Forestry Commission
231 Corstorphine Road
Edinburgh
EH12 7AT
www.forestry.gov.uk

Forests, Carbon and Climate Change: the UK Contribution

INFORMATION NOTE

BY MARK BROADMEADOW AND ROBERT MATTHEWS OF FOREST RESEARCH

JUNE 2003

SUMMARY

This Information Note outlines how forests in the UK contribute to the carbon cycle on both a local and a global scale. It explains the key terms that are used in discussions of the part played by forests and carbon in global warming and presents some of the facts and figures behind the many complex issues surrounding the subject. The roles played by growing trees and mature woodland, forest soils, harvested wood and wood products in use are discussed and compared. The statistics and supporting interpretation identify the current and potential contribution of UK woodland in mitigating global warming. Information is also provided on carbon management in forests which is relevant to woodland managers and forestry practitioners as well as to those considering involvement in carbon trading and carbon-neutrality schemes.

FORESTS, CARBON DIOXIDE AND GLOBAL CLIMATE CHANGE

The global carbon cycle

A discussion of UK forests and carbon-related issues must start with an overview of global climate change and greenhouse gas (GHG) emissions. Carbon dioxide (CO_2) is one of the so-called 'greenhouse gases' which are responsible for absorbing energy from the sun, leading to warming of the earth's atmosphere – the 'greenhouse effect'. Many GHGs occur naturally in the atmosphere and their presence is important for ensuring that the global climate is warm enough to support life.

Figure 1

Woodland has an important role to play in the global carbon budget.

In the absence of GHGs, the planet would be 30ºC cooler and most life in its present form would not exist. However, there is consensus among scientists that the world's climate is changing because the concentrations of GHGs in the atmosphere are rising. Carbon dioxide is the most important contributor to this enhanced greenhouse effect. During the 1990s, the atmospheric concentration of CO_2 increased by about 1.5 parts per million (ppm) per year, continuing an upward trend which has seen a pre-industrial concentration of ≃280 ppm rise to the current value of ≃370 ppm. Underlying this overall increase is a complex pattern of exchanges of carbon between the atmosphere, the oceans, terrestrial vegetation (including forests) and fossil fuel reserves, summarised in Figure 2 as a simplified global carbon budget.

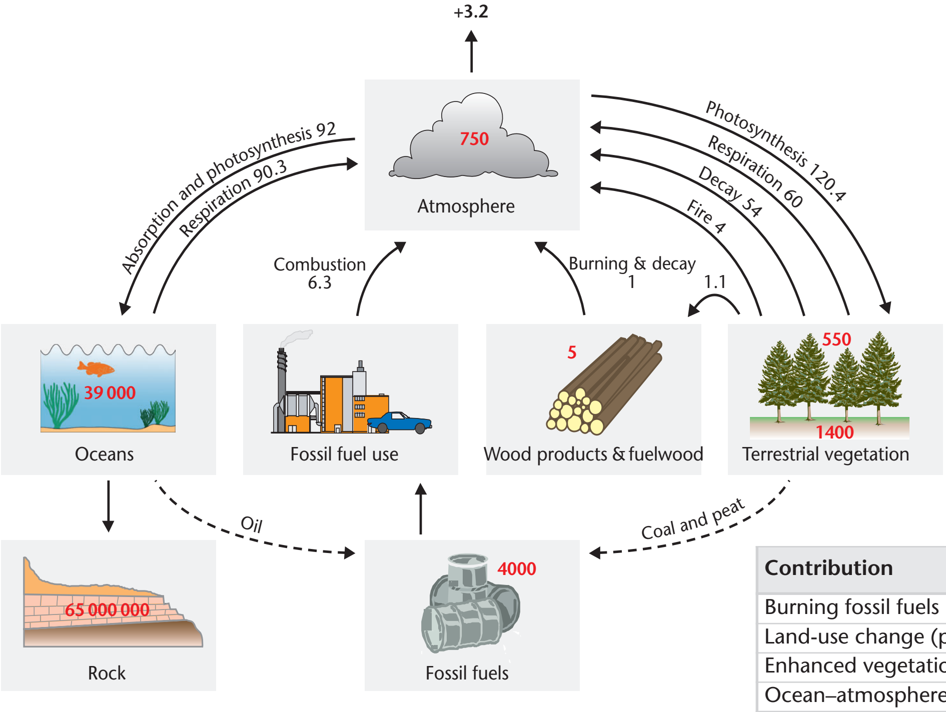
Forests and the global carbon cycle

The rate at which greenhouse gases are being released into the atmosphere has increased mainly due to the burning of fossil fuels for both domestic and industrial purposes, but also as a result of land clearance and deforestation. All plant material contains carbon (normally around 50% of dry weight), and burning or decomposition of cleared vegetation releases it to the atmosphere, mainly in the form of CO_2. Plants and particularly trees, because of their large biomass per unit area of land, continue to make an important contribution to the global carbon cycle. While deforestation is estimated to have released an additional 1.6 GtC[1] per year into the atmosphere during

[1] 1 GtC (1 gigatonne C) = 1000 million tonnes carbon = 10^{15} g carbon; 1 MtC (1 megatonne C) = 1 million tonnes carbon = 10^{12} g carbon.

Figure 2

The global carbon budget for the 1990s. The net increase of 3.2 GtC yr^{-1} into the atmosphere is small compared to the total carbon stocks in vegetation, soil, rocks and the oceans, and also when compared to the quantity of carbon in terrestrial vegetation alone. A simplified summary of the global carbon balance is also given.



All stocks (figures in red) and exchanges (figures in black) of carbon are shown in units of gigatonnes (thousand million tonnes) of carbon per year.

Contribution	Emitted (source)	Absorbed (sink)
Burning fossil fuels	6.3	
Land-use change (primarily deforestation)	1.6	
Enhanced vegetation growth		3.0
Ocean–atmosphere exchange		1.7
Total	**7.9**	**4.7**
Balance	**3.2**	

the 1990s, terrestrial vegetation is believed to have absorbed between 2 and 3 GtC per year at the same time. This is partly as a result of higher CO_2 concentrations in the atmosphere enhancing, or fertilising, plant photosynthesis, but also reflecting the re-growth of intensively managed or previously cleared forests in some regions. These observations have led to the view that certain forestry-related measures could make a significant contribution to the mitigation of climate change through:

- halting deforestation;
- supporting reforestation and afforestation;
- conserving or enhancing the contribution made by existing forests through forest management.

