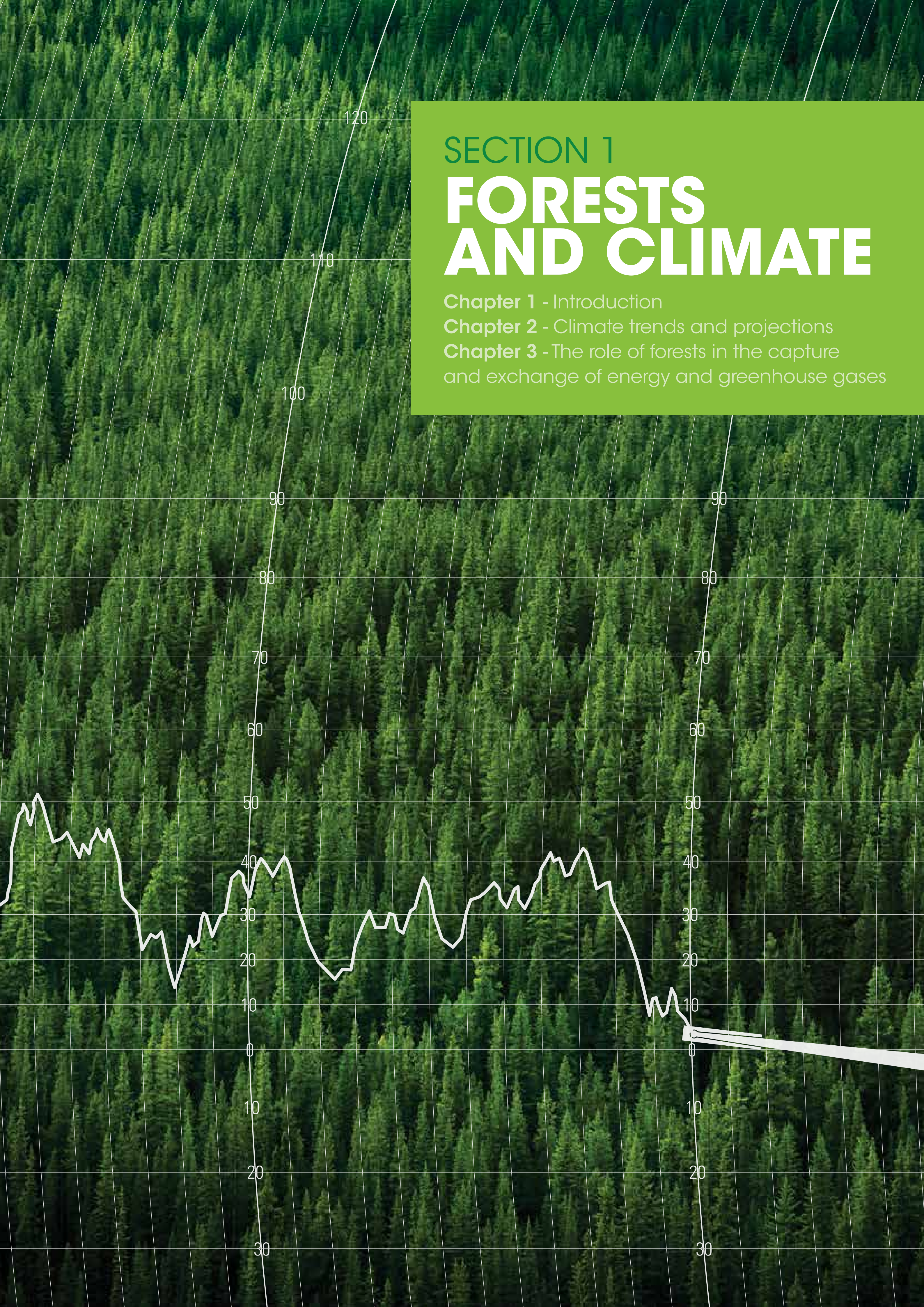
SECTION 1

FORESTS AND CLIMATE

Chapter 1 - Introduction
Chapter 2 - Climate trends and projections
Chapter 3 - The role of forests in the capture and exchange of energy and greenhouse gases



INTRODUCTION

Chapter 1

P. Snowdon

Key Findings

Forest cover in the UK has risen substantially in the past 90 years, although it remains significantly below the European average and current levels of woodland creation are low. The Government has recognised the need for a significant increase in planting to enable the potential of trees and woodlands to mitigate climate change.

Climate change has added major new policy objectives for the forestry sector. Sustainable forest management, and the provision of multiple social and environmental benefits, remain at the heart of forest policy. Effective standards, guidance and management plans will be essential in ensuring that climate change objectives are achieved in balance with other objectives.

Maximising the capacity of forests and woodlands to mitigate and adapt to climate change requires actions that are tailored to local and regional conditions. Devolution of forest policy has enabled such conditions to be recognised more explicitly and for appropriate actions to be taken forward.

National and international legislation has placed ambitious targets for the UK to reduce its emissions of greenhouse gases. Achievement of these targets is dependent upon thorough analysis of the potential for forestry to contribute to mitigation.

Forests are a unique and multi-purpose resource. They deliver a diverse range of benefits for economies, society and the environment. In particular, they play a critical role in the global carbon cycle through their role in the exchange of carbon between the land and the atmosphere.

Human activity is increasing the concentration of carbon dioxide (CO_2) in the atmosphere through emissions from fossil fuel combustion (about 30 Gigatonnes[1] of CO_2 globally in 2007; International Energy Agency, 2009) and from land-use change, primarily tropical deforestation (about 5.8 $GtCO_2$ per year globally in the 1990s; Denman *et al.*, 2007). About half of the emissions from fossil fuel combustion remain in the atmosphere. The rest of the emissions are absorbed by oceans and the land surface. It is estimated that the world's forests and other terrestrial vegetation absorbed about 3.3 $GtCO_2$ per year during the 10 years between 1993 and 2003 (Nabuurs *et al.*, 2007).

There is an urgent need to consider what actions are needed to minimise the impacts of the projected changes in our climate. Forestry is a special case because many decisions that we make now about our trees and woodlands will take effect years and decades into the future. The natural qualities and human uses of forests give them the capacity to mitigate against the threats posed by climate change. Forests absorb carbon from the atmosphere and store it in trees, vegetation and the soil. Human uses of wood from forests provide a renewable source of energy from woodfuel and store carbon in wood products. Importantly, woodfuel and wood products can be used in place of more fossil fuel-intensive fuels and materials (this is termed 'substitution'). At a global level, the average mitigation potential of the forest sector has been estimated at 5.4 $GtCO_2$ per year (Kauppi *et al.*, 2001). Trees and forests also increase the quality and resilience of our living and working environment, for example by providing shade and shelter and by helping to control flooding. In these ways, they help society to cope with the impacts of a changing climate.

It is more important than ever that the contributions of UK forests to climate change mitigation and adaptation are properly understood and that the potential for further

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[1] 1 Gigatonne or Gt = 10^9 or billion tonnes – see Glossary.

action is realised. To assess the potential of our trees and forests to tackle climate change, we need answers to some important questions:

- How are trees responding to climate change and what is projected to happen in the future?
- Can more carbon dioxide be absorbed from the atmosphere by planting new woodlands, and by changing the ways we manage existing woodlands?
- What is the potential to use wood as a fuel for heat and power instead of fossil fuels?
- What scope is there to use more timber in place of other more fossil-fuel intensive materials?
- How can we adapt our woodlands to climate change?
- How can trees and woodlands improve our urban and rural environment to help us cope with climate change?

This report aims to provide answers to these and many other questions for the UK. It gathers the existing evidence, sets out the current contribution of forests to climate change mitigation and adaptation and examines their potential to make a greater contribution in the future to tackling what is the greatest challenge for the UK in the 21st century. We hope that the contents will inform policy- and decision-makers, scientists, and all who have an interest in the future of our planet.

1.1 Background

Climate change is the focus of extensive research and analysis in the UK and globally. This has greatly strengthened the scientific case that global warming is taking place and that radical actions will be needed to avert its most severe effects. Recent assessment reports by the Intergovernmental Panel on Climate Change (IPCC) have done much to assemble the best evidence available, assess its quality and indicate where improvements are needed. Its fourth and latest report[2] noted that:

- Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and the rising global average sea level.
- Most of the observed increase in global average temperatures since the mid-20th century is very likely due to the observed increase in GHG concentrations from human activities.
- Continued GHG emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would very likely be larger than those observed during the 20th century.

The Stern Review (Stern, 2007) provided an economic perspective and stressed the importance of taking action now to avert the most serious effects (costs) of climate change in the future. Most recently, a major international review of the latest science has concluded that the speed and impacts of climate change are likely to be more severe than previously reported and that action to reduce emissions and to adapt is most urgently needed (Richardson *et al.* 2009). In deciding how to respond, we need evidence across all sectors of the economy on what actions might be most effective, the potential that they hold and how much they will cost.

The contribution of trees and forests to meeting the climate change challenge is significant. The IPCC's 2007 report stated that:

> 'Forestry can make a very significant contribution to a low-cost global mitigation portfolio that provides synergies with adaptation and sustainable development' (Nabuurs *et al.*, 2007, p. 543).[3]

It concluded, however, that only a small part of forestry's potential contribution has been realised to date, and that better evidence and data are needed to underpin this contribution. This report goes some way to providing this evidence base in the UK and highlights where gaps in our understanding exist. It is the first time that such an assessment has been carried out for the UK forestry sector.

1.2 Aims and objectives

The aim of this report is to provide an expert up-to-date assessment of the current and potential contribution of trees and forests across the UK, both in the private and government sectors, to addressing climate change. Specific objectives are to:

- review and synthesise existing knowledge on the impacts of climate change on UK trees, woodlands and forests;
- provide a baseline of the current potential of different mitigation and adaptation actions;
- identify gaps and weaknesses to help determine research priorities for the next five years.

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[2] See the Summary for Policymakers of the Synthesis Report. www.ipcc ch

[3] The report of Working Group III on Mitigation.

The report is intended to provide a critical step in identifying how forestry in the UK can improve its contribution to climate change mitigation and adaptation. It is aimed at those with research and policy interests as well as anyone wishing to increase their understanding of how our trees and woodlands can help to tackle the challenges of a changing climate.

1.3 Structure of the report

The report comprises 14 chapters grouped into six sections as follows:

- **Section 1** provides the background for the report. It describes the structure of UK forests and reviews the policy framework. It then describes current trends and projections in our climate. The final part of this section explains the science behind the relationship between trees and forests (including soils) and greenhouse gases (GHG).
- **Section 2** assesses evidence of the impacts to date and of the likely impacts of climate change in the coming decades, using climate projections from the UK Climate Impacts Programme.
- **Section 3** focuses on the contribution of forests to mitigating climate change. It reviews the role of forest planting and management in absorbing and storing carbon, and examines the use of woodfuel and wood products in place of fossil fuels and products whose manufacture generates high levels of GHG emissions (i.e. substitution). It also assesses different scenarios for woodland creation and management in order to estimate the potential for forestry to abate GHG, taking account of a range of factors that determine the cost of mitigating carbon.
- **Section 4** reviews the scope to adapt our woodland resource to a changing climate and examines the role of trees, woods and forests in helping society adapt to the impacts of climate change.
- **Section 5** places forestry in a broader context of land use and sustainable development. It provides an economic perspective and considers what might affect people's behaviour in responding to climate change, and the role of institutions in assisting appropriate responses.
- **Section 6** summarises our conclusions and sets out future research needs.

The intention throughout the report is to assess existing knowledge and evidence. Authors have identified research priorities at the end of each chapter and these are reviewed in Chapter 14.

1.4 Forests in the UK: structure, trends and values

Trees are a highly effective natural means of removing CO_2 from the atmosphere. It is therefore important to examine the size and structure of our forests, and how these change over time. The amount of woodland cover and the types of trees will have a major effect on the capacity of forests to absorb and store carbon and to help adaptation to climate change.

There has been a major increase in UK forest cover over the past 90 years. Woodland cover has increased from 5% in the 1920s to approximately 12% in 2008, covering an area of 2.8 million hectares (ha). As shown in Table 1.1, the increase has been most marked in Scotland, where woodlands now cover approximately 17% of the land area.

Conifers make up almost 60% of UK forests, although substantial variations exist at a regional level (Table 1.2). English woodland cover is largely broadleaved, whereas over three quarters of woodlands in Scotland are coniferous. The majority of woodland cover is planted forest. Just over 20% (646 000 ha) is semi-natural woodland, of which 326 000 ha are ancient (dating to 1600[4] or earlier). Conifer species tend to grow, and absorb carbon, at a faster rate than broadleaved species. Approximately one-third of the UK's forests is in public ownership (Table 1.2). The proportion of forest cover owned by the private sector has been increasing in recent years.

Most of the expansion of the forest area has been the result of substantial planting programmes in the decades following the First, and particularly the Second, World Wars. Two-thirds of woodlands in the UK have been planted since 1950, predominantly conifers. Since the late 1980s, the rate of new planting has been in steady decline, falling from around 30 000 ha per year to 7500 ha in 2008 (Figure 1.1), of which 99% is on private land. From the perspective of mitigating climate change through planting more trees, this fall in woodland creation is the opposite of what is needed. At a time when GHG emissions continue to rise, there is a pressing need to maximise carbon sequestration in our forests, alongside the other benefits that woodlands provide. An examination of ways forward is provided in Chapter 8.

The potential of our forests to tackle climate change is also constrained by the current age profile of the UK's woodlands. Our forests are dominated by mature coniferous woodlands, which will reach felling age over the next 15

[4] 1750 in Scotland.

Table 1.1
Total woodland cover in the UK, in thousand hectares (ha) and as a percentage of total land area.

Year	England		Scotland		Wales		Northern Ireland		UK	
	Area (000 ha)	(%)	Area (000 ha)	(%)	Area (000 ha)	(%)	Area (000 ha)	(%)	Area (000 ha)	(%)
1924	660	5.1	435	5.6	103	5.0	13	1.0	1211	5.0
1980	948	7.3	920	11.8	241	11.6	67	4.9	2176	9.0
2008	1127	8.7	1342	17.2	285	13.7	87	6.4	2841	11.7

Source: Forestry Commission (2008).

Table 1.2
Woodland type and ownership in the UK.

Ownership	Woodland area (000 ha)		
	Conifer	Broadleaf	Total
Forestry Commission/Forest Service (Northern Ireland)			
England	147	55	202
Scotland	424	28	452
Wales	92	14	106
Northern Ireland	56	5	61
UK	719	102	821
Non-Forestry Commission/Forest Service (Northern Ireland)			
England	219	706	925
Scotland	621	269	890
Wales	65	114	179
Northern Ireland	10	16	26
UK	915	1105	2020
All woodland			
England	366	761	1127
Scotland	1045	297	1342
Wales	157	128	285
Northern Ireland	66	21	87
UK	1634	1207	2841

Source: Forestry Commission (2008).

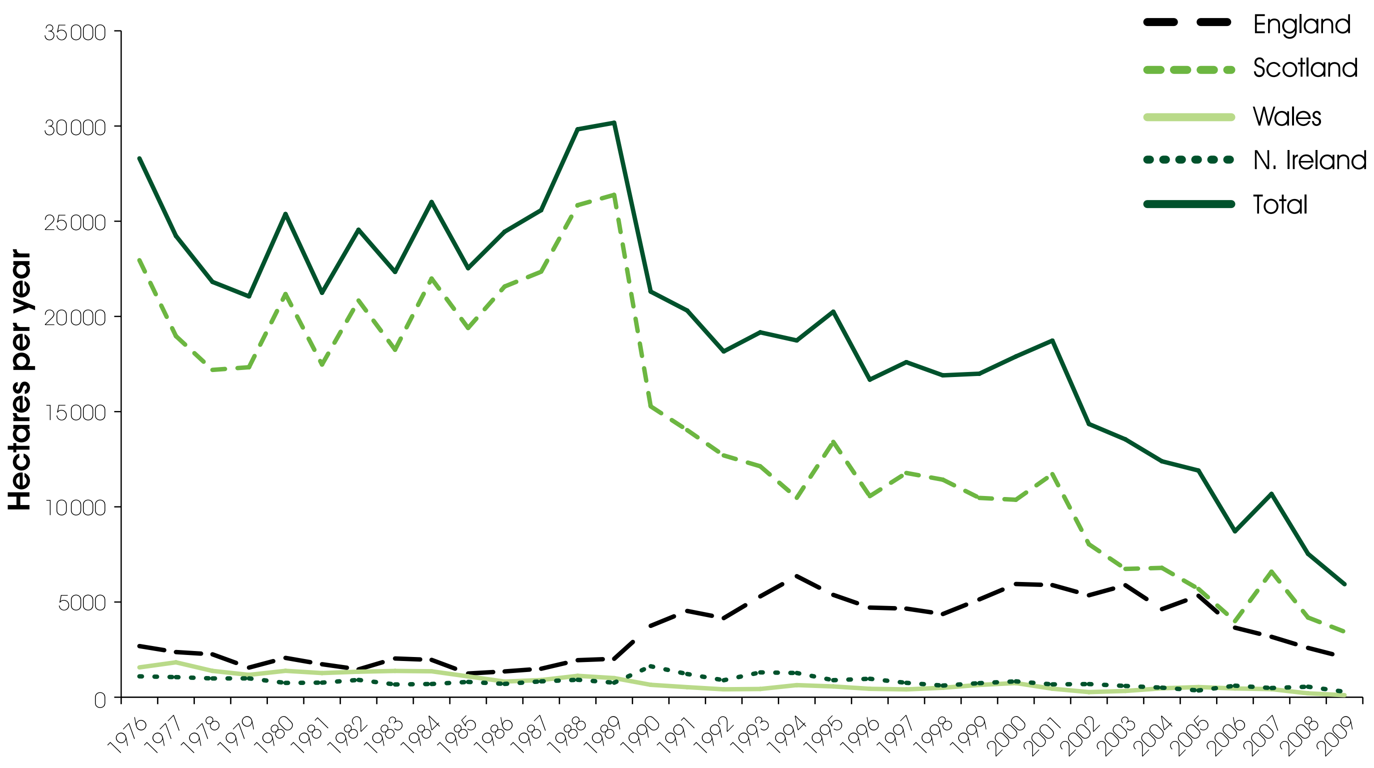
years (Figure 1.2). This will lead to a temporary trough in the net absorption of CO_2 by UK forests in the medium term as trees are felled and young trees are planted.

