	YC 12 SS/DF	3580	2600	111	160	-3753	271
H	YC 12 SS: ACF (shelterwood)	3580	2600	94	160	-4425	254
I	YC 12 SS/DF: ACF (selection)	3580	2600	94	160	-4425	254
J	SRC YC 20 willow	1310	1310	79	350	-5769	429
K	SRF YC 12 native species	5370	4070	353	260	-2995	613
L	SRF YC 16 energy forests	3580	2600	269	260	-2512	529

Note: Equivalent annual cost is the annual establishment and management cost plus the annuity derived from the PV of agricultural income foregone.

substituted for in the traded sector are reflected as an additional revenue stream based on the projected price of traded carbon (EUA: EU Allowance) as published by DECC, 2009a). In 2009 the central assumption is £21 per tCO<sub>2</sub>, rising to £200 per tonne in 2050. The result of this approach is that although total abatement is reduced, the cost-effectiveness of abatement in the non-traded sector improves. To some extent, this reflects GHG emissions reduction through renewable energy reduction being rewarded through energy market instruments (ROCs) but the untraded carbon remains unrewarded. However, it could be argued that any inclusion of social values from the traded sector in the revenue stream distorts the basis of the cost-effectiveness calculation which is to identify the social cost per tonne of carbon (net of social revenue) of achieving a given reduction in net emissions. For this reason, Table 8.8 considers cost-effectiveness both with and without the value of the carbon substituted for in the traded sector being included.

### 8.4.3 Ancillary benefits

A range of ancillary benefits (and dis-benefits) may be associated with woodland creation. If these can be given a monetary valuation they should ideally be included in a social appraisal. Possible co-benefits include energy security, environmental gains and positive impacts on rural development (see Section 5). Moran *et al.* (2008) recognised that the exclusion of co-benefits was a

weakness in their analysis since woodlands may deliver sizeable public good impacts. Furthermore, significant policy synergies are achievable – for example emissions abatement and improvement of water quality to meet Water Framework Directive objectives (Nisbet *et al.*, 2009). However, quantifying these is not straightforward, as outlined by Crabtree *et al.* (2009), in part because many of the environmental benefits are location specific. Some information is available in a UK context (Willis *et al.*, 2003; Crabtree *et al.*, 2003; Jaakko Poyry, 2006) and should be included in future evaluations, although it is not included in the evaluation presented here.

### 8.4.4 Cost-effectiveness of woodland options

Table 8.8 provides a ranking of the cost-effectiveness of the different woodland creation options based on a revenue calculation that includes a value for fossil fuel carbon emissions in electricity production that would be displaced. This produces negative CE values for SRC (option J), SRF (options B1, B2 and K) and the main conifer crops (i.e. socially desirable investments at no net cost). Native species and broadleaf options are less cost-effective but all give a CE below £100 per tCO<sub>2</sub> apart from SRF native species. This clearly highlights the potential for woodland creation to be employed as a cost effective approach to GHG emissions abatement. However, it is important to consider that woodland creation delivers abatement in the medium to longer term.

**Table 8.8**  
Cost-effectiveness and average emissions abatement of woodland creation options over a 100-year period.

Option	Cost-effectiveness (£/tCO <sub>2</sub> )	Cost-effectiveness (£/tCO <sub>2</sub> ) excluding traded carbon value	Abatement (tCO <sub>2</sub> ha <sup>-1</sup> year <sup>-1</sup> )
B1 SRF YC 36 energy forests	-60.8	24.8	15.1
J SRC YC 20 willow	-50.3	58.6	3.7
L SRF YC 16 energy forests	-45.3	41.3	8.4
B2 SRF YC 20 energy forests	-30.6	44.6	9.5
E1 YC 16 SS/DF	-17.3	-2.8	12.9
H YC 12 SS: ACF (shelterwood)	-11.2	-0.1	9.7
G YC 12 SS/DF	-9.6	5.3	9.1
I YC 12 SS/DF: ACF (selection)	-4.7	8.1	9.1
F YC 4/10/14 mixed broadleaf/conifer woodland: ACF (selection)	11.2	25.9	7.9
D2 YC 4 native pine woodland	21.1	21.1	7.0
K SRF YC 12 native species	34.3	114.6	4.5
D1 YC 4 native broadleaf woodland	40.7	40.7	8.4
C1 YC 6 broadleaf farm woodland creation	72.7	75.8	5.2

See Table 8.4 for key to abbreviations.