The main purpose of this Information Note is to describe the potential extent of this contribution, primarily with relevance to the UK. It provides a general background to the science associated with forests and carbon and explains the role of forests and forest products including bioenergy and woodfuel. Ongoing international negotiations are referred to, providing some context for the interest in the management of forests and forest products as means to help mitigate climate change. Finally, options are discussed for managing forests in the UK to maximise their contribution to reducing national GHG emissions.

THE KEY COMPONENTS OF FOREST CARBON

When considering the contribution made by woodland to the carbon balance at any scale, the rate at which CO_2 is removed from the atmosphere and/or the quantity of carbon retained in the woodland as a reservoir (also known as a carbon pool) should be assessed. This assessment should consider a number of pools in addition to the above-ground, visible components of the forest. While it is easy to appreciate that the roots of trees contain a significant but hidden proportion of forest carbon, the potentially large and changeable quantity of carbon in soil is not as immediately apparent. To these pools must also be added carbon associated with harvested timber and retained in the short or long term as wood products and, eventually, as a contribution to the landfill carbon pool. The following sections deal with each of these carbon pools in turn.

Trees and forests as collectors of CO_2

Like all green plants, trees assimilate CO_2 from the atmosphere through the process of photosynthesis. The simple sugar molecules that are initially formed from CO_2

are then combined to produce cellulose, as well as lignin in the case of woody plant organs. Much of the carbon that is assimilated through photosynthesis is released again as CO_2 through respiration – the energy costs associated with growth and maintenance of living material. The remaining carbon is allocated to leaf, root, seed, wood and branch biomass. At an annual timescale, the carbon associated with short-lived components of woodland is returned to the atmosphere through decomposition, with only a proportion of fixed carbon being retained in the longer term as wood. A typical carbon budget is given in Figure 3, based on measured and modelled elements of a lowland oak woodland ecosystem in southern England.

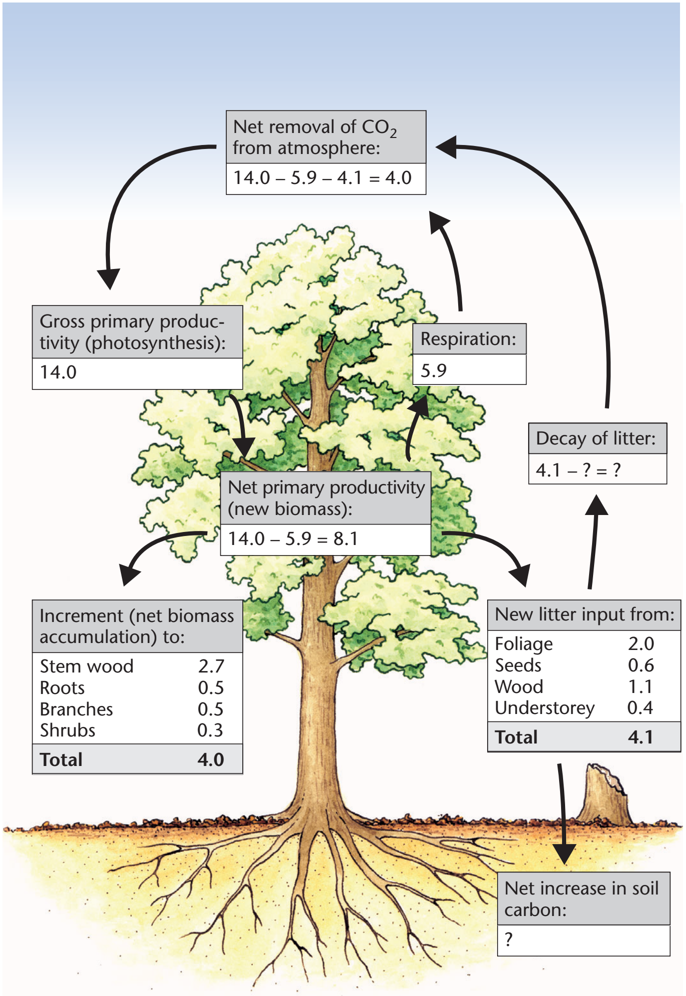


Figure 3

A summary of the carbon exchange (in tonnes of carbon per hectare per year) associated with the main components of oak woodland (general yield class 6 m^3 ha^{-1} yr^{-1}) at the Straits Enclosure flux station in Hampshire. For comparison with the value for increment given here (4.0 tC ha^{-1} yr^{-1}), a value of 3.8 tC ha^{-1} yr^{-1} was obtained for net ecosystem exchange in 2000 using eddy correlation (see Figure 8). Note that the quantity of carbon added to the soil carbon stock on an annual basis is unknown and, if significant, would reduce the quantity of carbon lost through litter decay.

The dynamics of carbon accumulation in woodland

The pattern of accumulation of carbon in woody biomass over the life cycle of a stand of trees reflects timber increment, since the dry weight of wood comprises 50% carbon, and stem wood comprises the bulk of tree biomass. Models or tables providing forecasts of timber growth and yield of forests can thus be used to estimate carbon stocks and accumulation rates (see page 8, assessing carbon stocks, sinks and sources), although only a range of management options are covered in published forest yield tables. Analyses for afforestation based on yield models and tables for even-aged stands have shown that the rate of carbon accumulation is relatively low during the stand *establishment* phase (and may even be negative as a result of carbon loss from vegetation and soil associated with ground preparation). This is followed by the *full-vigour* phase, a period of relatively rapid uptake, which levels off as the stand reaches the *mature* phase, and then falls, as shown in Figure 4. Ultimately, forest stands approach the *old-growth* phase during which they are in long-term equilibrium with losses of carbon through mortality and disturbance balancing any additional growth. Small amounts of carbon may continue to accumulate in the soil, with the time for soil carbon to reach equilibrium being much longer than that for forest biomass. The accumulation of carbon by forest stands is often referred to as carbon sequestration; see the definitions box overleaf for a more detailed discussion.