Changes to management practices have made the forests across the UK increasingly diverse in age and spatial structure and this will steadily reduce the peaks and troughs in the absorption of CO_2. Ongoing action of this kind will be very important in enabling forests to sustain their role as a major carbon sink and to fulfil that role consistently over time.

The main stocks of carbon within forests are the trees, other vegetation and soils. Important carbon stocks also exist outside of forests, notably in timber and wood products. The total stock of carbon in UK forests (trees only) is estimated to be about 150 million tonnes (Broadmeadow and Matthews, 2003). The average is therefore about 54 tonnes of carbon per hectare. Table 1.3 shows that most of this carbon is held in England and Scotland, in roughly equal quantities.

Actively growing forests in the UK sequester on average 3 tonnes of carbon per hectare per year, although this varies

Figure 1.1
Annual areas of new planting 1975–2009, in the UK.



Source: Forestry Commission, 2009.

Figure 1.2
Age structure of forests in the UK.

Source: National Inventory of Woodland and Trees 1995–99 (excludes Northern Ireland).

substantially with age, species and growing conditions (Morison *et al.,* 2009; Broadmeadow and Matthews, 2003). The UK GHG Inventory (Centre for Ecology and Hydrology *et al.,* 2008) shows that, in total, UK forests sequester over 4 MtC per year (see Table 1.3). Although the carbon stock in forests is roughly equal in England and in Scotland, the flows of carbon from the atmosphere to forests (i.e. sequestration) is much higher in Scotland due to the predominance of fast-growing conifer species.

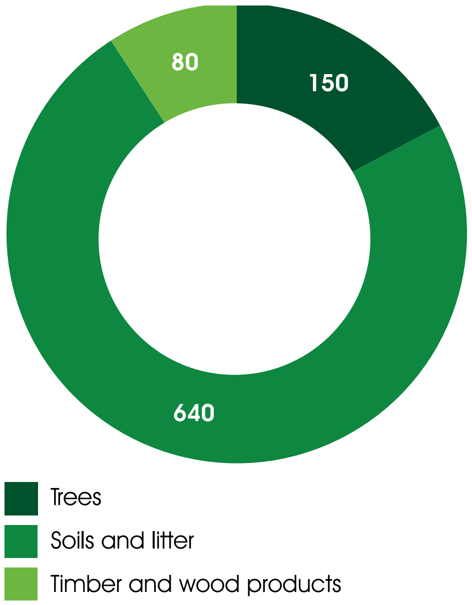
Table 1.3
Stock of carbon stored in UK woodlands (trees only).

	Stock of carbon[1] (MtC)	Flows of carbon from atmosphere to forests[2] (MtC per year)
England	63	0.89
Scotland	62	2.66
Wales	18	0.40
Northern Ireland	6	0.17
UK	150	4.12

Note: figures do not sum to totals due to rounding.
[1] Forest Research Woodfuel Resource (www.forestry.gov.uk/woodfuel).
[2] Centre for Ecology and Hydrology *et al.* (2008).

It is estimated that about 640 MtC are stored in UK forest soils, bringing the total carbon stock in all forest carbon pools to over 790 MtC (Morison *et al.,* 2009). Carbon stocks outside of forests (largely timber in construction) are estimated to hold a further 80 MtC (Broadmeadow and Matthews, 2003; Figure 1.3).

Figure 1.3
Carbon pools in UK Forests (MtC).



Forestry contributes to the economy in different ways. Wood production in the UK has been rising in recent years as a growing proportion of coniferous woodlands reach maturity. Production of softwoods, which accounts currently for 95% of the total, is predicted to rise from just over 9 Mt in 2007 to almost 12 Mt per year in the period 2017–21. The value of trees in absorbing carbon has important management implications for timber production, and for future forest management practices. If left standing, trees continue to absorb carbon beyond the age at which they are normally felled for timber and other uses, although this absorption will tail off in the longer term. Extended rotation lengths may, therefore, enhance the carbon sink effect of forests. However, an increase in rotation length affects the production of timber. It would also, after a time, reduce the rate of carbon absorption to low levels and would delay the benefits both from storing carbon in wood products and from the subsequent cycle of carbon absorption in a new tree crop. This issue is examined in Chapters 3 and 6. Analysis is needed to improve understanding on the balance, and potential trade-offs, between the role of forests in producing timber and mitigating climate change.

In 2006, forestry and primary wood processing supported an estimated 43 000 direct jobs and generated approximately £1.6 billion of gross added value to the UK economy (Forestry Commission, 2008). Consumption of wood products in the UK has risen in the past 10 years to over 55 million tonnes per year. The UK derives more than 70% of its timber imports from the countries of the EU27. In addition, about 18% is supplied domestically.

In addition to the timber production benefits from woodland, UK forests deliver a wide range of social and environmental benefits, which exist largely outside formal markets. Willis *et al.* (2003) estimated the non-market benefits of woodlands in Great Britain[5] to be worth approximately £1.25 billion per year (in 2008 prices). The largest values were found to be for forest recreation – over 250 million visits are made each year to UK woodlands (Forestry Commission, 2008) – and for woodland biodiversity, landscapes and carbon sequestration. Subsequent increases in the value ascribed by Government to the price of carbon (Department of Energy and Climate Change, 2009a) mean that carbon sequestration has now become the largest of these values. Trees and woodlands also deliver a range of other ecosystem services ranging from regulating water flows and quality to removing pollutants from the atmosphere. These services are of major value to the economy and society, providing a 'green

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[5] In this study data were not produced for Northern Ireland.

infrastructure' on which to base commercial activities, for example in tourism (Hill *et al.,* 2003).

In addition to their value in sequestering and storing carbon, trees and woodlands have become recognised for ameliorating the impacts of climate change. Further work is needed to assess the potential scale of the values pertaining to woodlands and climate change. This will increase awareness of the significant potential for forests in the UK to contribute to climate change mitigation – through sequestration and the use of wood fuel and wood products – and to adaptation to its inevitable impacts. These are the central themes considered in this report.

1.5 Review of forestry policy in the UK: a historical perspective

Recent forest policy in the UK can be traced to the establishment of the Forestry Commission in 1919. The Forestry Commission was empowered through the Forestry Act to purchase land for afforestation and to support and regulate the establishment of woodlands by private owners. The decades following the two World Wars focused on planting new woodlands to ensure a strategic supply of timber. This led to some controversy over the nature of forest plantings and the locations in which they took place, in particular with regard to their impacts on landscapes and the natural environment (Tsouvalis, 2000). In the latter part of the 20th century, a more varied and complex set of policy objectives emerged, based in large part on recognition of the role of woodlands in providing recreation and amenity and as a resource for biodiversity and the natural environment. Forests were recognised for generating multiple outputs, only some of which were valued by markets, and for yielding a flow of environmental benefits and costs which varied according to management and location. Increasingly, forest design and management became more focused on environmental objectives.

The diversity of our forests and their wide geographical spread has subsequently enabled trees and woodlands to contribute to many other objectives, including physical and mental health, urban regeneration, rural development, energy supply and a broader range of ecosystem services. Forests have become viewed as a tool to deliver wide-ranging Government objectives. Most recently, climate change has added another layer to forest policy and poses significant challenges to achieving an appropriate balance between the many demands placed on our forests and woodlands.

1.5.1 Sustainable forest management

The objectives of forest policy across the UK are encapsulated in the principle of sustainable forest management. The Second Ministerial Conference on the Protection of Forests in Europe (MCPFE), Helsinki, 1993 defined sustainable forest management (SFM) as:

> the stewardship and use of forests and forest lands in a way, and at a rate, that maintains their biodiversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological, economic and social functions, at local, national, and global levels, and that does not cause damage to other ecosystems.

Sustainable forest management is the basis of forestry policy, as demonstrated in the forestry strategies for England, Scotland and Wales, and the Sustainable Development Strategy identifies a similar role for forests in Northern Ireland. Forestry has also played a significant role, particularly since the 1980s, in attempts to develop a more integrated approach to land-use policy in tandem with, *inter alia*, agriculture, tourism, conservation and energy generation. This is evident, for example in the four EU Rural Development Programmes in the UK, which have brought together different activities and (formerly) separate funds into single programmes of support for development.

Compliance with internationally accepted standards of forest management is sought in the UK through both regulatory and voluntary means. On the regulatory side, The UK Forest Standard (UKFS) and procedures for giving grants and licences, require forest owners and managers to comply with wide-ranging environmental and socio-economic standards. The UKFS conforms to a set of pan-European criteria identified by the MCPFE. It defines the criteria and indicators of sustainable forest management for all forests in the UK, both planted and natural. The Forestry Act (1967) requires the granting of a felling licence before woodlands can be harvested. In most cases, permission to fell trees is conditional upon the area being replanted. This is a vital tool in ensuring that forest cover, and therefore its capacity for climate change mitigation and adaptation, is maintained in the long term. Some exceptions to conditional felling apply, for example where there are other over-riding environmental objectives, and where planning permission has been obtained.

Proposals for planting and felling trees and for building forest roads and quarries are also subject to Environmental

Impact regulations. Separate regulations apply in England and Wales, in Scotland and in Northern Ireland. Furthermore, woodland creation and removal proposals are subject to consultation with local authorities and other organisations with statutory powers in relation to land-use before the Forestry Commission gives approval. All such proposals are listed on the Forestry Commission's public register under the relevant country.

Voluntary compliance with international forest management standards is encouraged through internationally-recognised certification processes. All publicly owned forests managed by the Forestry Commission, and a significant proportion of private forests, conform to the UK Woodland Assurance Standard (UKWAS), which sets standards above the legally required minimum. The Forestry Commission's management process is based on a system of forest-wide design plans. These are renewed every 10 years and must comply with the UKWAS, the UKFS and UK grants and licences policy. Forest design plans are subject to public scrutiny. Private owners must submit detailed plans when applying for financial support from the Forestry Commission.

A defining feature of forestry policy in the 2000s has been the devolution of policy to separate administrations in England, Scotland, Wales and Northern Ireland, although some policy areas continue to be administered at a GB level, notably policy on research, international issues and plant health. Forest policy in each of the four countries is now focused on delivering objectives of the respective administrations. This has led to a range of policy objectives across the UK that, while similar in scope, differ in emphasis. For example, with regard to climate change, woodland creation has been given most weight in Scotland – where there is an aspiration to achieve 25% woodland cover by 2050 (Scottish Executive, 2006b). Since the late 1980s, such aspirations have been lacking in England and Wales – Figure 1.1 shows falling planting rates in recent years – but a recent Government white paper (HM Government, 2009b) has urged that new planting is needed to help mitigate climate change (see 1.5.3 below). In England, substantial potential has been identified to increase the supply of woodfuel from existing woodland. Some country-level policies have specific implications for the capacity of forestry to contribute to climate change mitigation and adaptation. These include the restoration of open habitats and an increase in continuous cover forestry (see Chapter 6).

A range of instruments is used to implement forest policy across the UK. Moxey (2009) classifies policy instruments into those that provide information, offer incentives or impose regulatory controls. Examples of each of these are currently in use, including support for research and advisory services, grants and tax breaks, and prescribed forest management activities. Almost one-third of UK woodlands are also under the direct management of the Forestry Commission. Grant payments cover woodland planting and management and other activities, as set out in the respective forestry strategies and policy documents in England, Scotland, Wales and Northern Ireland. Preferential tax treatment for forestry applies largely to productive forests and provides a significant spur for investment in the sector. Most recently, the potential is being explored to expand the use of markets in delivering environmental, non-market goods and services from forests – for example, carbon credits and water regulation – although this remains an emerging area of policy. UK forestry remains excluded from international markets in carbon credits, although voluntary, unregulated forest carbon schemes have developed in the UK private sector (see Chapter 12).

Analysis by Moxey (2009) has explored the extent to which the current range of instruments is suited to policy objectives. Grant payments have evolved significantly since the 1980s to tackle environmental and sustainability objectives and, to some extent, are addressing climate change objectives through, for example, payments towards the costs of investments in wood fuel boilers. It is arguable that major opportunities exist to develop further the suite of instruments so that they incentivise actions to mitigate and adapt to climate change. Such changes may include further alignment of tax breaks to sustainable forest management practices and new incentives for the use of timber as a sustainable material and for its role in carbon storage (see Section 5). Further work is needed to assess the potential from different instruments and where opportunities exist to target support for achieving a low-carbon economy.

1.5.2 International policy on climate change

International policy on climate change is now a major influence on forest policy across the UK. The United Nations Framework Convention on Climate Change (UNFCCC), established at the United Nations Conference on Environment and Development (UNCED) in 1992, is an international environmental treaty signed by the UK and over 180 countries and provides the foundation for the subsequent development of international climate change policy. Its objective is: 'to achieve stabilisation of greenhouse gas concentrations in the atmosphere at a low enough level to prevent dangerous anthropogenic interference with the climate system'.

The Kyoto Protocol, which came into force in 2005, was established under the UNFCCC. Industrialised countries (termed 'Annex 1' countries in the Protocol) that have ratified the Protocol, including the UK, are committed to reduce emissions of carbon dioxide and five other GHG, or to engage in emissions trading. The major distinction between the 'Protocol' and the 'Convention' is that the Convention *encouraged* industrialised countries to stabilise GHG emissions, whereas the Protocol *commits* them to do so. Under the Treaty, countries must meet their targets primarily through national measures. However, the Protocol offers additional means of meeting their targets through three market-based mechanisms that operate across national boundaries. These are:

1. Emissions trading (the European Union Emissions Trading Scheme is the largest in operation)
2. The Clean Development Mechanism (CDM)
3. Joint Implementation (JI).

These 'flexible mechanisms' are intended to allow countries with an emissions reduction or limitation commitment under the Kyoto Protocol (Annex B Party) to minimise their costs by buying and/or selling credits (trading scheme), or by implementing emission-reduction projects in developing countries (CDM) or other Annex B countries (JI). However, the contribution of forestry to mitigating climate change under these mechanisms is limited at present because it has only been used under the CDM to date.

Work is underway to develop a new regulatory framework for international action on climate change following the end of the first commitment period of the Kyoto Protocol in 2012. Negotiators aim to secure a new deal in Copenhagen at the end of 2009. Recent analysis (Eliasch, 2008) has highlighted the importance of including forestry within future emissions trading schemes, principally to reduce forest loss and degradation in developing countries. Deforestation is responsible for approximately 18% of global GHG emissions (Stern, 2007). Securing a deal on Reducing Emissions from Degradation and Deforestation (REDD) will be a major part of the negotiations at Copenhagen.

Complex accounting systems are required for the UNFCCC and the Kyoto Protocol to show whether parties to these agreements are meeting their commitments. The UNFCCC requires participating countries to submit national reports and annual inventories on implementation of the Convention. Annex I Parties that have ratified the Kyoto Protocol must include supplementary information on their emissions and removals of GHG to demonstrate compliance with the Protocol's commitments. The contribution of forestry is reported, as part of the UK's Greenhouse Gas Inventory, under the inventory and projections for the land-use, land-use change and forestry (LULUCF) sector (Centre for Ecology and Hydrology, 2008).