Ideally, a marginal abatement cost curve for forestry would be developed that could be incorporated within wider evaluations of the delivery of Government's GHG emissions reductions commitments. Indeed, Crabtree *et al.* (2009) do quantify abatement potential for England at a cost of less than £100 per tonne CO<sub>2</sub> of 0.7 MtCO<sub>2</sub> in 2022 and 5.9 MtCO<sub>2</sub> in 2050 (assuming an additional 471 000 ha of woodland is planted by 2050). However, it is difficult to establish a realistic value for either of the two area-based thresholds MTP or CFP. The estimates of cost-effectiveness presented in Table 8.8 do, however, provide a basis for developing a woodland creation programme to meet climate change objectives, including identifying where grant aid or other financial incentives might be required to achieve such a programme.

## 8.5 Conclusions: the potential of UK forestry to contribute to emissions abatement

It is clear that the forestry sector can make a significant contribution to emissions reduction commitments. If enhanced woodland creation and appropriate forest management measures were implemented as a matter of urgency, total emissions abatement delivered by the sector could reach 15 MtCO<sub>2</sub> annually by the 2050s (Figure 8.4b). This level of abatement would equate to about 10% of total GHG emissions from the UK if recent emissions reductions commitments are achieved. Planting a total of 23 200 ha year<sup>-1</sup> over the next 40 years would provide nearly 1 million additional hectares of woodland that would be required to achieve this level of abatement. Including the BAU level of woodland creation, this would represent a 33% increase in woodland area bringing total woodland cover to approximately 3.8 million hectares. Although this would clearly represent a major change in, and challenge to, the forestry sector it only represents a 4% change in land use. Indeed, the resulting forest cover of 16% would still be well below the European average. However, given the degree of change in the landscape, it would be important to ensure that the strong regulatory framework for woodland creation in the UK is maintained to prevent inappropriate woodland creation. Given the wide variation in cost-effectiveness measures reported above for new planting options, it will be important to ensure that the 'right' planting options are exercised in both the private and public forest estate.

Opportunities for forest management measures in the UK to contribute to GHG abatement are more limited than for woodland creation. This observation differs from that of the

IPCC (Nabuurs *et al.*, 2007), at least in part because of the relatively slow growth rate of UK forests compared with those in some other parts of the world. The low level of abatement that could be delivered by forest management – in absolute terms – also reflects the limited extent of woodlands in the UK. Importantly, forest management abatement measures are more difficult to interpret because much of the abatement is delivered outside the forestry sector through direct and indirect fossil fuel substitution. If an holistic view of abatement is not taken, supported by appropriate approaches to carbon accounting, there is a risk that measures will be implemented to maximise forest and soil carbon stocks that limit the delivery of abatement. Modest additional abatement can be delivered by optimising forest management for timber production, which will also provide raw materials for a future low carbon society.

## 8.6 Research priorities

- Development of the UK's LULUCF GHG inventory is required to reflect emissions from, and uptake by, forests that result from changes in management practice. This development should be coupled with improved reporting of forest carbon stocks through the National Forest Inventory.
- Improved understanding of changes in forest soil carbon stocks, based on empirical evidence, is required to underpin accounting models of forest carbon balance.
- A comprehensive evaluation of life cycle analyses for a wide range of wood products compared to alternative materials is required to better demonstrate the role of forest management and product displacement (indirect fossil fuel substitution) in GHG emissions abatement.
- The economic value of ancillary benefits of woodland creation (biodiversity, water quality, recreation, soil protection) needs to be incorporated within cost-effectiveness assessments, cost-benefit analyses and marginal abatement cost curve analysis for the forestry sector.
- An operational decision support system should be developed to downscale national level assessments of abatement potential through changes in forest management to aid the implementation of appropriate abatement measures.
- Development of carbon accounting models for new forest species and new silvicultural systems that take into account the possible effects of the changing climate and possible adaptation measures is required.