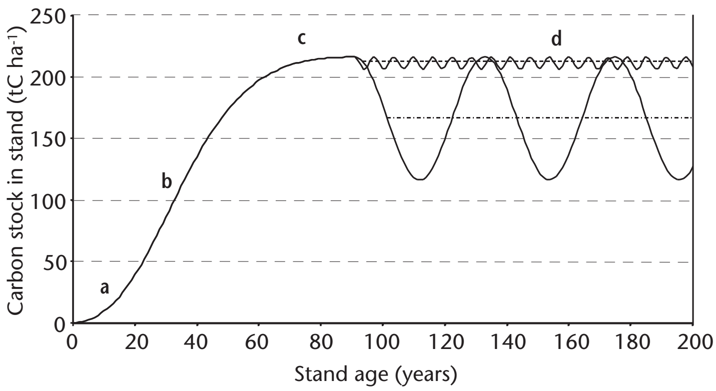


Figure 4

An example of carbon accumulation in a newly created stand of trees. Four phases of growth or carbon sequestration can be seen: a: establishment phase; b: full-vigour phase; c: mature phase; d: old-growth phase. Looking over several decades it is evident that, following an increase in carbon stocks on the ground due to the initial establishment of the stand, carbon stocks neither increase nor decrease because accumulation of carbon in growing trees is balanced by losses due to natural disturbances and decay of deadwood on site. Two examples of carbon dynamics with differing degrees of natural disturbance and thus long-term equilibrium carbon stocks are illustrated. The long-term average stock, as based on the two disturbance scenarios (dashed lines), is estimated to lie in the range 170 to 220 tC ha^{-1}. The estimates up to age 80 are representative of a stand of general yield class 12 Sitka spruce and have been made using the CARBINE carbon accounting model (Thompson and Matthews, 1989; Matthews, 1991).

Carbon sequestration, sinks and sources in vegetation – some definitions

The accumulation of carbon by forest stands is often referred to as *carbon sequestration.* In legal terms, the verb to sequester is defined as to seize temporary possession (of something). This makes a good analogy with the pattern of carbon dynamics described, highlighting four important features:

- Individual atoms of carbon are continually being exchanged between the atmosphere and a forest stand – i.e. an individual atom is only captured from the atmosphere temporarily.
- Over the lifetime of a forest stand, more carbon atoms are captured than are released so there is net accumulation of carbon in the forest.
- Carbon is only accumulated by a forest up until the point when equilibrium is reached, so that the quantity of carbon accumulated is strictly finite.
- The accumulation of carbon by a forest is reversible, with carbon being returned to the atmosphere through dieback, decay and burning of wood if the forest stands are not maintained.

The carbon balance of a forest needs to take into account the exchanges of carbon between the atmosphere and all the carbon pools associated with the forest. The sum of all the carbon pools is known as the *carbon stock* of the forest. A carbon balance is often described as representing a *sink* (resulting in carbon sequestration) if there is a net transfer of carbon (in the form of CO_2) from the atmosphere to one (or any combination) of the carbon pools associated with the forest and the wood products chain. When a forest is described as a *carbon source* there is a net transfer of carbon to the atmosphere.

Individuals, organisations and countries may consider using carbon sequestration to compensate for emissions of CO_2 associated with a particular activity. If they are successful, the activity may be claimed to be *carbon-neutral.* Initiatives based on this approach may be referred to as *carbon-offset or carbon-neutrality schemes.* Quantities of sequestered carbon claimed against CO_2 emissions are sometimes called *carbon credits,* and the buying and selling of these credits may be referred to as *carbon trading.*

The maximum rate of carbon accumulation during the full-vigour phase of fast growing stands in the UK is about 10 tC ha^{-1} yr^{-1}, although a realistic average over a full commercial rotation may be no more than 3 tC ha^{-1} yr^{-1}. The maximum potential for carbon accumulation in UK woodland, and by implication the quantity of CO_2 removed from the atmosphere over the life cycle of a stand of trees, is approximately 200 tC ha^{-1}. This represents the carbon reservoir in old-growth woodland allowing for periodic disturbance events. Managed felling occurs more frequently than disturbance by naturally occurring events and, generally, commercially managed stands do not reach old-growth conditions. As a rough guide, commercially managed stands can be assumed to accumulate up to approximately 100 tC ha^{-1} averaged over a number of rotations, as illustrated for a specific example in Figure 5. The situation for stands managed according to continuous cover methods is likely to be similar to that described above for even-aged stands. For example, the dynamics of carbon absorption in newly created continuous cover woodlands is likely to be very similar to that for even-aged stands up to the mature phase. From this point on, the pattern of carbon stocks maintained over time will depend on the specific silvicultural regime being practised. In a system based on patch felling or tree selection and regeneration, individual patches or trees may follow a pattern similar to that for carbon stocks shown in Figure 5. However, averaged over the stand, the pattern of carbon stocks may look more like one of the patterns illustrated in Figure 4.

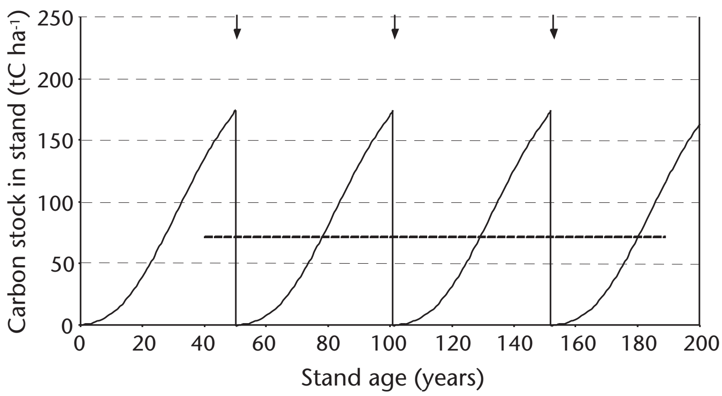


Figure 5

An example of the carbon stocks associated with above-ground biomass of an even-aged stand of trees, felled and replanted on a 50-year rotation in order to maintain a high growth rate in the stand. On the timescale of many rotations, carbon stocks in the standing trees follow a cycle between close to zero and about 160 tC ha^{-1}. The long-term average carbon stock maintained on the site is approximately 70 tC ha^{-1} as marked by the dashed line. The estimates up to age 50 are representative of a stand of yield class 12 Sitka spruce and have been derived using the CARBINE carbon accounting model (Thompson and Matthews, 1989; Matthews, 1991).

The lower rate of carbon sequestration in the mature phase compared to the full vigour phase has led some commentators to infer that young, faster-growing trees are 'better' for carbon sequestration. However, this interpretation is not supported by the long-term average carbon stocks of old-growth woodland and young plantation forests shown in Figures 4 and 5. These figures illustrate how the establishment of forest stands can increase on-site carbon stocks, whether or not periodic harvests are carried out. However, the level of the long-term carbon stock depends on the balance between the impacts of harvesting events and the rate of forest regeneration. A comparison of the two figures also illustrates how periodic harvesting of old trees and replacement with young trees can lead to a lower long-term carbon stock than would be the case if harvesting was avoided.

The quantity of carbon captured and retained by forests is generally significantly higher than the above-ground carbon reservoirs associated with other vegetation types, for example, perennial grassland (typically 5 tC ha^{-1}) and heathland (typically 10 tC ha^{-1}), and underlies the perceived importance of the role of forests in the global carbon budget. Ground vegetation, particularly where there is a well-developed understorey, can contribute to woodland carbon while, in some stands, the carbon associated with accumulating brash, leaf, seed and wood litter may also represent a significant carbon pool. The large amount of litter transferred to forest soils generally results in an increase in the carbon content of those soils, and this has been well demonstrated in studies of woodland colonisation of tilled farmland, an example of which is shown in Figure 6.