Commitments have also been made at a European level. Successive resolutions on Forests and Climate Change through the Ministerial Conferences on the Protection of Forests in Europe – most recently in Warsaw in 2008 – have committed signatory countries to play an active role in addressing climate change through forestry's roles in both mitigation and adaptation. These commitments are supported in the EU Forestry Strategy and the EU Forest Action Plan.

1.5.3 UK policy on climate change

The UK has a Climate Change Programme (HM Government, 2006) that aims to reduce carbon dioxide emissions by 20% on 1990 levels, by 2010. It is led by the Department of Energy and Climate Change (DECC) on behalf of the UK and devolved administrations. The UK has taken a proactive approach in developing climate change policy by introducing a Climate Change Act in 2008. The first of its type in the world, it applies to England, Wales and Northern Ireland and sets a legally binding target to reduce total GHG emissions by at least 80% by 2050 – compared with 1990 levels. A Committee on Climate Change was established under the UK Act and is empowered to set successive five-year targets for the UK's GHG account. In response to the Committee's advice (Committee on Climate Change, 2008), the Government has announced the budgets for 2008–12, 2013–17 and 2018–22, leading to a 34% reduction in GHG emissions with respect to 1990 levels, by 2020 (HM Government, 2009a).

A separate Climate Change (Scotland) Act is in force in Scotland. This sets a legally binding emissions reduction target of at least 80% by 2050, with an interim target in 2020 of a 34%, or possibly 42%, reduction from 1990 levels. The Act is supported by the Scottish Government Climate Change Delivery Plan, which describes how the Scottish Government would achieve the interim targets. Adoption of the 42% trajectory is dependent on the targets adopted by the EU and on advice from the Committee on Climate Change. The Delivery Plan lays out woodland expansion targets associated with the GHG reduction trajectories, and also identifies the growing role for biomass in renewable heat production. The Forestry Commission Scotland Climate Change Action Plan lays out a broader set of actions in relation to sequestration of carbon, as well as mitigation and adaptation to climate change. This is further supported by published Scottish Government policies on woodland expansion and woodland removal.

The UK Government has recently published a white paper, the UK Low Carbon Transition Plan. This sets out how the Government will achieve the targets in the climate change budgets, and draws attention to the contribution that forestry can make:

> 'Woodland creation is a very cost-effective way of fighting climate change over the long term … woodland creation represents 60% of the grant aid administered by the Forestry Commission. But to realise the potential for 2050, we need to see a big increase in woodland creation – and we need to plant sooner rather than later' (HM Government, 2009b).

Five UK forest management scenarios which consider realistic planting and management options to enhance abatement of GHG emissions in the future are analysed in Chapter 8 of this report.

The carbon benefits of wood biomass used to fire or co-fire power generation are recognised by the UK Renewables Obligation (RO), which rewards private sector investment in power generation in order to promote the generation of electricity from renewable sources in the UK. A UK Renewable Energy Strategy (Department of Energy and Climate Change, 2009b) was published in 2009 and sets a target of renewable sources producing 15% of the UK's energy requirements by 2020. Biomass has been identified as having the potential to meet 33% of the renewables target, with woodfuel and forestry making a significant contribution. These are described in Chapter 7.

The Government has also created an Adapting to Climate Change (ACC) Programme to bring together existing adaptation work, and co-ordinate future work. The ACC Programme has two phases. Phase 1, from 2008–11 is laying the groundwork necessary to implement Phase 2, a statutory National Adaptation Programme, as required by the Climate Change Act.

The objectives of Phase 1 of the Programme are to:

- develop a robust and comprehensive evidence base on the impacts and consequences of climate change in the UK;
- raise awareness of the need to take action now and help others to take action;
- measure success and take steps to ensure effective delivery;
- work across Government at the national, regional and local level to embed adaptation into Government policies, programme and systems.

The Programme is focused on England, although some elements will be UK-wide, and will be developed in partnership with the other UK administrations. The Programme is essentially domestic in scope, but consequences of climate change overseas will have an impact on the UK, because of the interconnected nature of our world. The Programme will therefore address those effects where there is a significant domestic risk. By considering the potential of forests to absorb carbon, this study will contribute to the objectives of Phases 1 and 2.

Furthermore, the UK Climate Change Act requires the Government to carry out, every five years, a national Climate Change Risk Assessment (CCRA), of which the first needs to be finished by 2012. An additional Adaptation Economic Analysis (AEA) will consider the costs and benefits of adaptation actions. The results of the CCRA and the AEA will inform a National Adaptation Programme, to be completed by the end of 2012, which will identify priority actions and allocate resources to meet them. The Act also gives ministers the power to require climate risk and adaptation reports from any body delivering a public good, and creates an Adaptation Subcommittee of the Committee on Climate Change, which will scrutinise the Government's adaptation actions. The Forestry Commission has been invited to submit a report to the CCRA (at time of writing). Woodlands have an important part to play in the work required to establish the National Adaptation Programme. They have ecological functions that people enjoy and value, and that can help to protect society from the impacts of climate change. The work reported in this study (in particular Sections 2, 3 and 4) will contribute to the evidence base required to support this risk assessment activity.

1.5.4 Forestry policy on climate change

Climate change is now a major focus of forest policy in the UK. The forestry strategies for England, Scotland and Wales, and the Sustainable Development Strategy in Northern Ireland, set out the objectives of forest policy on climate change. These emphasise the importance of carbon sequestration through woodland planting and management, the production of woodfuel as a renewable energy source, and the promotion of wood products in place of more fossil fuel-intensive materials. This study will inform the delivery of these objectives. The underpinning science for mitigation objectives is examined in Chapter 6. The strategies also emphasise the importance of adapting forests to the impacts of climate change, and developing the role of trees in helping society cope with a changing climate (e.g. by providing more shade and flood control in urban environments). The evidence underpinning these objectives is examined in Chapters 9 and 10.

At a UK level, the Forestry Commission has identified six priority actions that define the UK approach to forestry and climate change:

1. Protect and manage the forests that we already have
2. Reduce deforestation
3. Restore forest cover
4. Use wood for energy
5. Replace other materials with wood
6. Plan to adapt to a changing climate.

These actions resonate strongly with the conclusions of the IPCC's 4th Assessment Report on forestry and provide the context for much of the content of this report. They are embedded in the respective policies strategies in England, Scotland, Wales and Northern Ireland, and represent the priorities for forestry's contribution to climate change mitigation and adaptation in the coming years and decades. As will be seen in Chapter 8, these priorities are critical to providing a vision – through the identification of scenarios – of how forestry can help to provide a solution to the global challenge of climate change up until 2050 and beyond.

A major task for forest policy on climate change across the UK is to set standards for planning, managing and monitoring woodlands. Standards are important in providing benchmarks against which actions to deliver policy objectives can be assessed. In the forestry sector, it is vitally important that standards apply to the delivery of climate change objectives, while ensuring that the objectives of sustainable forest management are met.

Standards of sustainable forest management are set out in the UKFS (see 1.5.1 above), which is currently being revised and will include for the first time, a supporting Guideline on Forests and Climate Change. This strategic management guideline sets out requirements and advice on how to achieve the mitigation and adaptation potential of woodlands. This is a significant step in designing policy instruments to address forestry's role in tackling climate change. The contents of this report, including those dealing with the interactions between forests and the atmosphere (Chapter 3); the impacts of climate change on forests (Chapters 4 and 5); management actions for mitigation in different types of forest (Chapter 6) and adapting forests for climate change (Chapters 9 and 10), provide essential evidence to support the guideline.

Standards are also required in the operation of carbon markets. Carbon is widely traded in markets across the world, both in formal markets under the Kyoto Protocol (e.g. the EU Emissions Trading Scheme) and in voluntary markets. Forestry is largely excluded from formal international markets in carbon credits (see 1.5.2 above) – and therefore traded forestry credits are not currently used against international emissions targets – but it has become a significant player in voluntary markets. Forest carbon markets are examined further in Chapter 12. The quality of forestry projects in voluntary markets has been mixed, to date, and the Forestry Commission is currently developing a Code of Good Practice for Forest Carbon Projects to provide confidence in the marketplace that woodlands deliver projected carbon benefits. The Code will assure sustainable forest management (under the UKFS), put in place rigorous protocols for measuring woodland carbon, and establish criteria against which projects can be assessed. The Code will be launched in 2010.

As highlighted above (see 1.5.1), further analysis is needed to assess whether forest policy instruments currently in use, including the use of standards, require further changes to help to achieve the priority actions on climate change set out by the Forestry Commission.

1.6 Forest planning, projections and monitoring

Effective mechanisms for planning, monitoring and projecting the scale of forest resources are essential in assessing the current and future contribution that trees and woodlands can make to addressing climate change.

Planning takes place currently at strategic, forest management and site levels. The strategic level addresses the broad goals of an organisation and may comprise a number of forest areas. The forest management plan applies to a convenient unit or area for management and on which the requirements of sustainable forest management apply. Site planning is concerned with the operational detail of how proposals will be implemented. These plans also act as reference documents for monitoring and assessing the development of woodlands. Evidence is emerging that forest planning processes are starting to be amended for climate change objectives. This report provides evidence as to why such changes are needed.

The evidence provided by monitoring the amount of carbon in forest ecosystems is very important for developing policies on forestry and climate change, and for reporting forestry's contribution in GHG inventories under international processes for tackling climate change. Monitoring forest carbon is a complex task with significant technical challenges. The size of different stocks, or pools, of forest carbon is quantified above (see 1.4). A more detailed division of these pools is as follows:

1. Trees: both above ground (trunk, branches) and below ground (roots)
2. Wood products
3. Fine and coarse woody debris
4. Soil carbon
5. Other vegetation.

Forest managers in the public and private sectors in the UK routinely monitor the first two of these carbon pools but there is currently little consolidation and reporting of information at a national scale. This is in part due to the different ways that inventory data are managed in different organisations, i.e. the information is recorded in a variety of analogue and digital forms. For example, many private sector managers still rely on paper-based systems, while others have adopted geographic information systems (GIS). The Forestry Commission uses a bespoke GIS called 'Forester' to record all forest management activities and to forecast timber production.

A series of inventories for recording and monitoring forests has been produced in the past 60 years by the Forestry Commission. The latest of these is the National Forest Inventory (NFI), currently under development, which is the successor to the National Inventory of Woodlands and Trees. For production planning purposes, annual timber increment is expressed as Yield Class, which is the maximum mean annual increment of a crop in cubic metres per hectare. In conjunction with the specific gravity of timber, Yield Class can be used to estimate the amount of carbon in a forest. Yield Classes have been estimated for a range of species and associated management practices.

The NFI is being designed to record levels of carbon stocks in UK forests. This will produce a map, derived from 2003–07 aerial photography, showing the spatial extent, location and nature of all British woodlands over half a hectare in size. It is intended that the map will be updated using 'operational data' to a common baseline of 2008 and biannually thereafter. The scope of this work includes a field survey to estimate timber volumes in both the public and private sectors, and to facilitate more accurate production forecasting. The NFI will provide the most comprehensive assessment of forest resources to date in the UK, and will offer major improvements to the way that forest carbon across the UK is recorded and monitored. It will also become the basis for the forestry component of the UK's GHG Inventory (see 1.5.2 above). The first output of the NFI is the production in 2009 of the digital map of British woodlands. Full results from the NFI will be available by 2014.

The Forestry Commission is also examining how best to integrate assessments of the other carbon pools in woody debris, soil carbon and other vegetation, which are not routinely monitored, within the NFI. Models have been developed in Forest Research – the Forestry Commission's research agency – and elsewhere to estimate the carbon content of woodlands. These models are currently being enhanced to quantify carbon content in all woody biomass (e.g. branches, roots), forest litter and forest soils. In combination with inventory data, they will strengthen the evidence base on the potential contribution of forestry to sequester carbon, store it in wood and deliver substitution benefits through the use of wood fuel and wood products (see Chapter 8).

Other tools have also been developed that assist the monitoring of forest resources in relation to climate change. For example, the Ecological Site Classification (Ray, 2001) has been developed both as a stand-based and spatial tool (on a GIS platform) for matching tree species and native woodland communities to site types. It has been successfully used to inform forest policy, particularly in relation to the impact of future climate scenarios on tree species (see Chapter 5). This research programme is also developing stand-based and spatial climate change impact and adaptation tools, including new ways to assess the risk of biotic impacts of climate change scenarios.

In broad terms, existing and emerging procedures for projecting and monitoring the UK's forests place the UK in a good position to plan and review its forest resource. This should help it to take action on climate change in a sustainable way, depending on the relative costs of forestry investments as a source of mitigation and adaptation. However, it will be important to focus attention on whether the systems in place prove adequate for the new policy and management challenges presented by climate change. Current revisions to the UKFS and the introduction of a supporting guideline on climate change will help. But forest planning faces difficult decisions on how to address the many objectives of forestry. Managers will require ongoing input from the research community as to how woodlands can best deliver against the many demands placed on them. It is the intention of this report to evaluate existing knowledge and to identify gaps in understanding, so that the climate change elements of this management challenge can be met in the future.

References

BROADMEADOW, M. and MATTHEWS, R. (2003). *Forest, carbon and climate change: the UK contribution.* Forestry Commission Information Note 48. Forestry Commission, Edinburgh.

CENTRE FOR ECOLOGY AND HYDROLOGY, UNIVERSITY OF ABERDEEN, FOREST RESEARCH, NATIONAL SOIL RESOURCES INSTITUTE, CENTRE FOR TERRESTRIAL CARBON DYNAMICS, AGRI-FOOD AND BIOSCIENCES INSTITUTE and QUEEN'S UNIVERSITY (2008). *Inventory and projections of UK emissions by sources and removals by sinks due to land use, land use change and forestry*. Annual Report to DEFRA, July.

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.

DENMAN, K.L., G. BRASSEUR, G., CHIDTHAISONG, A., CIAIS, P., COX, P.M., DICKINSON, R.E., HAUGHLUSTAINE, D., HEINZE, C., HOLLAND, E., JACOB, D., LOHMANN, U., RAMACHANDRAN, S., DA SILVA DIAS, P.L., WOFSY, S.C. and ZHANG, X. (2007). Couplings between changes in the climate system and biogeochemistry. In: Solomon S., Qin, D., Manning M., Chen Z., Marquis M., Averyt, K.B., Tignor, M. and Miller H.L. (eds). *Climate Change 2007: the physical science basis*. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge. pp. 499–587.

DEPARTMENT OF ENERGY AND CLIMATE CHANGE (2009a). *Carbon valuation in UK policy appraisal: a revised approach.* Department of Energy and Climate Change, London.

DEPARTMENT OF ENERGY AND CLIMATE CHANGE (2009b). *The UK renewable energy strategy*. The Stationery Office, London.

ELIASCH, J. (2008). *Climate change: financing global forests: the Eliasch Review.* The Stationery Office, London.

FORESTRY COMMISSION (2008). *Forestry statistics.* Forestry Commission, Edinburgh

HILL, G., COURTNEY, P., BURTON, R., POTTS, J., SHANNON, P., HANLEY, N., SPASH, C., DEGROOTE, J., MACMILLAN, D. & GELAN, A. (2003): *Forests' role in tourism - phase 2.* Report to the Forestry Commission, Edinburgh

HM GOVERNMENT (2006). *Climate change – the UK Programme 2006*. Cm. 6764. The Stationery Office, London.

HM TREASURY (2009). *Building a low-carbon economy: implementing the Climate Change Act 2008.* HM Treasury, London.

INTERNATIONAL ENERGY AGENCY (2009). *CO_2 Emissions from fuel combustion.* Highlights. Paris. 124 pp.

KAUPPI, P.E., SEDJO, R.A., APPS, M.J., CERRI, C.C., FUJIMORI, T., JANZEN, H., KRANKINA, O.N., MAKUNDI, W., MARLAND, G., MASERA, O., NABUURS, G.J., RAZALI, W. and RAVINDRANATH, N.H. (2001). Technical and economic potential of options to enhance, maintain and manage biological carbon reservoirs and geo-engineering. In: Metz, B., Davidson, O., Swart, R. and Pan, J. (eds) *Climate change 2001: mitigation*. Contribution of Working Group III to the Third Assessment Report of the IPCC. Cambridge University Press, Cambridge. pp. 310–343.

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.

MOXEY, A. (2009). *Scoping study to review forestry policy instruments in the UK*. Report to the Forestry Commission, Edinburgh.

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.

RAY, D. (2001). *Ecological site classification decision support system V1.7*. Forestry Commission, Edinburgh.