## References

- BROADMEADOW, M. and MATTHEWS, R. (2003). *Forest, carbon and climate change: the UK contribution*. Forestry Commission Information Note 48. Forestry Commission, Edinburgh.
- COMMITTEE ON CLIMATE CHANGE (2008). *Building a low-carbon economy: the UK's contribution to tackling climate change*. The First Report of the Committee on Climate Change, December 2008. The Stationery Office, London.
- CRABTREE, R., PEARCE, D. and WILLIS, K. (2003). *Economic analysis of forestry policy in England*. Final report to the Department for Environment, Food and Rural Affairs and H.M. Treasury. CJC Consulting, Oxford.
- CRABTREE, R., MATTHEWS, R.W., HARRIS, D. AND RANDLE, T.J. (2009). *Analysis of policy instruments for reducing greenhouse gas emissions from agriculture, forestry and land management - forestry options*. Final contract report to Defra and the Forestry Commission. ADAS, Abingdon.
- DEPARTMENT OF ENERGY AND CLIMATE CHANGE (2009a). *The UK low carbon transition plan: national strategy for climate and energy*. The Stationery Office, London.
- DEPARTMENT OF ENERGY AND CLIMATE CHANGE (2009b). *The UK renewable energy strategy*. The Stationery Office, London.
- DEPARTMENT OF ENERGY AND CLIMATE CHANGE (2009c). *Carbon valuation in UK policy appraisal: a revised approach*. Department of Energy and Climate Change, London.
- DEWAR, R.C. (1990). A model of carbon storage in forests and forest products. *Tree Physiology* 6, 417–428.
- DEWAR, R.C. (1991). Analytical model of carbon storage in trees, soils, and wood products of managed forests. *Tree Physiology* 8, 239–258.
- DEWAR, R.C. and CANNELL, M.G.R. (1992). Carbon sequestration in the trees, products and soils of forest plantations: an analysis using UK examples. *Tree Physiology* 11, 49–71.
- EDWARDS, P.N. and CHRISTIE, J.M. (1981). *Yield models for forest management*. Forestry Commission Booklet 48. HMSO, London.
- FORESTRY COMMISSION (2001a). *National inventory of woodland and trees: England*. Inventory report. Forestry Commission, Edinburgh.
- FORESTRY COMMISSION (2001b). *National inventory of woodland and trees: Scotland*. Inventory report. Forestry Commission, Edinburgh.
- FORESTRY COMMISSION (2002). *National inventory of woodland and trees: Wales*. Inventory report. Forestry Commission, Edinburgh.
- FORESTRY COMMISSION (2007). *A woodfuel strategy for England*. Forestry Commission England, Bristol.
- FORESTRY COMMISSION (2009). *Climate Change Action Plan 2009–11*. Forestry Commission Scotland, Edinburgh.
- FORSTER, D. and LEVY, P. (2008). *Policy options development and appraisal for reducing GHG emissions in Wales*. Report to Welsh Assembly government. AEA Energy and Environment, Harwell.
- GREAT BRITAIN PARLIAMENT (2008). *Climate Change Act 2008*. The Stationery Office, London.
- HARDCASTLE, P. (2006). *A review of the potential impacts of short rotation forestry*. Final report to the Forestry Commission. LTS International, Edinburgh.
- HM TREASURY (2008). *The green book: appraisal and evaluation in central government*. Treasury guidance. The Stationery Office, London.
- HM TREASURY (2009). *Budget 2009: Building Britain's future*. Economic and fiscal strategy report and financial statement and budget report. The Stationery Office, London.
- IPCC (2006). *Guidelines for National Greenhouse Gas Inventories, 2006*. Prepared by the National Greenhouse Gas Inventories Programme. IPCC, Japan.
- JAAKKO POYRY (2006). *Woodland and forest sector in England. A mapping study carried out on behalf of the English Forest Industries Partnership*. Jaakko Poyry Consulting, Cheam.
- KURZ, W.A., DYMOND, C.C., WHITE, T.M., STINSON, G., SHAW, C.H., RAMPLEY, G.J., SMYTH, C., SIMPSON, B.N., NEILSON, E.T., TROFYMOW, J.A., METSARANTA, J. and APPS, M.J. (2009). CBM-CFS3: a model of carbon dynamics in forestry and land-use change implementing IPCC standards. *Ecological Modelling* 220, 480–504.
- LAVERS, G. M. (1983). *The strength properties of timber*. 3rd edn. Building Research Establishment Report. HMSO, London.
- MATTHEWS, G.A.R. (1993). *The carbon content of trees*. Forestry Commission Technical Paper 4. Forestry Commission, Edinburgh.
- 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. Painatuskeskus, Helsinki. pp. 105–14.
- 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, Vol. 40. Springer-Verlag, Berlin. pp. 233–243.