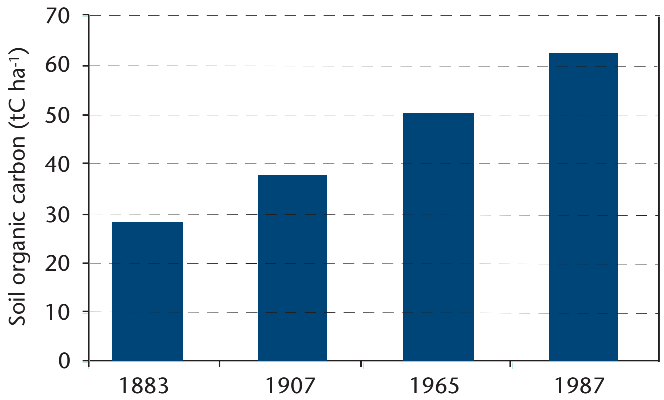


Figure 6

The accumulation of carbon stocks in soil in a field at Rothamsted, Hertfordshire. The field was initially managed for arable agricultural production but 'set aside' in 1875 to create a 'wilderness'. Over the past 100 years or more, the field has regenerated naturally into an area of mixed broadleaf woodland. Redrawn after Poulton (1996).

Forest soils as carbon reservoirs

Forest soils can contain more carbon than the trees comprising the forest – particularly many of the peat-based soils common in the uplands. Table 1 gives average soil carbon contents for a variety of land cover types in Britain. Two main reasons account for the variation in soil carbon content for the different land-use classes. Firstly, in some parts of the UK, many of the commercial forests have been planted on upland soils which already contained high levels of organic matter. For example, many forests in Scotland were planted on moorland which generally has a high soil carbon content. The high carbon density of forest soils in Scotland is, therefore, not necessarily a result of afforestation but may reflect the carbon density of the previous land cover. Secondly, soil carbon density is generally higher under forests and semi-natural vegetation than under more intensive land-uses such as arable agriculture.

Table 1

Average soil carbon stocks (tC ha^{-1}) for different land cover types in the UK, based upon information provided by the National Soil Resources Institute, the Macauley Land Use Research Institute and Queen's University Belfast (Milne, 2001). Semi-natural vegetation includes heathland, moorland and scrub vegetation as land cover types.

Land cover	England	Scotland	Wales	Northern Ireland
Semi-natural	487	1048	305	551
Woodland	217	580	228	563
Arable	153	156	93	151
Pasture	170	192	200	178
Other	33	141	43	102

Changes in woodland soil carbon depend on a balance between the accumulation of dead biomass, its incorporation into the soil and losses due to respiration and decay. The rates of litter input and decomposition can be influenced by management practice, while any change in climate, particularly rainfall patterns and temperature, will also affect the rate of carbon loss or gain in woodland soils. Any soil disturbance associated with forest management may release carbon to the atmosphere, and should be minimised to optimise soil carbon stocks.

Peatlands, greenhouse gases and forestry

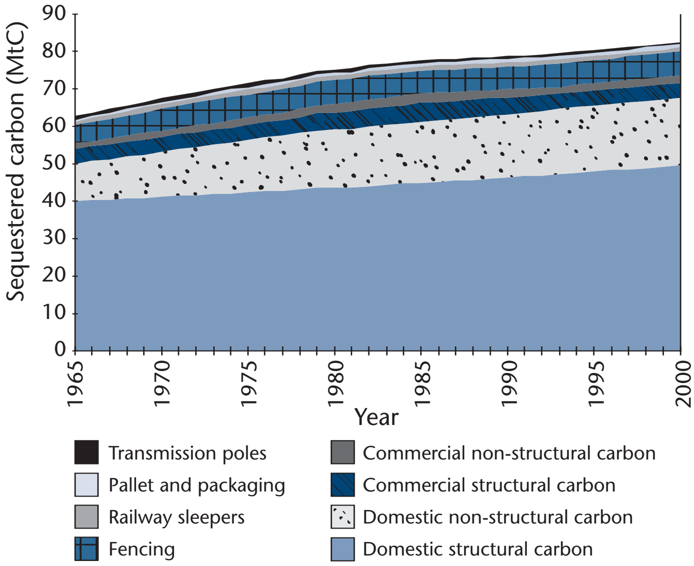
The practice of draining peat-based soils, either prior to or as a result of afforestation, has led to debate over the potential for carbon losses. When these soils are drained, either artificially or through trees using more water than the previous land-cover and lowering the water table, oxidation of the peat increases and considerable quantities of carbon can be lost to the atmosphere as CO_2. One study has indicated that following planting on an upland peat soil, more carbon may be lost than gained by a stand of Sitka spruce for a period of 8–12 years. However, recent research suggests that growth of grass and other vegetation on newly afforested peatland can compensate for this loss of carbon and so net uptake may begin sooner than previously thought. The picture becomes even more complicated if other GHGs are taken into account. Although drainage may lead to an initial increase in CO_2 emissions, naturally occurring methane emissions from the peat fall at the same time. Methane (CH_4) is a more potent GHG than CO_2, and calculations indicate that over some timescales tree planting could be beneficial in terms of GHG balance of peat. Further complications arise due to a probable contribution from increased emissions of another GHG, nitrous oxide (N_2O), highlighting the complex issues surrounding GHG balance of peatlands and the need for further research. The scientific uncertainty associated with afforestation of peatlands and their GHG emissions indicates that there is not a strong case for the conversion of peatland to woodland when the sole objective is carbon sequestration.

Wood products

Wood products such as paper, joinery and timber used in the construction industry represent a secondary carbon reservoir associated with the management of forests. However, for wood products to sequester carbon, the size of this reservoir must grow – simply replacing old products with new does not increase the amount of carbon in the wood products pool. The main component contributing to this pool is timber associated with the construction industry (Figure 7). However, it has been estimated that the carbon in wood disposed (currently and historically) to landfill in the UK constitutes an even larger pool than that associated with wood products in use. At present, the wood products pool in the UK (excluding landfill) is estimated to contain 80 MtC (just over half that contained in the biomass of UK forests) and to be increasing at a rate of 0.44 MtC yr^{-1}. These numbers bear comparison with those for living biomass in UK forests. This is a consequence of the relatively small area of forests in the UK compared to the volumes of wood consumed and the

Figure 7

Estimated carbon stocks in wood products in primary and secondary use in the UK over the period 1965 to 2000 showing the contributions made by different types of product. Carbon stocks in wood products disposed of to landfill are not included. Note that currently, approximately 90% of the harvested wood making up UK wood products is imported from outside the UK. Redrawn from Alexander (1997).



dominant contribution (about 85%) from imported timber. At the global scale, the contribution from harvested wood products to the forest carbon sink is much less important. The use of harvested wood products is one of the activities that may in future form part of national carbon accounting. As explained later (page 10), wood products have a broader role in the carbon balance beyond simply contributing to forest carbon stocks.