RICHARDSON, K., STEFFEN, W., SCHELLNHUBER, H., ALCAMO, J., BARKER, T., KAMMEN, D., LEEMANS, R., LIVERMAN, D., MUNASINGHE, M., OSMAN-ELASHA, B., STERN, N. and WAEVER, O. (2009). *Synthesis Report – climate change: global risks, challenges and decisions*. University of Copenhagen, 10–12 March. Online at: www.climatecongress.ku.dk

SCOTTISH EXECUTIVE (2006a). *Changing our ways – Scotland's climate change programme*. Scottish Executive, Edinburgh.

SCOTTISH EXECUTIVE (2006b). *The Scottish forestry strategy*. Forestry Commission Scotland, Edinburgh.

STERN, N. (2007). *The economics of climate change: The Stern Review.* Cambridge University Press, Cambridge.

TSOUVALIS, J. (2000). *A critical geography of Britain's state forests*. Oxford University Press, Oxford.

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.

CLIMATE TRENDS AND PROJECTIONS

Chapter

2

C. C. West and J. I. L. Morison

Key Findings

The climate of the UK has already changed recently as a result of global emissions of greenhouse gases through human activity; an increase in mean annual temperatures is particularly evident.

Current Climate Projections (UKCP09) indicate that the climate in the UK will continue to warm through this century and there will be changes in rainfall and its seasonal distribution, which will vary regionally.

Climatic factors, primarily temperature and precipitation, interact with geology, geomorphology and soil characteristics in determining the type and productivity of woodlands and forests. These climate and soil factors determine many of the species and community patterns in our semi-natural woods and they strongly influence the choice of species or provenance for wood production. As climate changes, so the tree and woodland cover will change.

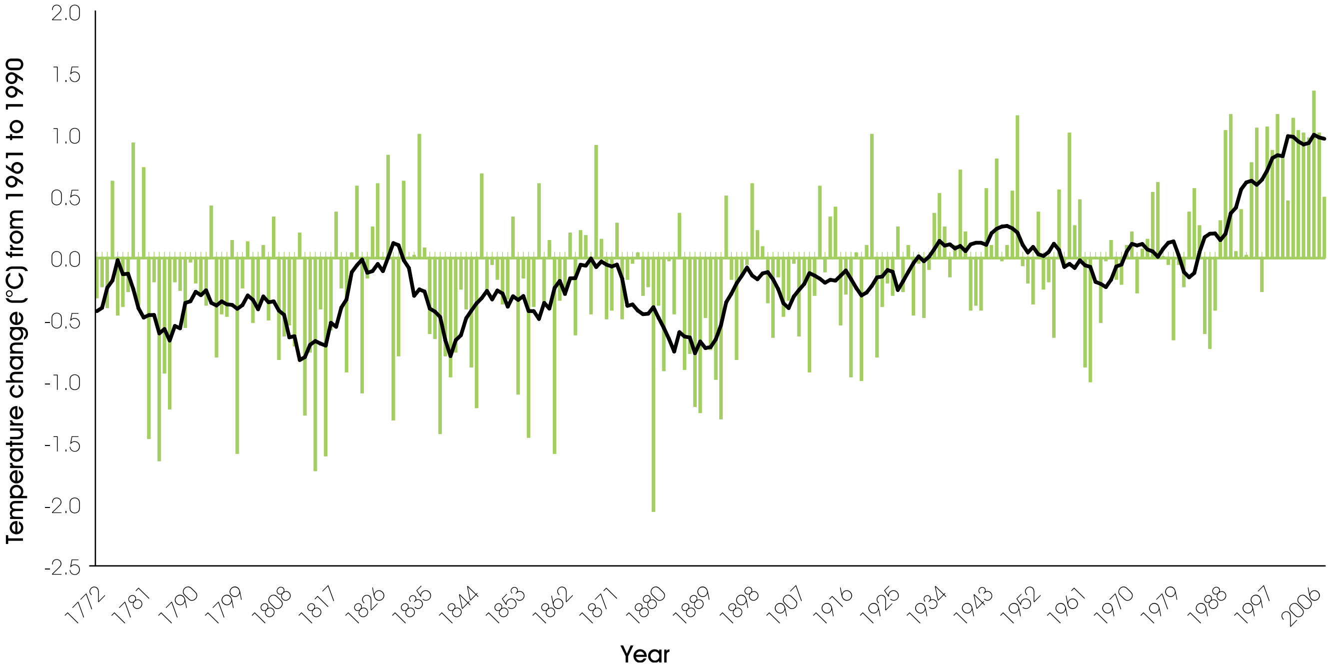
Subsequent chapters of this report assess the scientific understanding of and evidence for the impacts of climate change on forestry and its role in climate change mitigation and adaptation. It is important to set the context for this assessment by describing the latest evidence on how the climate has already changed and is projected to change in the UK over the coming decades under different GHG emissions scenarios. However, it should also be recognised that climate changes elsewhere in the world will affect global patterns of forest productivity, forestry sector activity and the demands of other land uses, which will indirectly influence UK forestry (see Chapters 4 and 5).

2.1 Observed trends in the UK climate

The evidence of recent change in the climate of the UK is compelling with, for example, the instrumental Central England Temperature record showing a substantial increase (Figure 2.1). Jenkins *et al.*, (2008) identified the following climate trends in the UK:

- Central England Temperature has risen by about 1ºC since the 1970s, with 2006 being the warmest in the 348-year long record. It is likely that global emissions of man-made GHG have contributed significantly to this rise.
- Sea levels rose by about 1 mm per year during the 20th century but the rate of rise in the 1990s and 2000s has been higher than this.
- Temperatures in Scotland and Northern Ireland have risen by about 0.8ºC since 1980, but this rise has not been attributed to specific causes.
- Annual mean precipitation over England and Wales has not changed significantly since records began in 1766. Seasonal rainfall is highly variable, but there has been a slight trend over the last 250 years for decreased rainfall in summer and increased in winter, although with little change in the latter over the past 50 years.
- All regions of the UK have experienced an increase over the past 45 years in the contribution to winter rainfall from heavy precipitation events. In summer, all regions except north east England and northern Scotland show decreases.
- There has been considerable variability in the North Atlantic Oscillation, but with no significant trend over the past few decades.
- Severe windstorms around the UK have become more frequent in the past few decades, although not above that seen in the 1920s.

Figure 2.1
Changes in annual values for Central England Temperatures (green bars) from 1772 to 2008, relative to the average over the 1961–1990 baseline period (about 9.5°C). Decadal variations in temperature are shown in black.



Source: Met Office Hadley Centre.

2.2 Climate Projections for the UK

The UK Climate Projections 2009 (UKCP09) are the latest in a series of government-funded descriptions of future climate in the UK. The principal advance in modelling under the UKCP09 is the ability to run multiple versions of a model in order to explore the modelling uncertainty. Whereas before, one projection based on a single formulation of a model was used, UKCP09 is based on probabilistic data derived from multiple runs of a Hadley Centre model, combined with single runs of other climate models, with weighting from performance of the models over the 20th century. Three IPCC emissions scenarios are used, high, medium and low (respectively, A1F1, A1B and B1). Further details are in Jenkins *et al.,* (2009) and Murphy *et al.,* (2009). Instead of a single outcome, users have a wide range of outcomes with relative measures of the strength of evidence that supports each outcome. This type of information can better inform risk-based decisions, but does require users to explore both the sensitivity of their system to change, and their own attitude to risk. The full range of UKCP09 material, together with scientific reports and guidance on the use of the projections, is accessible online at: http://ukclimateprojections.defra.gov.uk.

A number of issues should be borne in mind when interpreting the findings of UKCP09:

- Projections of climate change take into account uncertainty due to natural variability and due to modelling, i.e. our incomplete understanding of the climate system and its imperfect representation in models. The projections do this by giving the probabilities of a range of possible outcomes, as estimated by a specific methodology.
- Probability in UKCP09 can be seen as the relative degree to which each climate outcome is supported by current evidence, taking into account our understanding of climate science, observations and using expert judgement.
- Probabilistic projections are given at a resolution of 25 km over land, and as averages over administrative regions, river basins and marine regions, for seven overlapping 30-year periods and for three future emissions scenarios.
- Confidence in the projections varies, depending on the geographical scale and the variable under discussion. There is moderate confidence in projections at continental scale. Those at 25 km resolution are indicative to the extent that they reflect large-scale changes modified by local conditions such as mountains and coasts.
- Errors in global climate model projections cannot be compensated by statistical procedures no matter how complex, and will be reflected in uncertainties at all scales.

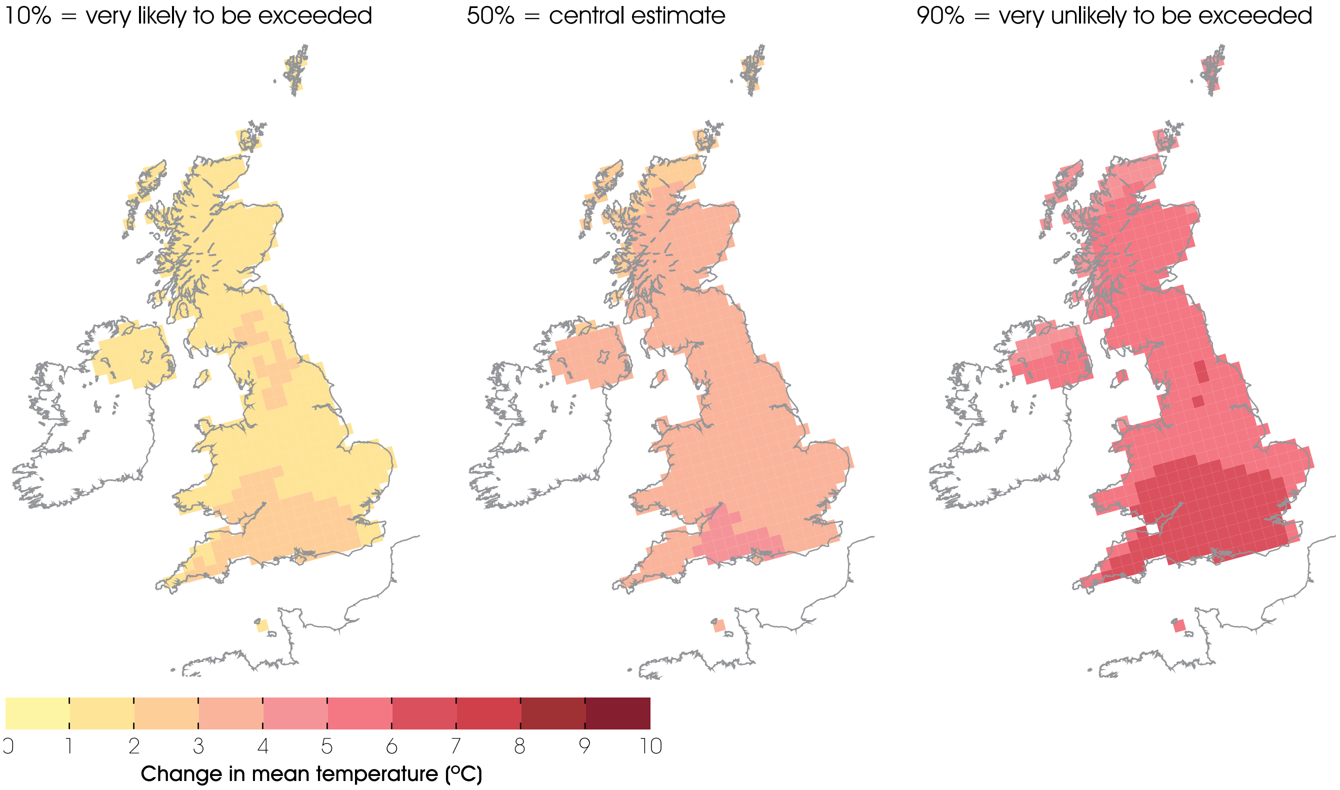
2.2.1 Projected seasonal and annual changes

The methodology developed for UKCP09 to convert climate model simulations into probabilistic estimates of future change necessitates a number of expert choices and assumptions, with the result that the probabilities we specify are themselves uncertain. We do know that our probabilistic estimates are robust to reasonable variations within these assumptions.

Changes by the 2080s (relative to a 1961–90 baseline) under the 'medium' emissions scenario are given below. Central estimates of change (those at the 50% probability level) are followed, in brackets, by changes which are very likely to be exceeded, and very likely not to be exceeded (10% and 90% probability levels, respectively).

- All areas of the UK warm, more so in summer than in winter. Changes in summer mean temperatures are greatest in parts of southern England (up to 4.2ºC; 2.2–6.8ºC) and least in the Scottish islands (just over 2.5ºC; 1.2–4.1ºC). Mean daily maximum temperatures increase everywhere. Increases in the summer average are up to 5.4ºC (2.2–9.5ºC) in parts of southern England and 2.8ºC (1–5ºC) in parts of northern Britain. Increases in winter are 1.5ºC (0.7–2.7ºC) to 2.5ºC (1.3–4.4ºC) across the country.
- Changes in the warmest day of summer range from +2.4ºC (–2.4 to +6.8ºC) to +4.8ºC (+0.2 to +12.3ºC), depending on location, but with no simple geographical pattern.
- Mean daily minimum temperature increases on average in winter by about 2.1ºC (0.6–3.7ºC) to 3.5ºC (1.5–5.9ºC) depending on location. In summer it increases by 2.7ºC (1.3–4.5ºC) to 4.1ºC (2.0–7.1ºC), with the biggest increases in southern Britain and the smallest in northern Scotland.
- Central estimates of annual precipitation amounts show very little change everywhere at the 50% probability level. Changes range from –16% in some places at the 10% probability level, to +14% in some places at the 90% probability level, with no simple pattern.
- The biggest changes in precipitation in winter, increases up to +33% (+9 to +70%), are seen along the western side of the UK. Decreases of a few percent (–11 to +7%) are seen over parts of the Scottish highlands.
- The biggest changes in precipitation in summer, down to about –40% (–65 to –6%), are seen in parts of the far

Figure 2.2(a)
Mean summer temperature change (June, July, August), relative to 1961–90 means. Data are for 2080s under the 'medium' (SRES A1B) emissions scenario. The change at 50% probability level, called the central estimate, is that which is as likely as not to be exceeded by 2080.



south of England. Changes close to zero (–8 to +10%) are seen over parts of northern Scotland.

- Changes in the wettest day of the winter range from zero (–12 to +13%) in parts of Scotland to +25% (+7 to +56%) in parts of England.
- Changes in the wettest day of the summer range from –12% (–38 to +9%) in parts of southern England to +12% (–1 to +51%) in parts of Scotland.
- Relative humidity decreases by around –9% (–20 to 0%) in summer in parts of southern England – by less elsewhere. In winter, changes are a few percent or less everywhere.
- Summer-mean cloud amount decreases, by up to –18% (–33 to –2%) in parts of southern England (giving up to an extra +20 Wm^{-2} (–1% to +45 Wm^{-2}) of downward shortwave radiation) but increase by up to +5% (0 to +11%) in parts of northern Scotland. Changes in cloud amount are small (–10 to +10%) in winter. Projected changes in storms are very different in different climate models. Future changes in anticyclonic weather are equally unclear.
- It has not been possible to provide probabilistic projections of changes in snow and wind speed. The Met Office Hadley Centre regional climate model projects reductions in winter mean snowfall of typically –65% to –80% over mountain areas and –80% to –95% elsewhere. It projects changes in winter mean wind speed of a few percent over the UK, but wind speed projections are very uncertain.
- There is no assessment of how the urban heat island effect may change.
- It is very unlikely that an abrupt change to the Atlantic Meridional Ocean Circulation (Gulf Stream) will occur this century.