- MATTHEWS, R.W. and DUCKWORTH, R.R. (2005). BSORT: a model of tree and stand biomass development and production in Great Britain. In: Imbabi, M.S. and Mitchell, C.P. (eds) *Proceedings of World Renewable Energy Congress, 22–27 May, Aberdeen, UK*. Elsevier, Oxford.
- MATTHEWS, R.W., ROBERTSON, K., MARLAND, G. and MARLAND, E. (2007). Carbon in wood products and product substitution. In: Freer-Smith, P.H., Broadmeadow, M.S.J. and Lynch, J.M. (eds) *Forestry and climate change*. CABI, Wallingford. pp. 91–104.
- MOHREN, G.M.J. and KLEIN GOLDEWIJK, C.G.M. (1990). *CO<sub>2</sub>FIX: a dynamic model of the CO<sub>2</sub>-fixation in forest stands*. "De Dorschkamp", Report 624. Research Institute for Forestry and Urban Ecology, Wageningen.
- MOHREN, G.M.J., GARZA CALIGARIS, J.F., MASERA, O., KANNINEN, M., KARJALAINEN, T. and NABUURS, G.-J. (1999). *CO<sub>2</sub>FIX for Windows: a dynamic model of the CO<sub>2</sub> fixation in forest stands*. Institute for Forestry and Nature Research (The Netherlands), Instituto de Ecología (UNAM, Mexico), Centro Agronomico Tropical de Investigacion y Enseñanza (Costa Rica) and European Forest Institute (Finland).
- MORAN, D., MACLEOD, M., WALL, E., EORY, V., PAJOT, G., MATTHEWS, R., MCVITTIE, A., BARNES, A., REES, B., MOXEY, A., WILLIAMS, A. and SMITH, P. (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*. Final Report to the Committee on Climate Change. Scottish Agricultural College, Edinburgh.
- MORISON, J.I.L., MATTHEWS, R.W., PERKS, M., RANDLE, T.J., VANGUELOVA, E., WHITE, M.E. and YAMULKI, S. (2009). *The Carbon and GHG balance of UK forests - a review*. Forest Research, Farnham.
- NABUURS, G.J. (1996). Significance of wood products in forest sector carbon balances. In: Apps, M.J. and Price, D.T. (eds) *Forest ecosystems, forest management and the global carbon cycle*. NATO ASI Series I, Vol. 40. Springer-Verlag, Berlin.
- NABUURS, G.J., MASERA, O., ANDRASKO, K., BENITEZ-PONCE, P., BOER, R., DUTSCHKE, M., ELSIDDIG, E., FORD-ROBERTSON, J., FRUMHOFF, P., KARJALAINEN, T., KRANKINA, O., KURZ, W.A., MATSUMOTO, M., OYHANTCABAL, W., RAVINDRANATH, N.H., SANZ SANCHEZ, M.J. and ZHANG, X. (2007). Forestry. In: Metz, B., Davidson, O.R., Bosch, P.R., Dave, R. and Meyer, L.A. (eds) *Climate change 2007: mitigation*. Contribution of Working Group III to the Fourth Assessment. Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.
- NISBET, T.R., SILGRAM, M., SHAH, N., BROADMEADOW, S.B. and MORROW, K. (2009). *Woodlands and the Water Framework Directive*. Final contract report to the Environment Agency and Forestry Commission. Environment Agency, Bristol.
- ROBERTSON, K., FORD-ROBERTSON, J., MATTHEWS, R.W. and MILNE, R. (2003). Evaluation of the C-FLOW and CARBINE carbon accounting models. In: Milne, R. (ed.) *UK emissions by sources and removals by sinks due to land use, land use change and forestry activities*. Report to DEFRA (contract EPG1/1/160). Centre for Ecology and Hydrology, Edinburgh.
- SCOTTISH EXECUTIVE (2006). Scottish forestry strategy. Forestry Commission Scotland, Edinburgh.
- THOMPSON, D.A. and MATTHEWS, R.W. (1989a). *The storage of carbon in trees and timber*. Forestry Commission Research Information Note 160. Forestry Commission, Edinburgh.
- THOMPSON, D.A. and MATTHEWS, R.W. (1989b). CO<sub>2</sub> in trees and timber lowers greenhouse effect. *Forestry and British Timber* 18 (October), 19, 21, 24.
- THOMSON, A. (ed.) (2009). *Inventory and projections of UK emissions by sources and removals by sinks due to land use, land use change and forestry*. Annual contract report (GA01088) to Defra. Centre for Ecology and Hydrology, Edinburgh.
- TIPPER, R., CARR, R., RHODES, A., INKINEN, A., MEE, S. and DAVIS, G. (2004). The UK's forest: a neglected resource for the low carbon economy. *Scottish Forestry* 58, 8–19.
- 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. Phase 2 report*. Centre for Research in Environmental Appraisal and Management, University of Newcastle-Upon-Tyne, Newcastle. Report for the Forestry Commission, Edinburgh.