BALANCING SOURCES AND SINKS: SIZING UP THE CHALLENGE

Many commentators believe that climate change and the global carbon budget are key to the future of the global environment and its potential effect on mankind. In recognition of the importance of managing emissions of GHGs, a number of both political and practical initiatives have been proposed, with the intention of minimising GHG emissions and maximising carbon sinks. Some of these proposals include important roles for forestry. The following sections describe these initiatives and assess the extent of the contribution that woodlands in Britain might make.

International negotiations and the political context

The contribution that the UK can make to global emissions reductions takes place within an international framework. The development of this framework originated in 1988 when the World Meteorological Organisation (WMO) and United Nations Environment Programme (UNEP) established the Intergovernmental Panel on Climate Change (IPCC) following concerns over the possible impacts of climate change. The remit of the IPCC is to assess available scientific, economic and technical material relating to human-induced climate change, but not to carry out research or monitoring activities itself. Three assessment reports have been produced (1990, 1995 and 2001), the first of which led to the adoption of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992. To date, it has been ratified by over 180 governments. Article 2 of the UNFCCC states as a primary objective: *to achieve stabilisation of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.* Negotiations through the framework of the UNFCCC subsequently resulted in the drafting of the Kyoto Protocol (see box below) on GHG emissions reductions in 1997, which has so far been ratified by over 100 governments.

The potential contribution of UK forests

The forest estate of the UK covers an area of 2.8 million hectares, or 11.6% of the land surface, equivalent to an area about the size of Wales. The biomass which constitutes these forests contains about 150 MtC, which is roughly equal to one year of CO_2 emissions from burning fossil fuels and certain industrial processes in the UK, as shown in Table 2. For the UK to become carbon-neutral (in terms of CO_2 emissions at current rates) through afforestation alone, it would be necessary to create 50 million hectares of forest that maintained an average rate of carbon sequestration of around 3 tC ha^{-1} yr^{-1} over the period from establishment to the old-growth phase. This is approximately double the land area of the UK. Moreover, once the forests attained the old-growth phase (perhaps after 100 years) they would stop acting as a carbon sink. Clearly, forest carbon sequestration alone cannot be used to offset GHG emissions from fossil fuel consumption and industrial processes associated with contemporary ways of living and working. However, the carbon sink associated with UK forests could make a useful contribution as policies and initiatives are developed to reduce GHG emissions.

The Kyoto Protocol – what is it?

The Kyoto Protocol is an agreement among governments that sets targets for reductions in GHG emissions and specifies the mechanisms that may be used to achieve them. These include reductions in the consumption of fossil fuels and options involving carbon sequestration through forestry activities. The IPCC is continuing to develop a framework and methodologies by which governments can realise and report their national GHG emissions reductions. There are three Articles of the Protocol directly relevant to forests and forest management:

- **Article 2.1** calls for the 'protection and enhancement of sinks and reservoirs of greenhouse gases' and the 'promotion of sustainable forest management practices, afforestation and reforestation'.
- **Article 3.3** states that 'the net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities limited to afforestation, reforestation and deforestation since 1990, measured as verifiable changes in carbon stocks in each commitment period, shall be used to meet commitments under the Protocol'. By any generally accepted interpretation, restricting the accounting to afforestation, reforestation and deforestation activities since 1990 (sometimes referred to as the 'Kyoto forests') means that only a very small percentage of the world's forests are covered by Article 3.3. The Protocol further stipulates that greenhouse gas emissions by sources and removals by sinks associated with these activities shall be reported in a 'transparent and verifiable manner' (see page 8, assessing carbon stocks, sinks and sources).
- **Article 3.4** allows countries to account for carbon stock changes and non-CO_2 GHG emissions arising from other activities including the management of forests existing before 1990. The magnitude of any carbon sequestration due to human intervention must be verifiable. The Kyoto Protocol places restrictions on the extent to which carbon sequestration of this kind can be claimed, and details of how this would be monitored and reported are currently being elaborated by the IPCC.

The Kyoto Protocol also makes provision for industrialised countries (so-called 'Annex I' countries) to claim carbon credits in 'non-Annex I' countries through specific projects aimed at reducing GHG emissions (*the Clean Development Mechanism:* Article 12) or through collaboration with other Annex I countries such that emissions reduction credits can be transferred (*Joint Implementation:* Article 6).

Table 2

Comparison of UK carbon emissions inventories for the years 1990 and 2001. Values are for CO_2 emissions only (i.e. not counting other GHGs) and are expressed as million tonnes of carbon per year. The land-use change and forestry inventory includes entries for both emissions and removals, reflecting carbon losses associated with land-use change on one hand and vegetation growth on the other. Source: National Emissions Database, NETCEN.

Source	UK carbon emissions (MtC yr^{-1})			
	1990		2001	
	Emissions	Removals	Emissions	Removals
Road transport fuel consumption	31.8		33.6	
Energy industries fuel consumption	62.2		54.3	
Other fuel consumption	61.1		60.6	
Industrial processes	3.9		3.2	
Land-use change and forestry	5.3	−2.9	4.0	−3.2
Waste incineration	0.5		0.4	
Total	**164.8**	**−2.9**	**156.1**	**−3.2**

Under the Kyoto Protocol, the UK is committed to reducing CO_2 emissions from the rate reported for 1990 of 165 MtC yr^{-1} by 12.5 % (or 20.6 MtC yr^{-1}) during the five-year period from 2008 to 2012. A larger, voluntary target has been adopted within the UK to reduce emissions below the 1990 level by 20% (about 33 MtC yr^{-1}) by 2010. The UK's Climate Change Programme sets out measures across the economy intended to make this goal achievable. It has been estimated that carbon sequestration through afforestation in the UK accounted for some 0.4 MtC yr^{-1} in 2001, rising to a value of around 2.9 MtC yr^{-1} if the contribution of forests planted before 1990 ('non-Kyoto forests') is included. Projections to 2010 are for these values to rise to 0.7 and 3.2 MtC yr^{-1}, respectively, representing a contribution of either 3.4 % or 15.5 % to the emissions reduction target set for the UK in the period 2008 to 2012 under the Kyoto Protocol. To place the UK's role in climate change mitigation in a global context, the total emissions reductions negotiated under the Kyoto Protocol in 1997 amounted to 208 MtC yr^{-1}.