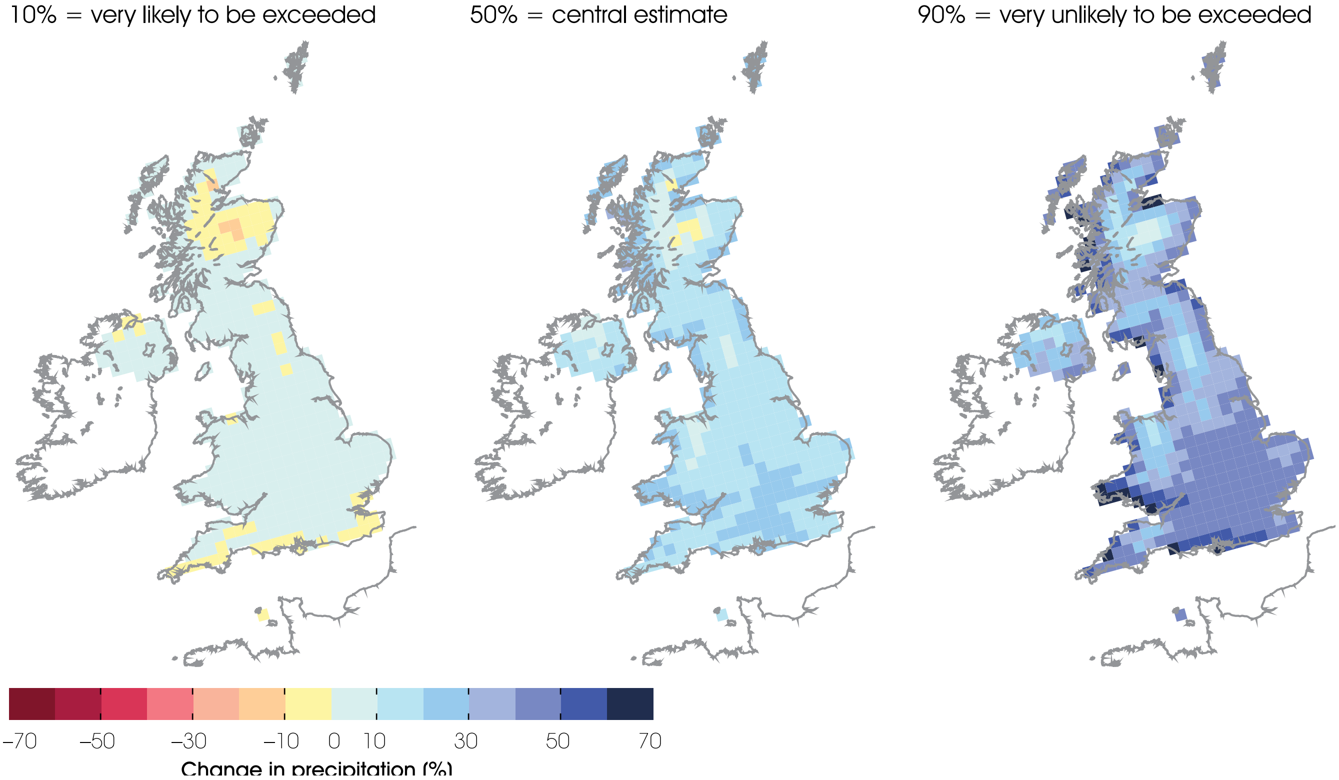
Examples of the UK-wide projection for the 2080s for mean summer temperature and mean winter precipitation are given in Figure 2.2, showing the 10%, 50% and 90% probability levels.

2.2.2 Projected changes in daily climate

UKCP09 provides synthetic daily time series of a number of climate variables from a weather generator, for the future 30-year time periods, under the three emissions scenarios.

Analysis of results from the Weather Generator shows that increases in the number of days with high temperatures are

Figure 2.2(b)
Mean winter precipitation change (December, January, February), relative to 1961–90 means. Data are for 2080s under the 'medium' (SRES A1B) emissions scenario. The change at 50% probability level, called the central estimate, is that which as likely as not to be exceeded by 2080.



found everywhere, particularly in south east England, and reductions in the number of frost days are found, greatest where frost days are currently more frequent. Increases in the number of 10-day dry spells across the UK are found, and are more pronounced in southern England and in Wales.

2.2.3 UKCIP02 and UKCP09

Having stressed the need for users to consider the full range of uncertainty given in UKCP09, it is nonetheless instructive to compare the central estimate (50% probability) of the projected changes with the single projections (for an identical emissions scenario) in the previous projections released in 2002 (UKCIP02). The following conclusions may be drawn.

- In the case of mean temperature, projected changes in UKCP09 are generally somewhat greater than those in UKCIP02.
- The summer reduction in rainfall in UKCP09 is not as great as that projected in UKCIP02.
- The range of increases in rainfall in winter seen in UKCP09 are very broadly similar to those in UKCIP02, although with a different geographical pattern. A few areas are projected to be drier in winter in UKCP09; in UKCIP02 all areas were projected to be wetter.
- Small changes in cloud cover are projected in winter, as in UKCIP02. Projections of summer decreases in cloud are similar to those in UKCIP02.

2.3 Forestry and the changing climate

The projected changes in our climate in the UK are likely to lead to a wide range of direct and indirect effects on trees, woodlands and forests. These include:

- changing growing conditions, including altered cloudiness patterns, extended growing seasons, modified soil moisture seasonal patterns and altered soil nutrient availability;
- modified rates of plant development, growth and wood production;
- changes in the type and frequency of abiotic disturbance such as waterlogging, flooding and storms;
- changes in both types of invertebrate and vertebrate pests and diseases, and in their severity, timing and seasonality;
- changes in distribution and potential range of many species (including invasive species); leading to
- changes in the species composition of woodland communities.

More details on these changes are given in Sections 2 and 3, and the issues about adaptation to them are discussed in Section 4.

The projections of anticipated temperature and rainfall suggest that forests in southern and eastern Britain are likely to experience a greater frequency and severity of summer dry spells, whereas areas in north western Britain will experience a moister and milder climate. Therefore, the climatic limitations to species survival, particularly for southern England, may shift away from factors like frost and cold hardiness, to others such as tolerance of summer drought. There may also be problems associated with earlier flushing in the spring, exposing trees to the risks of late spring frosts and/or delayed onset of dormancy in the autumn resulting in inadequate cold hardening. Such events are likely to be more influential upon species survival than average conditions.

One way to think of these projected changes is that forests in southern Britain will be experiencing climates with some characteristics of west central France by the 2050s and of Mediterranean Europe by the 2080s. Similarly, forests in central Scotland will experience the climate of southern Britain by the 2050s and of central France by the 2080s. This approach is useful for informing adaptation strategies, but such climate analogues are imperfect because many factors, especially latitude, are not included. These projected changes of climate are used as the basis for scientific evaluations of the interactions between UK forests and climate change which are described in this Assessment.

References

JENKINS, G.J., PERRY, M.C. and PRIOR, M.J.O. (2008). *The climate of the United Kingdom and recent trends.* Met Office Hadley Centre, Exeter.

JENKINS, G.J., MURPHY, J.M., SEXTON, D.S., LOWE, J.A., JONES, P. and KILSBY, C.G. (2009). *UK climate projections: briefing report.* Met Office Hadley Centre, Exeter.

MURPHY, J.M., SEXTON, D.M.H., JENKINS, G.J., BOOTH, B.B.B., BROWN, C.C., CLARK, R.T., COLLINS, M., HARRIS, G.R., KENDON, E.J., BETTS, R.A., BROWN, S.J., HUMPHREY, K.A., MCCARTHY, M.P., MCDONALD, R.E., STEPHENS, A., WALLACE, C., WARREN, R., WILBY, R. and WOOD, R.A. (2009). *UK climate projections science report: climate change projections.* Met Office Hadley Centre, Exeter.

THE ROLE OF FORESTS IN THE CAPTURE AND EXCHANGE OF ENERGY AND GREENHOUSE GASES

Chapter

3

P. G. Jarvis, R. J. Clement, J. Grace and K. A. Smith

Key Findings

Climate Change or 'Global Warming' is the rise in temperature of the troposphere (the lowest 17 km of the atmosphere). Greenhouse gases (GHG) absorb particular wavelengths of long-wave radiation and reduce the escape to space of radiation from the surface of earth. The ongoing rise in atmospheric GHG contents resulting from human activity is the major cause of climate change. Forests influence climate in two main ways. First, they absorb solar radiation energy and directly transfer sensible heat into the troposphere. Second, they influence the contents of GHG in the troposphere. UK forests exchange all the naturally occurring GHG (i.e. CO_2, CH_4, O_3, N_2O and water vapour) with the troposphere to a larger or smaller extent.

Because the albedo (solar radiation reflection coefficient) of forest stands is very similar to that of the vegetation that woodlands have replaced in the UK, the increase of forest area which occurred between the 1920s and 1980s has not, in general, changed local solar radiation budgets. Since UK weather and hydrological cycles are, in general, determined by weather patterns formed at large scales over the Atlantic Ocean, Europe and Russia, the contribution of differential energy partitioning by our forested land to our local weather is likely to be small.

The optimum temperature for growth of young Sitka spruce is above current projections at around 18°C, if other variables do not change. But as air temperature rises, the local water vapour pressure deficit (VPD) also tends to increase. Sitka spruce, in particular, and some other conifers, are very sensitive to VPD. On the rare occasions that air temperature currently rises above 20°C in UK forests, the stomatal pores in the needle surfaces of Sitka spruce close, the needles cease to absorb CO_2, and the forest may emit CO_2 for a short period until the VPD declines.

The existing UK forest cover is both a stock of carbon and a system removing CO_2 from the troposphere. If re-stocking follows harvest, without major disturbance, the forest carbon stock remains constant and, in a long-term well-managed forest, all stages in the tree life cycle and forest management cycle are represented equally in the forest. This system has the potential to remove CO_2 continuously from the troposphere and transfer it into storage in the soil and into commercial products that may for example, substitute for fossil fuels or be used for construction. Average annual removal of CO_2, from the atmosphere by closed-canopy Sitka spruce in northern Britain, Yield Class 14–16, is currently about 24 tCO_2 per hectare between years 17 and 40. Taking into account initial losses from 'soil' respiration stimulated by site preparation (see below), a conservative average annual figure over a typical 40-year rotation is about 14 tCO_2, per hectare. This is the average annual rate of CO_2 removal that we can expect from the afforestation of one million hectares of coniferous forest between 1950 and 1990 – unless major disturbance intervenes. Established mixed deciduous oak–ash forest in southern England removes CO_2 from the atmosphere at half to two-thirds of this rate.

Whereas removal of CO_2 from the atmosphere by UK forests currently accounts for only a small fraction of UK GHG emissions, the removals of CO_2 by the forests in Scotland currently account for around 12% of Scotland's GHG emissions.

Soil organic matter (SOM) has accumulated progressively in our northern soils since the ice retreated about 8000 years ago and is, in general, a large reservoir of organic carbon. In northern forests, particularly on the common peaty-gley soils in northern UK, there may be more organic carbon in the SOM than in the trees. This SOM is susceptible to oxidation and consequent emission of CO_2 to the atmosphere, particularly if the SOM is disturbed. Disturbance of the SOM results from either: (1) forces of nature, such as windthrow, or (2) consequences of management practices, in particular site preparation, thinning, harvest and stump removal. Windthrow, site preparation by ploughing and stump removal (on sites in northern Britain and southern Sweden) may cause annual emissions of CO_2 from the SOM of 14–20 tonnes per hectare. It may take 15 years for young trees planted on such disturbed sites to turn the site from a carbon source into a carbon sink.

All crops, forests included, require nutrient resources, particularly nitrogen (N). Emissions of CO_2 are the down-side of site preparation; the up-side is that mineralisation of soil organic matter (SOM) leads to the concurrent release of available nitrogen in the soil. Peaty-gley SOM has a C:N ratio of between 25:1 and 30:1, which is also the range of C:N of spruce needles. As a result of oxidation of the SOM, sufficient nitrogen is made available to provide for growth of the complete forest stand up to canopy closure. Thus, on most forest sites (other than problem sites with, for example, heather-check), there is no requirement for application of nitrogen fertiliser, which carries with it with the associated risk of release of nitrous oxide (N_2O) (a potent GHG). Once the forest canopy is up, resources are to a considerable extent recycled within the forest. The primary requirement for additional resources is to grow the wood, which has a C:N ratio of 400:1 to 700:1, depending on species. In contrast with the situation for conventional agricultural crops, for forest crops sufficient nitrogen is available for growth from the on-going turnover of SOM and the continuous addition of wet and dry deposition of nitrogen in various forms from the atmosphere. Because N_2O is an important GHG, the production of biomass from woody crops without the need for mineral fertilisers with the associated production of N_2O is important in UK climate change mitigation strategies.

There has been controversy over whether current forest CO_2 sinks, particularly those in the tropics, will continue into the future. Mainly as a result of increased photosynthesis caused by elevated CO_2, increases in the troposphere CO_2 lead to appreciable increases in the growth of young trees. A simplistic hypothesis is that as concentrations continue to increase, photosynthesis will saturate with respect to CO_2 and forest respiration will increase in relation to temperature, so that CO_2 emissions will come to exceed CO_2 removals in the foreseeable future. However, three different, independent forest system models (developed respectively in UK, Australia and the USA) that explicitly combine forest carbon and nitrogen cycles (including nitrogen deposition, turnover and emission) with the expected rise in atmospheric temperature and CO_2 concentration, lead to the conclusion that the Norway spruce carbon sink in Sweden and the Sitka spruce carbon sink in Scotland will continue as at present for at least the next 100 years.

Trees and forests interact with the atmosphere through exchanges of energy and greenhouse gases (GHG) such as carbon dioxide (CO_2) in the troposphere – that part of the atmosphere extending from the earth's surface to a height of around 17 km. Current projections (UKCP09) indicate that the climate in the UK will continue to warm through this century, and that there will be changes in rainfall and its seasonal distribution that varies regionally.

Forests will react to these changes but they also have the capacity to influence them at regional, national and global scales in two main ways: first, by absorbing solar radiation energy and directly transferring the energy as sensible heat into the troposphere; second, by exchanging GHG with the troposphere. The processes underlying these interactions between forest and atmosphere are discussed in this chapter.

As the ice retreated from the British Isles after the last glaciations, microorganisms in the rock debris gave way to green plants, and soil formation was initiated; forests followed and carbon (C) and nitrogen (N) accumulated. The most significant aspect of forests from the perspective of climate change is that they comprise both trees and soil. In forests world-wide, there is four times as much carbon in the soils as in the trees. In tropical forests, this ratio is about 1:1, and it increases northwards to 4:1 in the north-temperate forests, up to 8:1 in the boreal forests and over 10:1 in the tundra. While only remnants of those forests remain in Britain, the peaty-gley soils that developed have very largely provided the basis for the woodland creation in northern Britain described in Chapter 1. The carbon in these soils is as, or more, vulnerable to return to the atmosphere as the carbon in the trees. In considering interactions between forests and the atmosphere, we must take into account the role of both the trees and the soils, sometimes together, sometimes separately.

In addition to our historical native broadleaf and Scots pine woodlands, the one million hectares (ha) of conifers, 80% Sitka spruce *(Picea sitchensis)*, recently planted between 1950 and 1990, are a major resource today, available as they mature for a range of end-uses, including structural timber and woodfuel, and for making other contributions to climate change mitigation. The importance of Sitka spruce in commercial conifer plantations has led to it being the focus of much of the detailed characterisation and understanding of the processes underlying conifer tree growth in the UK that is discussed here.

In the first instance in this chapter, we consider a stand or compartment as the spatial scale (i.e. a scale of about 10–20 ha of similar trees at the same point in the management cycle) and we take the period of the rotation as the temporal scale (i.e. around 40 years for conifers). In later sections, for some purposes we consider the scale of a forest of several thousand hectares made up of compartments representing all stages in the management cycle, and ultimately, we consider the forest in a landscape also comprising agriculture and other land uses.

3.1 Greenhouse gases

Greenhouse gases (GHG) are gases that have absorption bands at particular wavelengths that absorb long-wave radiation and thus reduce the escape to space of the radiation emitted from the surface of the Earth. The rise in atmospheric GHG contents attributable to human activity is the major source of anthropogenic climate change. The calculated global warming potential (GWP) of the long-lived GHG depends on the lifetime or turnover time of the gas in the troposphere, and this depends strongly on a number of other, different, reactive atmospheric gases.

The relevant natural GHG in the troposphere are, in order of their significance: water vapour, carbon dioxide (CO_2), methane (CH_4), ozone (O_3) and nitrous oxide (N_2O) (IPCC, 2007). Forests exchange all these GHG with the troposphere to a larger or smaller extent (see 3.6 below).

Water vapour: is the main natural GHG, but its concentration is only indirectly affected by human activity, by our effect on evaporation rates from the land surface which vary with land use, irrigation and drainage. Evaporation from forests may influence the water vapour content of the local atmosphere at any time, but the large-scale tropospheric water content depends on the hydrological cycle, and in the UK case particularly the weather that reaches us from the Atlantic ocean, so that any change in UK forest evaporation would barely affect the water content of the troposphere at the global scale.

Carbon dioxide (CO_2): is the most effective anthropogenic GHG globally. Growing trees take up CO_2 from the local troposphere in photosynthesis, and forests globally mitigate climate warming significantly (Royal Society, 2001).

Methane (CH_4): methane's global warming potential (GWP) is 23 times that of CO_2 on a 100-year timescale. Waterlogged forest soils can be sources of methane, whereas drier forest soils may be sinks. Emission of methane from forest canopies has been postulated, but evidence is lacking.

Ozone (O_3): ozone is both a tropospheric GHG and a strong oxidant with damaging metabolic effects on tree function, particularly on the photosynthetic systems in leaves, as well as on human health (Royal Society, 2008). Compared with the other GHG, ozone is very short-lived, turning over rapidly in the troposphere. In forests, it may be formed continuously from isoprene and terpenes that are produced by tree leaves during photosynthesis. The significance of such forest sources is not well quantified.

Nitrous oxide (N_2O): nitrous oxide's GWP is 296 times that of CO_2 on a 100-year timescale. Both nitrification and denitrification can lead to emissions from forest soils. The application of fertilisers containing nitrogen over crops, pasture and, to a much lesser extent, forest, is a major source of N_2O in the troposphere.

3.2 Forest radiation and energy balance

3.2.1 Solar radiation, albedo and thermal radiation

Life on planet Earth depends on energy from our sun. The sun is a high temperature radiation source, so that solar radiation is essentially short-wave radiation. In addition to solar radiation, tree canopies exchange long-wave (or 'thermal') radiation with the atmosphere in proportion to their temperature (see Box 3.1).

A proportion of the incident solar radiation is reflected by forest canopies back through the atmosphere, the proportion depending on the structure and optical properties of the forest canopy, and the height of the sun above the horizon (i.e. dependent on latitude, time of year and time of day). The average proportion of solar radiation reflected, or *albedo*, defines how much of the sun's energy is not retained in the forest to drive processes. For a closed canopy, the properties of the leaves, their surfaces, arrangement and their spatial distribution, determine the *albedo*. The midday or mean daily albedo of closed canopy coniferous forest in summer lies in the range 8–12% (i.e. 88–92% of incident solar radiation is

BOX 3.1 Radiation partitioning

The net amount of solar radiation absorbed by a forest compartment (S_n) is:

$S_n = S(1 - \alpha)$,

where S is the incident solar radiation and α is the solar reflectance (or *albedo*).

The net amount of **thermal radiation, i.e. the radiation emitted by terrestrial bodies such as the atmosphere, soil and biomass**, absorbed by the forest (L_n) is

$L_n = L_d - L_{u,}$

where L_d is the down-welling and L_u the up-welling thermal radiation.

Thus, the **net all-wavelength** absorbed solar and thermal radiation, $R_{n,}$ is:

$R_n = S_n + L_n$

The energy in the **net all-wavelength radiation** is partitioned into different processes:

$R_n = G + H + \lambda(E+T) + P$

where G is the heat transfer into the soil; H is the transfer of sensible heat to the atmosphere; E the evaporation of intercepted rain (also called interception loss) and T the transpiration. λ is the latent heat of vaporisation of water and P the amount of energy used in photosynthesis. Note that P is very small compared with the other components of the energy balance, so is usually ignored.

Thus the energy **available** (A) to drive sensible heat transfer and evapo-transpiration is:
$A = R_n - G = H + \lambda(E+T)$.

Energy partitioning by the forest canopy is expressed by:

- the Bowen ratio $\beta = H/\lambda(E+T)$, and
- the evaporative fraction, $E_f = \lambda(E+T)/R_n$

All the above properties may be expressed as instantaneous values (e.g. midday) or as period-averaged, e.g. over a half-hour, daytime, month, season or year.

absorbed). This range of values of albedo is quite similar to the albedo of heathland that has been replaced by conifers during recent woodland creation. The albedo of closed canopy broadleaf forest when fully leafed is generally much larger, in the range 18–22 %, and comparable with values for agricultural crops. During the leafless phase of the annual cycle and in the absence of snow, in winter the albedo of broadleaf forest drops to lower values.

3.2.2 Leaf dynamics and solar radiation absorption

The growth of a stand of trees, and indeed of forests, depends on the amount of solar radiation that is intercepted and absorbed by the tree crowns that comprise the forest canopy. It is the size, spatial distribution, angular distribution, grouping and overall area of the leaves that determine the amount of solar radiation that is intercepted and absorbed by a forest canopy. Canopies differ widely with respect to these five properties. In general, it is the overall area of leaves, and their distribution within the canopy space, that has the largest effect on CO_2 uptake by a canopy (Wang and Jarvis, 1991).

In Sitka spruce stands, the leaf area index (LAI, see Box 3.2) reaches around 10 at canopy closure and then drops back to a stable value of around 8 that is maintained through the rotation, as needles are dropped from the two or three lower-most whorls of branches. Viewed looking down from above, the canopy appears as an array of brightly-lit cones with large black holes tapering downwards between them, as a result of multiple reflections and effective absorption of solar radiation (Norman and Jarvis, 1974). A consequence of this structural arrangement is that around two-thirds of the absorption of solar radiation by the trees, once the canopy is closed, occurs in the well-lit upper one-third of the tree crowns. This is maintained throughout the rotation, unless the LAI is temporarily reduced, for example by defoliation or thinning.

BOX 3.2 Leaf area index

Leaves absorb solar radiation and absorb CO_2 from the atmosphere. The leaf area index (LAI) is the dimensionless metric used to describe the amount of leaf present in a canopy. It is the summed plan area of leaves per unit area of ground; e.g. a LAI of 8 is 8 m^2 of leaves in a vertical cylinder of 1 m^2 in cross-section through a canopy, measured laid out horizontally without overlap, and expressed per 1 m^2 of ground area.

If leaves are randomly distributed in space through a canopy, with a random distribution of leaf angles, one would expect 95% interception of solar radiation to occur at a LAI of 6. However, if leaves are grouped into crowns, and within the crowns the leaves are grouped into whorls of branches, and on the branches they are further grouped around the shoots, a much larger LAI can be maintained than if the leaves were randomly distributed in space, with random inclination and azimuthal angles (Wang and Jarvis, 1990, 1991).

In general, canopies of broadleaves have a smaller LAI (4–6) than those of conifers, and the leaves are more horizontal and less grouped than in conifers, but with higher photosynthetic capacity per unit leaf area. The result of a shorter growing season is somewhat lower rate of CO_2 removal from the atmosphere by broadleaves than conifers (Figures 3.3 and 3.6).

3.2.3 Partitioning of the absorbed energy

The radiation energy available to drive exchange processes within a forest, *A* (see Box 3.1) is the algebraic sum of the incoming and outgoing short-wave and long-wave radiation fluxes. During the daytime, vegetation canopies are generally warmer than the atmosphere because of the absorption of solar radiation, and consequently heat is transferred directly from canopies to the troposphere. In the absence of solar radiation at night however, the net emission of long-wave radiation leads to cooling down of canopies, dew formation and sometimes frost.

The *evaporative fraction* defines the proportion of the absorbed energy that cools the local air but also adds water vapour to it. The Bowen ratio (β), is a measure of the relative proportion of the absorbed radiation energy that is directly transferred into warming the local air.

Energy flux measurements over coniferous forests with dry foliage show that the Bowen ratio is generally larger than 1 and frequently larger than 2; i.e. more than twice as much of the available energy is transferred directly into the troposphere as sensible heat, rather than as transpiration, because transpiration is restricted by the apertures of the pores in the leaves, the stomata. This situation is rather different in the case of broadleaves and agricultural crops, for which β is generally less than unity, i.e. more of the absorbed energy is used to evaporate water by crops and less to heat the ambient air directly.

By comparison with crops and herbaceous vegetation, forests are very well coupled to conditions in the troposphere because of the height of the trees and the aerodynamic roughness of the canopy, both of which enhance turbulent transfer of heat and water vapour (McNaughton and Jarvis, 1983). As a result, evaporation of water from forest canopies is predominantly driven by the water vapour pressure deficit (VPD) of the ambient air, rather than by the available solar energy (*A*, Box 3.1) (Jarvis and McNaughton, 1986). The VPD is also the primary driver of transpiration from forest canopies, which is consequently more effectively controlled by the aperture of the stomatal pores in the leaves than in shorter agricultural crops for which solar radiation is the primary driver of both evaporation and transpiration (for a summary, see Monteith and Unsworth, 1990, p. 197).

Furthermore, the stomatal pores of Sitka spruce, and many other conifers, are very sensitive to the ambient VPD, closing at large values of the VPD (see 3.3.4 below). Thus, as local temperatures rise and VPD increases, we can expect less transpiration and a larger proportion of the available energy going into *direct* warming of the troposphere as sensible heat. On the other hand, water vapour is also a GHG, and, like CO_2, it impedes the escape of long-wave radiation to space. Thus, closure of stomata, caused by the large VPDs that occur at higher temperatures, results in contrasting reduced addition of water vapour to, and reduced removal of CO_2 from the troposphere (Jarvis, 1994). The balance of effects between 'additional direct heating', reduced 'water vapour emission' and reduced 'CO_2 removal' is not easily calculated and requires a model for solution in particular circumstances.

3.3 Measured growth responses of trees to atmospheric variables

3.3.1 Growth responses to intercepted solar radiation

Growth of a tree stand is proportional to the solar radiation intercepted by the canopy (Monteith, 1977; Jarvis and Leverenz, 1983; Wang *et al.,* 1991) and the relationship is relatively consistent across a range of species (Linder, 1985; Landsberg *et al.,* 1996). The interception of solar radiation depends on the development of canopy leaf area, which depends on a number of environmental resources, particularly the availability of nutrients during the initial phase of stand development (see 3.4.9 below).

Empirical relationships between the growth in tree and stand dry mass with time and the concurrent intercepted solar radiation have proved to be quite consistent across a range of species, spacing, fertiliser and management treatments and are the basis of more than one widely-used stand growth model (e.g. 3PG). A commonly obtained figure for a number of forest species is 0.85 kg tree dry mass per giga joule (GJ) of intercepted solar radiation (Linder, 1985; Landsberg *et al.,* 1996). This commonality occurs because both interception of radiation and photosynthetic absorption of CO_2 are primarily dependent on the amount of leaf present. An investigation over four years, making use of stands of Sitka spruce in a thinning and fertiliser experiment (± thinning, ± N and ± P) at Tummel forest, central Scotland, gave a maximum of 0.85 kg tree dry mass per GJ intercepted solar radiation (Wang *et al.,* 1991) and this is not atypical for coniferous forest stands. Nonetheless, Cannell *et al.,* (1987), Milne *et al.,* (1992) and Sattin *et al.,* (1997) obtained values of up to 1.4 kg dry mass per GJ intercepted for small plots of short-rotation willows and poplars, near Edinburgh.

3.3.2 Growth responses to atmospheric CO_2 concentration

During the 1990s, a large number of experimental studies were made in Europe to investigate the responses of forest tree species to a doubling of the current atmospheric CO_2 concentration, i.e. to concentrations in the range of around 700–750 ppmv CO_2. Young broadleaves of *Fagus sylvatica, Betula pendula, B. pubescens, Alnus glutinosa, Prunus avium, Quercus robur, Q. petraea, Q. rubra, Populus* hybrids and the conifers *Picea abies, P. sitchensis* and *Pinus sylvestris* between 1 and 10 years old were grown in a range of chambers, most commonly in outdoor open-topped chambers of 3 m diameter and 4 m height (Jarvis *et al.,* 1998). Meta-analysis of the data showed a mean increase in total biomass in response to the doubling in atmospheric CO_2 concentration of 54% over all species (above and below-ground biomass, in stressed and unstressed conditions) over *c.* 5 years of growth: 50% for the broadleaves; 56% for the conifers (Medlyn *et al.,* 1999, 2000). The mean response of Sitka spruce was an increase in dry mass of 32% without fertiliser addition and over 100% with added fertiliser; the response of oak ranged from 5% to over 100% with added irrigation. In general, the effect of growth in elevated CO_2 concentration was large in small, young plants and became magnified as a result of subsequent exponential growth.

While increase in the ambient CO_2 concentration would be expected to increase the concentration of CO_2 at the photosynthetic reaction sites in the chloroplasts within the leaves, and thus to increase photosynthesis and biomass production, the stomata of many species reduce in aperture at higher ambient CO_2 concentrations, thereby reducing the entry of CO_2 into leaves, so that it is not immediately obvious that the projected increase in ambient CO_2 concentration will lead to increase in growth. A meta-analysis of stomatal conductance data from 13 of the long-term, field-based experiments with trees in open-top chambers found an average 21% decrease in stomatal conductance in response to doubling of the ambient CO_2 concentration (Medlyn *et al.,* 2001). However, the stomata of a few species, including Sitka spruce and Scots pine, were not very responsive to the increase in CO_2 concentration, consistent with earlier laboratory-based studies (e.g. Beadle *et al.,* 1979; Morison and Jarvis, 1983).

Trees can be grown to larger sizes and exposed to elevated CO_2 concentrations in individual tree chambers and in stands. For example, Silver birch (*Betula pendula*), was grown for four years from seedlings to a height of 4.2 m in individual ventilated tree chambers near Edinburgh, in ambient air to which CO_2 was added to give 700 ppmv. Leaf area increased by 60% and net photosynthesis by 68%, relative to the plants in the current ambient CO_2, but biomass growth increased only by 59% because of larger losses of carbon from fine root production and mycorrhizas (Rey and Jarvis, 1997; Wang *et al.,* 1998). In a number of comparable experiments in Europe and in the USA with indigenous species, similar results have been obtained. In central Sweden, for example, individual 10 m tall trees of Norway spruce, growing in plantations with nutrient fertilisation, in air-conditioned chambers, to which CO_2 was added to give a concentration of 700 ppmv, increased in stem growth by 15 to 20% relative to the controls over 3 years (S. Linder *et al.,* pers. comm.). In the USA, free-air exposure of stands of pole-stage *Pinus taeda* (loblolly pine) to an increase of the CO_2 concentration of 200 ppmv above ambient (using the so-called FACE technology), led to a differential increase in tree height of the dominant trees of 7%, relative to the controls, over 10 years (R. Oren *et al.,* 2009, pers. comm.). Comparable results using FACE methods on other tree stands have been summarised by Karnosky *et al.,* (2005).

There can be no doubt therefore, that young trees and stands of pole-stage trees grow faster in an atmosphere with increased CO_2 concentration. However, there is limited information on the responses of *mature* trees to increase in ambient CO_2 concentrations.

3.3.3 Growth responses to ambient temperature and VPD

Examination of independent responses to ambient air temperature and VPD, which are both expected to increase together in the future, requires the use of more sophisticated controlled environment facilities in which only small, young trees up to around 70 cm in height can be grown. Such experiments, in which other environmental variables have been kept constant within narrow limits, have shown that the optimum temperature for growth of young Sitka spruce is a regime of around 20/14°C day/night temperature (Neilson *et al.,* 1972). However, in natural conditions, increase in air temperature is invariably accompanied by an increase in VPD, and other experiments in which VPD was *not* independently controlled, have shown a lower temperature optimum. Similar experiments have shown a substantial negative growth response to increase in the ambient VPD (Neilson and Jarvis, 1975). Thus, the dominant effect of the projected rise in temperature on Sitka spruce is likely to be mediated through the negative response to VPD in closing the stomata and thereby reducing CO_2 influx and growth.

3.3.4 Stomatal conductance responses to atmospheric VPD

Laboratory investigations of leaf physiology have demonstrated that CO_2 exchanges of Sitka spruce, and other species of both conifers and broadleaves, are very sensitive to the local ambient VPD, because large VPD leads to closure of the stomata, independent of the plant water status, thereby reducing the influx of CO_2 into leaves, as well as the exchanges of other gases and volatile compounds (e.g. Sandford and Jarvis, 1986). A meta-analysis of stomatal conductance data from the long-term, chamber-based experiments across Europe referred to in 3.3.2 above, found that both Sitka spruce and Scots pine showed a substantial decrease in stomatal conductance with increasing VPD but that *Quercus robur* and other species were rather more sensitive, irrespective of whether grown in ambient or elevated atmospheric CO_2 concentration (Medlyn *et al.,* 2001).

A consequence of this sensitivity of stomata to VPD, observed at stand scale in forests, is that the net carbon influx to stands of Sitka spruce (see 3.4.6 below) may fall to zero or less during days in which the ambient air temperature rises above around 20ºC, in part because of the associated increase in the ambient VPD (Jarvis, 1994). Anecdotal and mensurational forestry evidence that Sitka spruce grows less well in the east of Scotland than in the west, *despite adequate soil water*, is consistent with this negative physiological response to ambient VPD.