Carbon neutrality, carbon offset and carbon trading schemes

A number of schemes are currently operating which offer individuals and organisations the opportunity to have trees planted on their behalf with the aim of offsetting emissions of GHGs. An estimate is made of the carbon sequestered over the lifetime of the woodland and this is marketed as a carbon credit to offset emissions resulting from specified activities of an individual or organisation. Concerns have been raised over schemes that award credits in advance of the carbon being sequestered. There is also a question mark over the long-term future of woodlands created for this purpose, because of uncertainties over future land management or the occurrence of natural events such as storms and droughts or the effects of climate change itself. Availability of land for afforestation limits the potential for individuals or organisations to take up these schemes, both in the UK and globally. One of the examples most frequently encountered is that of 'carbon-neutral car use'. As a rough guide, the carbon sequestered by half a hectare of woodland over one rotation can compensate for the CO_2 emissions associated with car fuel consumption during an average driver's lifetime: this sounds a small area, but it should be borne in mind that with 30 million registered drivers in the UK, three-quarters of the land area of the nation would have to be afforested to make car use alone carbon-neutral.

ASSESSING CARBON STOCKS, SINKS AND SOURCES

Any framework for negotiating emissions reductions or trading carbon credits must be on the basis of scientifically robust, verifiable measurements. There are two principal ways by which the sizes of carbon pools or rates of carbon sequestration are commonly measured.

Measurement of stock change by periodic inventory

The simplest method of assessment involves measuring the difference in carbon stocks between two points in time. Conventional forest mensuration methods are used either to measure or model timber volumes, which are then converted to dry weight by reference to tables of wood specific density, generally in the range of 0.33 to 0.45 t m^{-3} for softwoods and 0.49 to 0.56 t m^{-3} for hardwoods in the UK. The carbon content (typically 0.5 tC t^{-1}) is then used to convert dry weight to carbon. Estimates derived in this way represent quantities of carbon in the stemwood of trees, either standing or harvested as appropriate. In order to account for carbon in non-stem components as well as stemwood, the estimates are increased by a factor known as a 'total:merchantable' ratio or 'expansion factor'. The value of this factor depends greatly on tree species, stand age, management and environmental conditions. The range of values published for mature trees varies between 1.3 and 1.8.

In this inventory-based accounting system, leaf biomass, ground vegetation and litter are often not included. The carbon content of the soil, although of great importance, has seldom been included because of difficulties in defining and carrying out cost-effective assessments of soil carbon. Moreover, stock changes that may be small in comparison to total soil carbon stocks are difficult to identify, particularly when uncertainties associated with the measurements are considered. An alternative method to account for changes in soil carbon is to combine inventories of carbon in forest vegetation with estimates of soil carbon produced by models of soil carbon dynamics. Depending on the purpose of the inventory, carbon stocks or stock changes in harvested wood products may or may not be assessed. Accounting for carbon stocks in wood products is impossible for individual stands of trees because of uncertainty over the long-term fate of harvested wood once it has left the forest. At a district, national or global scale, some assessment of the size of (and changes to) the wood products pool may be possible by reference to relevant industrial and domestic statistics.

Measurement of flux

An alternative method of assessment is known as the flux-based approach. This approach directly measures the net flow of carbon into or out of the forest. Technology has been developed so that it is now possible to continuously monitor carbon exchange between all the carbon pools in a forest ecosystem and the atmosphere (see Figure 8), although the small amount of carbon that may be lost from a stand as particulate and dissolved organic carbon in rain-water drainage and runoff is not measured. Rather more important is that losses of forest carbon due to harvesting cannot be measured directly. The advantage of the flux-based approach is that a net ecosystem flux is measured, accounting for all carbon pools, including deadwood and litter and other fractions which prove difficult to measure using stock-change methods. The major drawback of the approach is its cost, and thus the small number of flux stations that have been established to date. In the UK, there are only three long-term flux monitoring stations in forests, while across Europe, there are more than 30 such sites. The choice of site is also limited by area and topography and the measurements are only representative of the species, site and growth stage under investigation. As with the stock-change approach, carbon in the wood products pool associated with a specific stand cannot be accounted for.

Figure 8

Measurements of net ecosystem flux at a short time resolution can provide verification of inventory-based carbon stock assessments, including an analysis of changes to the magnitude of pools which are otherwise difficult to measure. Measurements are made continuously from a tower above the canopy at highly instrumented sites. Technical details of the methodology are available from www.ierm.ed.ac.uk/research/edisol.

The choice of approach

The stock-change and flux-based approaches are best applied at different scales of space and time. The best method to use depends mainly on the objective of the assessments being made and, crucially, on the geographical scale that needs to be considered and on the resources available. An inventory-based approach, particularly if used to assess carbon stocks or sequestration in woody biomass only, can be used to cover large land areas and a variety of species and site conditions. This approach could also be based upon existing forest inventory networks such as the UK permanent sample plot network and the EU and ICP (Forests) Forest Monitoring Programme. The flux-based approach works best at providing information on short-term variations in the magnitude of the carbon sink and in quantifying net carbon exchange in forest systems where the individual pools are difficult to measure. A further role is to provide data for the development and calibration of process-based forest growth models. However, the most important role of flux-based assessments is to provide a crosscheck for inventory methods across different forestry systems and to provide essential information on how the environment, particularly climate, may modify rates of carbon exchange. A combined approach using the methods described above, together with remote sensing technology (satellite imagery and aerial photography), probably represents the most robust and cost-effective way to monitor carbon stocks and stock changes.

THE CONTRIBUTION FROM FOREST MANAGEMENT – THE SUM OF THE PARTS, OR MORE?

Earlier sections of this Information Note have explained the process of carbon sequestration in the key components of forest ecosystems and their associated carbon pools. For simplicity, these pools may be defined as above- and below-ground living biomass, dead biomass, soil carbon and the carbon associated with the wood products pool in its many forms. However, the potential for forestry activities to reduce or offset emissions of GHGs is not simply the sum of the impacts on these carbon pools. There is another, often potentially very important impact on the carbon balance due to forestry activities arising from opportunities to use wood products to reduce the consumption of fossil fuels.