3.4 Temporal CO_2 dynamics

3.4.1 Stocks and fluxes: some basic concepts and definitions

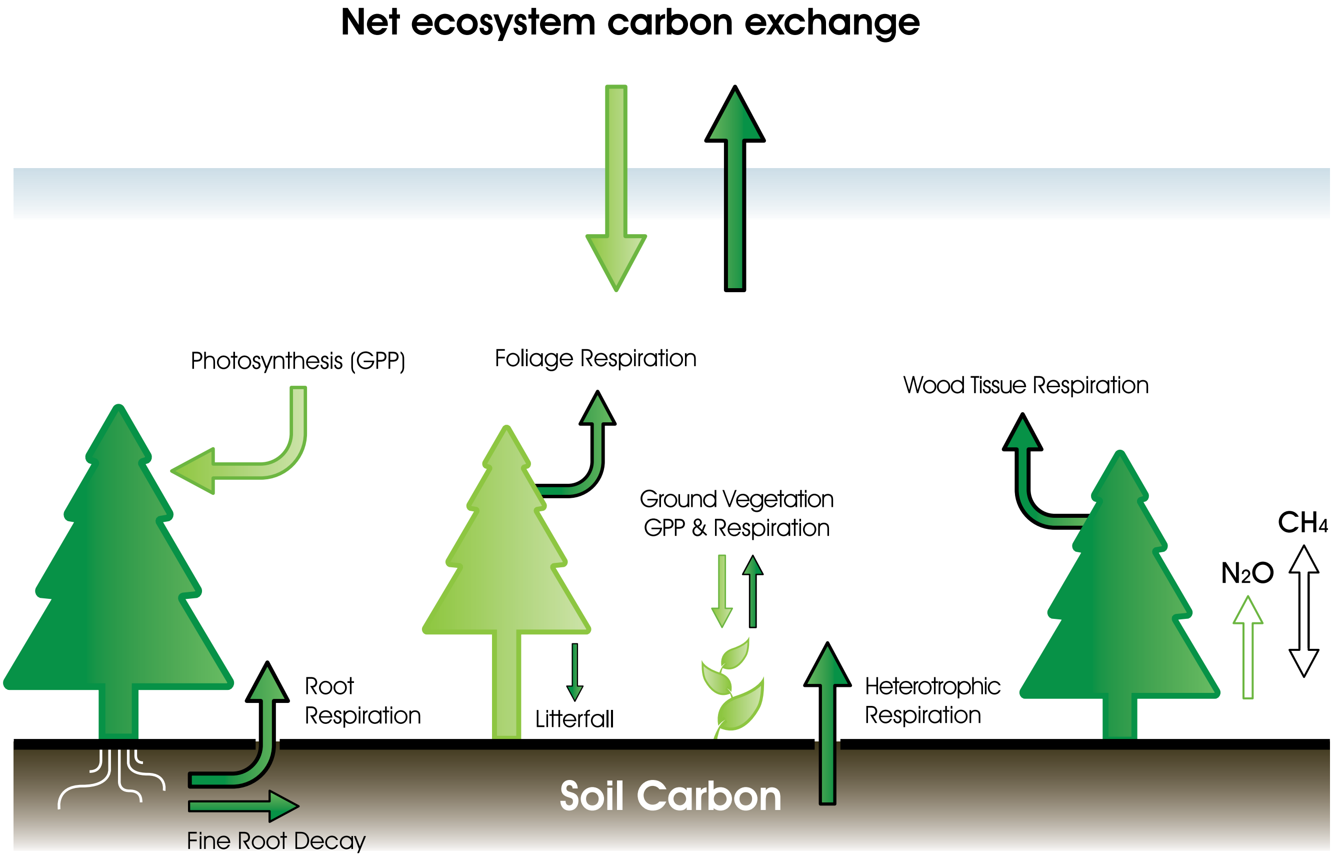
As a consequence of their photosynthetic activities, forest stands contain significant stocks of carbon in trees and soil, and continuously exchange CO_2 with the atmosphere. The main fluxes of CO_2 and the two other key GHGs, N_2O and CH_4, in forest stands are illustrated in Figure 3.1 and appropriate variables are defined in Box 3.3 and Figure 3.2.

3.4.2 Measurements of CO_2 fluxes in UK forests

Measurements of the exchanges of CO_2 between forests and the troposphere are crucial to identifying, quantifying and understanding: (1) the processes that determine carbon accumulation and growth of forests and (2) the capability of forests to mitigate climate change by removing CO_2 from the troposphere. First measurements were made in the early 1970s on a campaign basis using the so-called energy budget or Bowen ratio approach. Our capacity to measure CO_2 exchanges (or fluxes) continuously and quantitatively developed in the 1990s, using the so-called eddy-covariance technology, which required very fast (5–10 Hz) CO_2-measuring sensors and sonic anemometers.

Although there are today possibly over 100 forest sites where CO_2 fluxes are being measured in forests across Europe, only sites in Ireland have a reasonably similar maritime climate and comparable tree species to forests in the UK. The overriding influence of the North Atlantic drives

Figure 3.1
The emissions and removals of the main trace gas fluxes in a forest stand. The interrelationships among the principal carbon fluxes are defined in Box 3.3 and by Figure 3.2.



(Note: O_3 is not shown in this figure because of indirect formation through VOC production and direct deposition).

BOX 3.3 Some definitions

GPP – 'Gross Primary Production', i.e. removal of CO_2 from the atmosphere by photosynthesis in leaves, is driven by the fraction of visible radiation absorbed by leaf pigments and is a function of LAI, leaf age, position, N content and acclimation to the solar radiation flux

R_A – autotrophic respiration of living cells in twigs, branches, wood, bark, roots

NPP – 'Net Primary Production' (GPP – R_A)

R_H – heterotrophic respiration in the soil

R_R – autotrophic root-system respiration

R_S – soil respiration (= $R_H + R_R$)

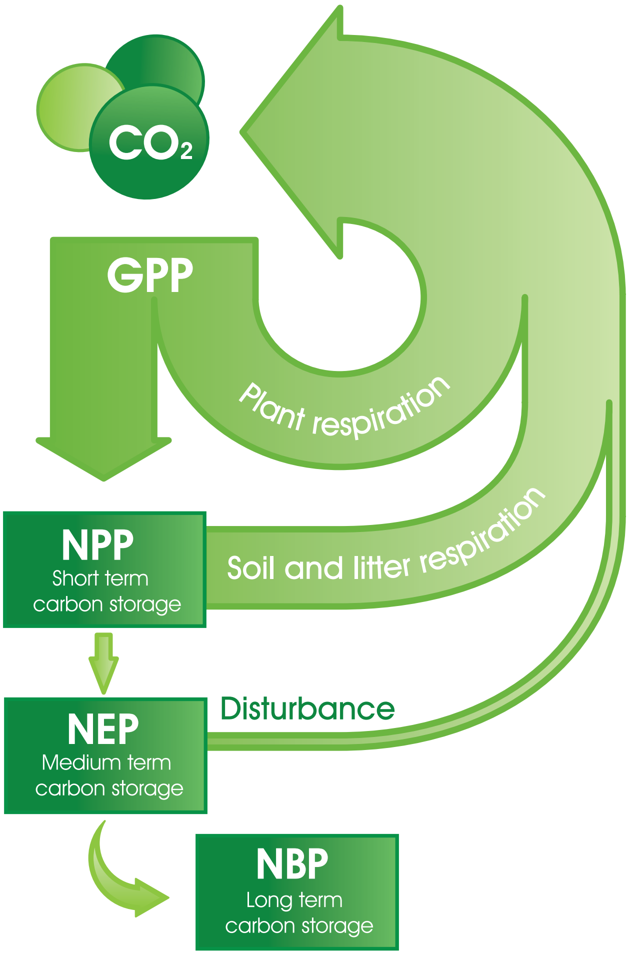
R_E – ecosystem respiration (= $R_A + R_H$)

NEP – Net Ecosystem Production (= GPP – $R_A - R_H$), see Figure 3.2.

NEP is a measure of the total CO_2 influx (or gain) less the total CO_2 emission (or loss) and thus it is *the measure of net removal of CO_2 from the atmosphere* by a forest stand. At the scale of an extensive forest (e.g. 5000 ha or so, with compartments at various stages of management, or a landscape comprising a range of additional land uses, the net CO_2 exchange, as seen from a tall tower or an aircraft, will likely be less than the NEP as a result of natural, accidental or managerial '*disturbance*' (*D*) of various kinds.

Thus, NBP – Net biome production integrates CO_2 exchanges across the landscape (NEP – *D*).

Figure 3.2
Diagrammatic representation of the relationships among the carbon fluxes defined in Box 3.3.



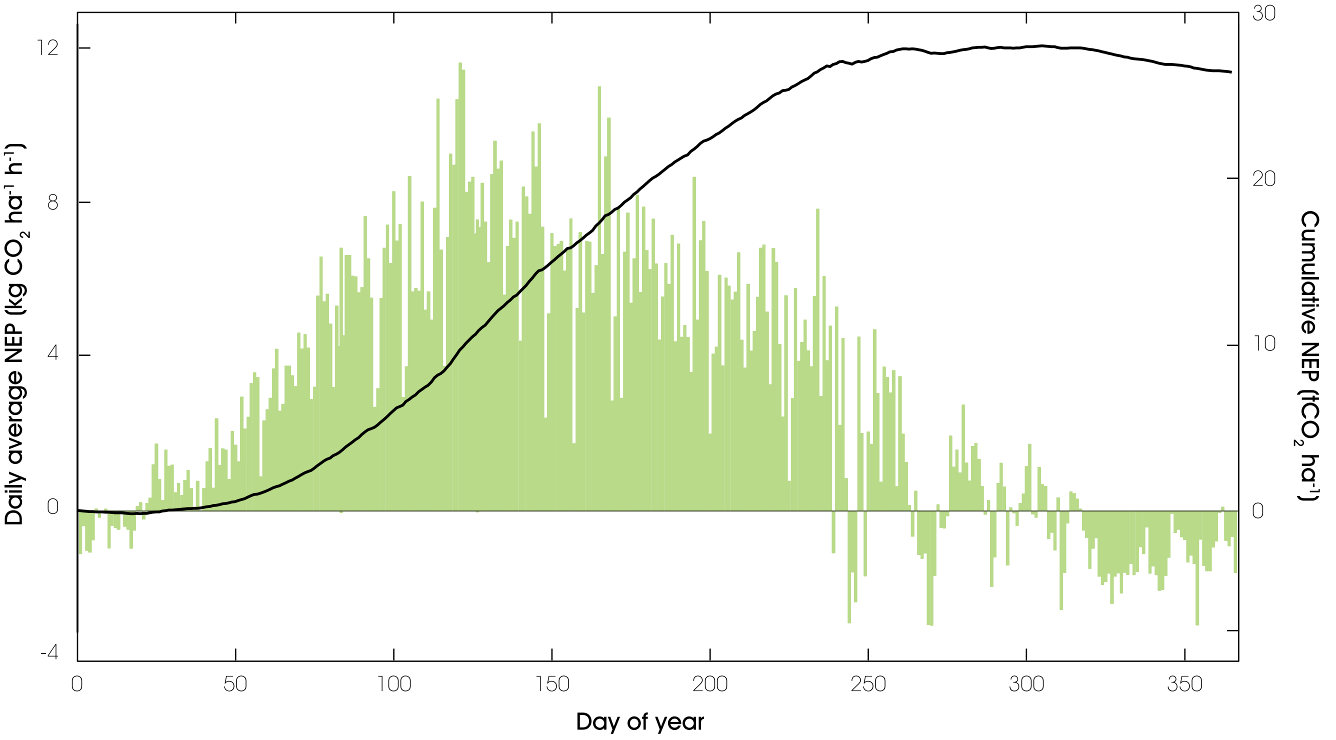
the climate and determines that the forest trees, races and genotypes used in the British Isles are often distinctive. Here, we focus initially on continuous or semi-continuous measurements made since 1997 in the UK, using eddy-covariance technology. Short-term measurements and relevant measurements from nearby Europe supplement the long-term data. There are two on-going, long-term, forest sites in the UK where CO_2 fluxes have been measured continuously, second by second, since 1997: an evergreen, coniferous forest site, with 80% of the tree species Sitka spruce (*Picea sitchensis*) in the Griffin Forest near Aberfeldy, Perthshire, and a deciduous, broadleaf, oak-dominated woodland in The Straits Enclosure, near Alice Holt, Hampshire.

Eddy-flux measurements in coniferous forests

Continuous measurements of CO_2 fluxes have been made in a young stand (Yield Class 14–16, planted 1980) of Sitka spruce at the Griffin Forest in Perthshire since 1997 (Clement *et al.,* 2003). Figure 3.3 shows the annual time-course of *daily* CO_2 fluxes averaged over five years. The seasonal day-to-day variability in the flux is clear, despite the averaging of five years data, particularly its consistent variability in the autumn. The superimposed cumulative curve gives the 5-year-average total annual removal of CO_2 from the atmosphere at the end of the year (i.e. the NEP) which is 24 tonnes CO_2 per hectare.

Sitka spruce in Scotland is at least as effective as many other spruce forest sites in Europe in removing CO_2 from the atmosphere (Figure 3.4). However, in Ireland, where the national average yield class for Sitka spruce is Yield Class 18, an average annual removal from the atmosphere (NEP) of 33 tCO_2 per hectare has been measured in a stand of Yield Class 24 (Black *et al.,* 2009). Average seasonal

Figure 3.3
The vertical columns show the daily (24 h) net CO_2 fluxes for every day of the year, averaged over 5 years. The columns above the zero line show the net 24 h removals from the atmosphere and gains by the forest; the columns below the zero line show net daily emissions by the forest and additions to the atmosphere. The solid line shows the 5-year average of accumulated removals from the atmosphere. (Sitka spruce at the Griffin Forest, Perthshire 1997–2001.)



removals of CO_2 from the atmosphere each hour of the day show the daytime absorption and night-time emissions (Figure 3.5). The period of night-time emissions is long in the winter but the magnitude is small because of the low temperatures. As the season progresses and temperature increases, the emissions increase in magnitude but the period of emissions decreases with the increase in day length. The period and magnitude of the daytime removals of CO_2 from the atmosphere very clearly increase through the spring to a maximum in mid-summer, and decrease in the autumn. These data integrated over 12 months and averaged over 5 years give an average annual *removal* from the atmosphere of 24.2±1.4 tonnes CO_2 per ha per year (tCO_2 ha^{-1} $year^{-1}$). The measurements continue to this day; however, the sequence was interrupted at the Griffin Forest in 2004 to investigate the effect of thinning on the CO_2 fluxes.

The Sitka spruce measurements at the Griffin Forest have been supplemented by intermittent measurements using the same methodology in an age series (0–30 years) of comparable stands in the Harwood Forest, Northumberland, during 2000–2003 (Grace *et al.,* 2003; Magnani *et al.,* 2007). Very close synchrony and similarity in magnitude of the carbon fluxes were obtained between contemporaneous measurements at Harwood in the 30-year-old stand and concurrent measurements at Griffin in the 24-year-old stand, around 150 km apart.

Figure 3.4
Cumulated monthly sums of NEP over the 12 months of 1997 at five spruce forests sites in Europe. The solid black line is for Sitka spruce at the Griffin Forest, Perthshire, Scotland. The other lines represent stands of predominantly *Picea abies* in Germany and Belgium (modified and updated from Bernhofer *et al.,* 2003).