Sustainably harvested wood can substitute directly for fossil fuels in the form of renewable wood fuel (or 'bioenergy'), or indirectly as renewable wood products replacing, where appropriate, materials such as concrete and steel which involve high fossil fuel consumption in their production. These two roles of wood products and their potential impact on the carbon balance of woodland are illustrated by examples in Figures 9 and 10. As a consequence of this important dimension to the carbon balance of forestry systems, maximising the carbon benefits of an area of woodland is not always a simple question of leaving the trees to grow and maximising the on-site carbon stock.

Figure 9

Illustration of the recycling of carbon as biomass accumulates in energy crops and forests and is consumed in a power station. a: CO_2 is captured by the growing crops and forests; b: carbon is retained in the biomass of the plants and trees; c: carbon in harvested biomass is transported to the power station; d: the power station burns the biomass, releasing the CO_2 captured by the plants back to the atmosphere. Considering the process as a whole, there are no net CO_2 emissions from burning the biomass. In practice, an element of fossil fuel consumption is usually needed for crop and forest management, biomass transport and processing and also for the running of the power station.

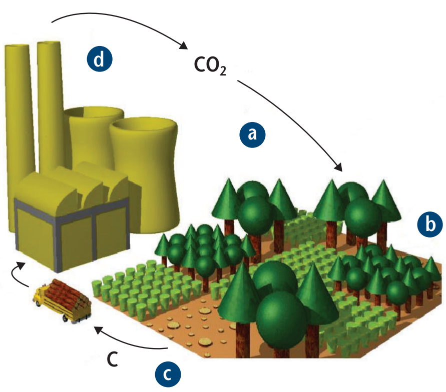
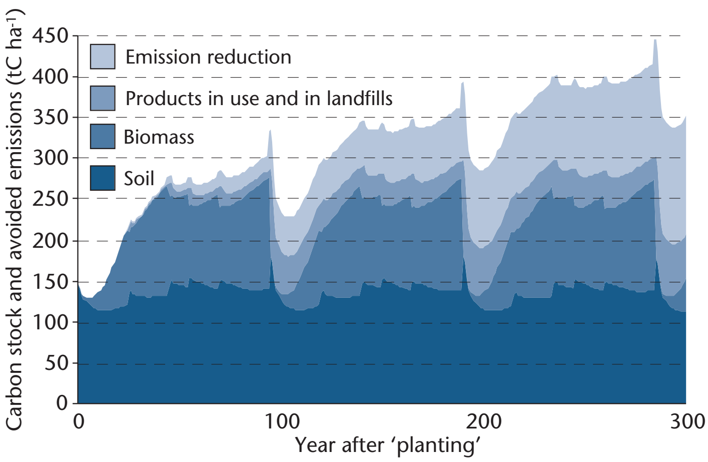


Figure 10

A simulation of carbon stock changes in a forestry system together with carbon emissions avoided through reduced fossil fuel consumption arising from wood utilisation. The simulation was produced using the carbon accounting model CO2FIX and represents a 'typical' commercial, even-aged stand of Norway spruce growing in Europe on a rotation of 75 years and subjected to periodic thinning. In this example soil carbon represents the largest contribution to the stock of carbon in the forest ecosystem in the timescale considered. The contribution made by wood products harvested from the stand to overall carbon stocks is relatively small compared to stocks in forest biomass and soil. The carbon stock in wood products harvested from the stand rises over several rotations to a maximum, after which no further accumulation takes place. This is due to the relatively short lifetimes of wood products compared to the rotation period of the stand from which they are harvested. However, as more and more wood products and bioenergy are harvested through thinning and felling activities, a succession of opportunities arise to use harvested wood to avoid consumption of fossil fuels. As a result, the magnitude of the emissions reduction through avoided fossil fuel consumption accumulates indefinitely, in sharp contrast to the cycling of carbon stocks in the biomass, soil and wood products pools. By the end of the third rotation the emission reduction achieved is similar in magnitude to the sum of carbon stocks in biomass, soil and wood products and in subsequent rotations will greatly exceed them. Redrawn after Nabuurs (1996).



FOREST CARBON MANAGEMENT

Forest carbon management requires an in-depth assessment of numerous factors including site conditions, potential productivity, vulnerability to natural events, proximity to point of use and the local practicalities of the best and most realistic options for end-use of harvested wood. Most of these considerations go beyond the commercial, social and environmental issues which currently form the basis of conventional forest management plans in the UK. A number of options are available for maintaining or enhancing the carbon benefits of forests based on widely differing forest management systems and objectives. An evaluation of these options for a stand, forest or region can be based on a common set of principles, most importantly:

- Maintenance or enhancement of long-term on-site carbon stocks in the woodland itself.
- Minimisation of disturbance to litter and soil, to avoid carbon emissions and soil degradation.

- Ensuring energy efficiency in woodland management operations and in the conversion of harvested trees to products.
- Matching timber and woodfuel production to possible end-uses to achieve optimal utilisation of wood in reducing fossil fuel consumption.
- Harmonising carbon management with other objectives and with practical constraints.

Options for woodland management

Three contrasting options for woodland carbon management, based on the principles described in the previous section, are outlined below and an indication is given of their relative merits and potentials. These options are not prescriptive or exhaustive, but do indicate the general range of approaches that are available for forest carbon management. This section also shows how the above principles may be used to evaluate management options in terms of woodland carbon balance.

Carbon reserve management. This option is characterised by minimal intervention, with a gradual long-term increase in carbon stocks. In addition to a climate change mitigation role, carbon reserve management may also have significant amenity and biodiversity benefits, particularly if native species are planted. Loss of carbon through fire, drought, floods or storm damage is minimised. For this reason it is necessary to take account of wind-hazard, flood risk and climate change predictions regarding the suitability of a particular site-species combination to achieve this objective. At the same time, the use of fossil fuel during woodland management operations should be minimised so as not to negate any enhancement of carbon stocks. Carbon reserve management is particularly well suited to forest stands with very low growth rates and poor stem quality, or in localities where there are limited opportunities for utilisation of harvested wood. The most extreme example of carbon reserve management might involve conservation of existing forest carbon stocks through avoidance of deforestation.

Carbon substitution management. This is characterised by cyclical changes in carbon density in the forest ecosystem (Figures 5 and 10), with maintenance of on-site carbon stocks being of secondary importance. This form of carbon management and its objectives are not far removed from the production forestry practised across most of the UK forest estate. Woody biomass is harvested as good quality stemwood for use in product displacement and renewable woodfuel (in the case of thinnings and harvest residues). Soil disturbance following thinning or clearfell is minimised to limit carbon emissions. Because of the high nutrient content of a significant proportion of branchwood compared with timber, often only a carefully selected fraction of this material is harvested, primarily avoiding the removal of foliage. As with carbon reserve management, there may be benefits associated with the woodland in addition to its climate change mitigation role. Carbon substitution (or displacement) management is particularly well suited to even-aged forest stands with moderate to high growth rates in localities with obvious opportunities for utilisation of harvested wood. Short rotation coppice managed for bioenergy production represents the ultimate expression of carbon substitution management. Stem quality may also require consideration when options are being evaluated, because it will have an impact on the potential to convert stemwood into different products.

Selective intervention carbon management. This option is similar to carbon reserve management but, in addition, there is low-level harvesting of certain trees to clearly defined specifications in order to supply high-value niche applications. It is well suited to stands containing trees of variable quality where risk of significant natural disturbance is low and which may be some distance from centres of population or industry. Examples of this type of management include occasional tree harvests in stands to meet a requirement for fuelwood in a small local community and selective felling in continuous cover forestry systems to satisfy specialist timber markets.

As a general guide, selective intervention and carbon reserve management will usually result in higher long-term carbon stocks within a given woodland ecosystem. On the other hand, only substitution and, to a lesser extent, selective intervention carbon management have the potential to deliver long-term reductions in GHG emissions due to the forestry system beyond the one-off increase in the carbon pools associated with new or conserved woodland.

CONCLUSIONS: THE LIMITED BUT IMPORTANT ROLE OF FORESTRY

The world's forests currently play an important role in minimising the extent and progress of climate change. The carbon that they contain would be enough to raise atmospheric CO_2 concentrations to well over 1000 ppm and with it a potentially catastrophic rise in temperature of 5–8°C. Maintaining global forests is therefore an essential element of any programme of measures to mitigate climate change. In the UK, our forest estate covering about 12% of the land contains only as much carbon as the nation emits in a single year from fossil-fuel burning. It would be impractical for the UK to compensate for its GHG emissions through tree planting alone, although carbon sequestration could be viewed as one of the environmental benefits associated with new woodland creation. Harvested wood products can make a significant contribution to climate change mitigation through their potential to substitute for fossil fuels, both directly in the form of bioenergy, and indirectly through product substitution. Where carbon-offset schemes or activities aimed at claiming carbon credits are under consideration, caution should be exercised as sequestration through afforestation is finite, potentially short-term and reversible, and verification procedures are not well developed at present. On the other hand, any measures taken now to protect and expand forest areas can increase the biomass resource potentially available to future generations and, in principle, support any efforts to move towards a 'low-carbon' economy.

REFERENCES AND USEFUL SOURCES OF INFORMATION

ALEXANDER, M. (1997). *Estimation of national carbon stocks and fluxes of wood based products*. MSc thesis, University of Surrey.

BROADMEADOW, M., ed. (2002). *Climate change: impacts on UK Forests*. Forestry Commission Bulletin 125. Forestry Commission, Edinburgh.

CANNELL, M.G.R. (1999). Growing trees to sequester carbon in the UK: answers to some common questions. *Forestry* **72**, 237–247.

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.

FAO (2000). Forest resources of Europe, CIS, North America, Australia, Japan and New Zealand. UN/ECE and FAO, Geneva.

IPCC (2000). *Land-use, land-use change and forestry*, eds R.T. Watson, I.R. Noble, B. Bolin, N.H. Ravindranath, D.J. Verardo and D.J. Dokken. A Special Report of the IPCC. Cambridge University Press, Cambridge.

IPCC (2001). *Climate change 2001: the scientific basis*, eds J.T. Houghton, Y. Ding, D.J. Griggs, M. Noguer, P.J. van der Linden and D. Xiaosu. WG1 Report to the IPCC Third Assessment. Cambridge University Press, Cambridge.

MARLAND, G. AND MARLAND, S. (1992). Should we store carbon in trees? Special Issue: *Natural sinks of* CO_2, eds J. Wisniewski and A.E. Lugo. *Water, Air, and Soil Pollution* **64**, 181–195.

MATTHEWS, R.W. (1991). Biomass production and storage by British Forests. In: *Wood for energy: the implications for harvesting, utilisation and marketing*, ed. J.R. Aldhous. Proceedings of a discussion meeting, Heriot-Watt University, Edinburgh, 5–7 April 1991.

MATTHEWS, R. AND ROBERTSON, K. (2002). *Answers to ten frequently asked questions about bioenergy, carbon sinks and their role in global climate change*. IEA Bioenergy Task 38: Greenhouse gas balances and bioenergy systems. Joanneum Research, Graz, Austria.

MILNE, R. (2001). *Land use change and forestry: The 1999 greenhouse gas inventory for England, Scotland, Wales and Northern Ireland: 1990, 1995, 1998 and 1999*, eds A.G. Salway *et al*. National Environmental Technology Centre, AEA Technology, Harwell.

NABUURS, G.-J. (1996). Significance of wood products in forest sector carbon balances. In: *Forest ecosystems, forest management and the global carbon cycle*, eds M.J. Apps and D.T. Price. NATO ASI Series I, vol. 40. Springer-Verlag, Berlin, 245–256.

POULTON, P.R. (1996). Geescroft Wilderness, 1883–1995. In: *Evaluation of soil organic matter models using existing long-term datasets*, eds D.S. Powlson, P. Smith and J.U. Smith. NATO ASI Series I, vol. 38. Springer-Verlag, Berlin, 385–390.

SCHLAMADINGER B. AND MARLAND G. (2000). Land use and global climate change: Forests, Land Management, and the Kyoto Protocol. Pew Center on Global Climate Change (www.pewclimate.org/projects/land_use.cfm).

THOMPSON, D. AND MATTHEWS, R.W. (1989). *The storage of carbon in trees and timber*. Research Information Note 160. Forestry Commission, Edinburgh.

www.ipcc.ch
www.ukcip.org.uk
www.futureforests.com
www.forestry.gov.uk/forest_research/carbon
www.eccm.uk.com
www.ierm.ed.ac.uk/research/edisol
www.forestry.gsi.gov.uk/economics
www.defra.gov.uk/environment/climatechange
www.nbu.ac.uk/ukcarbon
www.aeat.co.uk/netcen/airqual/statbase
www.dti.gov.uk/energy
www.unece.org/trade/timber/fra
www.shu.ac.uk/rru

Enquiries relating to this publication should be addressed to:

Mark Broadmeadow
Environmental Research Branch
Forest Research
Alice Holt Lodge
Wrecclesham
Farnham
Surrey
GU10 4LH

Tel: 01420 22255
Fax: 01420 23653
Email: mark.broadmeadow@forestry.gsi.gov.uk

ISSN 1460-3802
ISBN 0-85538-595-2

FCIN048/FC(ECD)/8TH-2.5K/JUN03