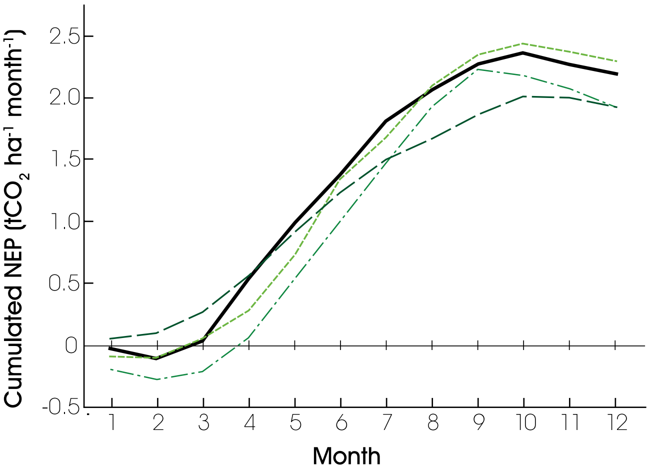
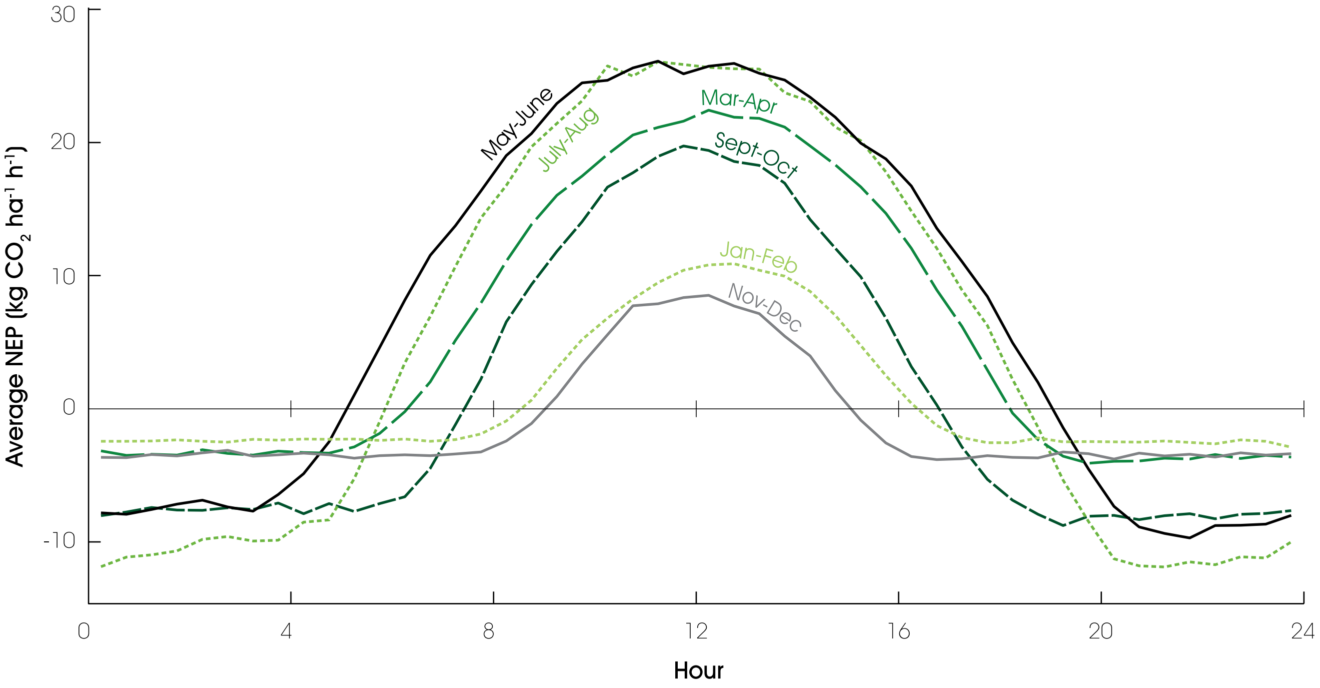


Figure 3.5
The diurnal course of NEP fluxes averaged over two-monthly periods throughout the course of the year. The data above the zero line show the net 24 h removals from the atmosphere and gains by the forest; the data below the zero line show the net daily emissions by the forest and additions to the atmosphere. Sitka spruce at Griffin Forest, averaged over the 5 years 1997 to 2001 inclusive. Note the impact of time of year on day-length and the relative magnitudes of the night-time and day-time fluxes.



Eddy-flux measurements in deciduous broadleaved forests

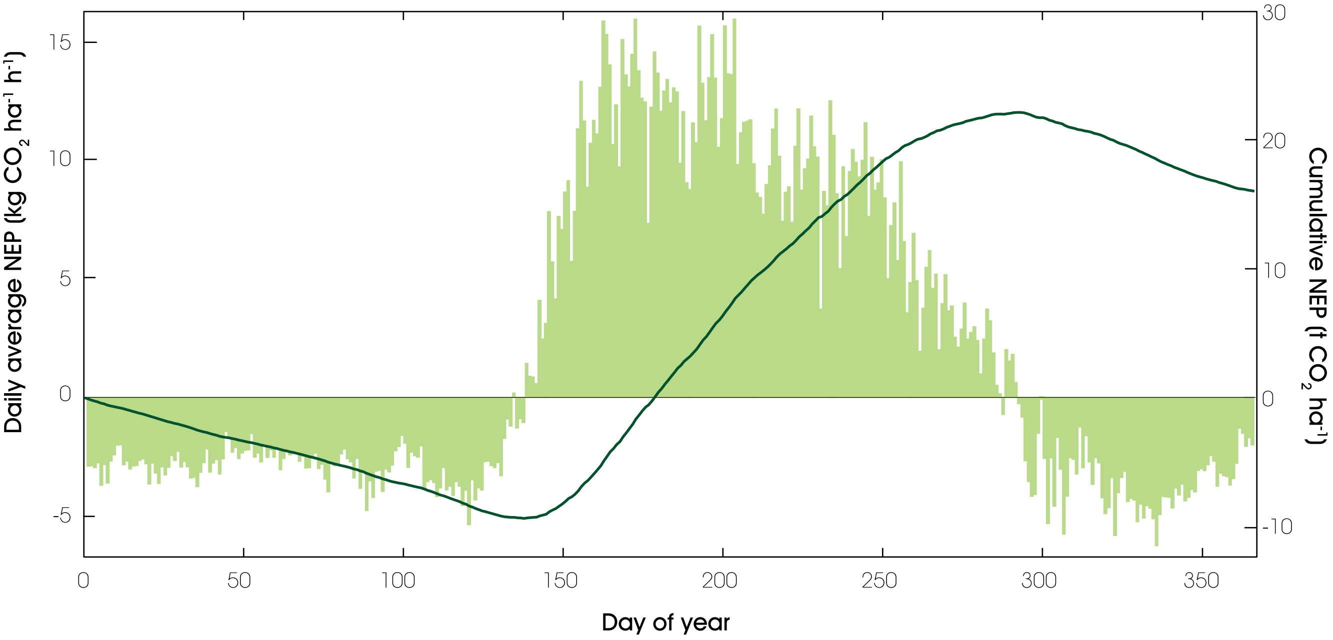
Continuous measurements of CO_2 flux, starting in 1998, have been made in a mature stand of mixed broadleaves with a predominant overstorey of oak (*Quercus robur*), with some ash (*Fraxinus excelsior*) at the Straits Enclosure, near Alice Holt (Broadmeadow *et al.,* pers. comm.). The equipment and software used are similar to that used for Sitka spruce at the Griffin and Harwood Forests. The stand was planted in the 1930s and was brought into management as a research site in around 1990. The stand was thinned in 1991, 1994 and 1999, to 495 overstorey trees per hectare. Tree height is around 23 m and the LAI around 6 around the flux tower. When in full leaf, the overstorey absorbs between 60% and 75% of the incident solar radiation. Comparable measurements are being made in stands of broadleaves, predominantly beech (*Fagus sylvatica*) and oak (*Q. robur*) in Denmark and Belgium, respectively, and the results are not dissimilar.

Figure 3.6 shows CO_2 flux data for The Straits broadleaves over the period (1999–2007) The annual average net removal of CO_2 from the atmosphere for the eight-year period is 15.1 tCO_2 ha^{-1} $year^{-1}$, with a range of 13.1–19.8. Comparison between Sitka spruce forest in the north and oak forest in the south show that removals of CO_2 from the atmosphere by the oak forest are 62% of those achieved by Sitka spruce. The measurements are continuing at the present time on both sites.

Short-term eddy-flux measurements

Eddy-flux measurements made on a short-term basis at sites of different aged stands of Sitka spruce on *deep-peat* (0.5–5.0 m depth) in the west and north of Scotland, found initial annual *emissions* of 7–15 tCO_2 ha^{-1} $year^{-1}$ from newly ploughed and drained peatlands. The range of emission rates depended on the temperature, depth, water-logging and degree of disturbance of the peat. These emissions turned progressively to annual *removals* from the atmosphere as, first, the ground vegetation returned and, second, as the trees slowly grew, eventually reaching net annual removals of up to *c.* 18 tCO_2 ha^{-1} $year^{-1}$ on sites supporting YC 10. At the same time annual emissions from the peat continued at rates of up to 4 tCO_2 ha^{-1} $year^{-1}$ (Hargreaves *et al.,* 2003). Similar rates of soil CO_2 emissions from an age-series of afforested, drained (but with high water table), blanket peat sites have been

Figure 3.6
The vertical columns show the daily (24 h) net CO_2 fluxes for every day of the year, averaged over 8 years. The columns above the zero line show the net 24 h removals from the atmosphere and gains by the forest; the columns below the zero line show net daily emissions by the forest and additions to the atmosphere. The solid line shows the 8-year average accumulated removals from the atmosphere. (Mixed oak deciduous woodland at the Straits Enclosure, Alice Holt, Hampshire, 1999–2006.)



reported from Co. Galway in Ireland (Byrne and Farrell, 2005). In conclusion, the CO_2 fluxes from deep peat sites are in general similar but smaller than fluxes from peaty-gleys, as at Harwood and Griffin, declining pro-rata with the general yield class. Afforestation of deep peat lands is no longer acceptable because of their conservation value for wildlife and water resources; their CO_2 effluxes also support arguments for minimising their disturbance.

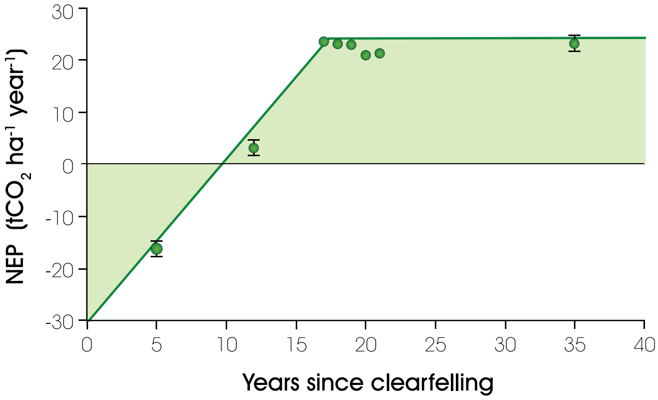
The earliest measurements of forest CO_2 fluxes in the UK were made using the so-called Bowen ratio methodology, in Sitka spruce at Fetteresso Forest, Kincardine, in 1970–2 and in Scots pine at Thetford Forest, Norfolk, in 1975–6. The measurements at Fetteresso found NEP close to zero on days on which the air temperature exceeded 17°C and negative when temperatures exceeded 20°C (Jarvis, 1994), largely because of closure of the stomata in response to the increase in atmospheric VPD, but also in part because of the increase in emissions in response to temperature (Jarvis, with a modelling appendix by Y.P. Wang, 1986). Very similar results were obtained with Douglas fir (*Pseudotsuga menziesii*) on Vancouver Island, by Price and Black (1990, 1991). The measurements at Thetford in 1976, a drought year with summer temperatures frequently in the range 25–30°C, with concurrent exceptionally large VPDs, showed severe reductions in both CO_2 and transpiration fluxes in these extreme conditions (Jarvis *et al.,* 2007) – a possible portent of things to come.

3.4.3 Rotation average CO_2 removal by Sitka spruce forests

Measurements made on the age series of sites at the Harwood Forest have shown that site preparation by ploughing and subsequent planting, led to appreciable decomposition of the exposed soil organic matter and to significant emissions of CO_2 through the rotation (Zerva *et al.,* 2005; Zerva and Mencuccini, 2005b; Figure 3.7), as earlier noted by Cannell *et al.,* (1993). At the same time, growth of the young trees progressively removed more CO_2 from the atmosphere. For the young Sitka spruce it took 12 years for the emissions from the soil (a peaty-gley) to be compensated by removal of CO_2 from the atmosphere by the growing trees. Subsequent to that break-even point, removals from the atmosphere exceeded emissions from the soil, resulting in a *net removal* of CO_2 from the atmosphere by the forest, trees and soil together (i.e. an increasing NEP) (Figure 3.7; Jarvis and Linder, 2007). Canopy closure was reached after another 4 or

5 years, i.e. around 17 years after planting. During this period, the leaf area of the trees further increased to the maximum LAI of 8, which absorbed around 95% of the incoming solar radiation, and the rate of atmospheric CO_2 removals rose to equal the rates measured at both Harwood and Griffin Forests, i.e. an annual *net* removal of CO_2 from the atmosphere of around 24 tCO_2 ha^{-1} $year^{-1}$ (Clement *et al.,* 2003).

Figure 3.7
Net exchanges of CO_2 following site preparation and planting. Emissions of CO_2 from the soil dominate until *c.* year 11 (the break-even point) followed by increasing net removals of CO_2 from the troposphere by the growing young trees, reaching a plateau at canopy closure *c.* year 17.



The average CO_2 removal over a rotation depends on the period and magnitude of emissions prior to the break-even point and canopy closure. Integrating over a 40-year rotation, these data indicate an average annual removal over a 40-year rotation of 56% of the closed canopy rate, i.e. 13.5 tCO_2 ha^{-1} $year^{-1}$ (Magnani *et al.,* 2007). The above quantity of 13.5 tCO_2 ha^{-1} $year^{-1}$ would be the appropriate average annual amount for an entire 'mature' forest, *in which all age classes were represented more or less equally throughout the forest.*

However, for historical reasons, the ups and downs of markets, or windthrow, for example, the age distribution of compartments is generally not uniform, and alternative methods are required to estimate the CO_2 dynamics at the larger spatial scales of extensive forest comprising compartments of clumped age and alternative species (see 3.5 below). Where, for example the younger age classes predominate, as in the most recent woodland creation, a more realistic average rate of removal of CO_2 from the troposphere is likely to be around 40% of the post-canopy-closure rate, i.e. an annual rate of around 10 tCO_2 ha^{-1} $year^{-1}$, whereas in older forests the factor may be around 60% or more of the closed canopy rate.

3.4.4 Nitrogen requirements for effective carbon sequestration

Trees require resources to grow leaves and fine roots for the acquisition of carbon from the atmosphere and nutrients from the soil, respectively. Nitrogen is in general the most significant nutrient required for growth of Sitka spruce on peaty-gley soils. Artificial nitrogenous fertiliser has sometimes been applied in the past to speed-up canopy closure, particularly on nutrient-poor sites and especially on compartments experiencing heather-check as a result of inhibition of the tree root mycorrhizas, but application has sometimes been more general. Urea was, for example, applied universally at the Griffin Forest when the trees were 16–17 years old; but the canopy was already closing fast, and the effect on canopy and stem-wood growth was small and transient. Furthermore, there is some evidence that application of fertiliser nitrogen has an inhibitory effect on decomposition of soil organic matter, and consequently on the mineralisation of the indigenous nitrogen (Fog, 1988; Ågren *et al.,* 2001; Hyvönen *et al.,* 2007).

In addition, there are significant amounts of nitrogen in the rainfall (wet deposition) and the air (dry deposition). Although these amounts have been declining since the 1960s, typical annual wet deposition over Scotland ranges from 5–10 kg N ha^{-1}. The dry deposition probably adds an additional 30% but is less routinely measured and less accurately definable, in part because of the possibility of some direct uptake from the air into leaves within forest canopies (Mencuccini *et al.,* in manuscript). Magnani *et al.,* (2007) found a very significant relationship between NEP and wet deposition of nitrogen across a number of sites in northern Europe, including sites in northern UK, but their relationship was severely criticised as unrealistic because they did not add in estimates for the dry deposition of nitrogen.

Irrespective of the atmospheric deposition, management operations lead to the release of significant amounts of nutrients, particularly nitrogen, from the soil organic matter (SOM). We consider the demand in relation to the supply for the stand life cycle in two periods – the first period to grow the canopy of leaves, the second to grow the wood (see Box 3.4).

Box 3.4 The carbon to nitrogen ratio (C:N) for different components

Leaves	20:1 to 30:1
Fine roots	30:1 to 40:1
Branches and coarse roots	100:1
Stem wood	500:1 (400:1 to 700:1 for different species)
SOM	25:1 to 35:1

Period 1: The N demand to grow the tree to canopy closure (years 0–18):

The nitrogen content of Sitka spruce needles: around 2.0 g N m^{-2} (leaf area).

LAI of closed canopy Sitka spruce: 8

The N required to grow the leaf canopy: 160 kg N ha^{-1}

Estimated approx. total tree N required: around 720 kg N ha^{-1} (= 40 kg N ha^{-1} $year^{-1}$).

The N supply (years 0–18):

Mineralisation of SOM (Zerva *et al.,* 2005; Zerva and Mencuccini, 2005b): 3.6 tonne C ha^{-1} $year^{-1}$ @ C:N 30:1: 120 kg N ha^{-1} $year^{-1}$; i.e. approximately 3x the demand (front loaded), not including atmospheric deposition.

Period 2: The N demand to grow the tree trunk (years 18–40):

Trunk carbon content at 40-year harvest (YC 14): 115 tC ha^{-1}.

The N requirement to grow the trunk (C:N 500:1): 230 kg N ha^{-1} (=11 kg N ha^{-1} $year^{-1}$.

The N supply (years 19–40):

For central Scotland, annual wet deposition is now about 7 kg N ha^{-1}; dry deposition a likely additional 30%, adding up to a total N deposition of around 10 kg ha^{-1}.

In addition, nitrogen continues to be available from oxidation of the SOM, as a result of the original site preparation.

Nitrogen demand to grow the leaf canopy, fine root network and tree structure (years 1–18).

On average more than enough nitrogen is supplied as a result of ‘site preparation’ to grow the forest canopy and basic tree structures. However, in practice, the annual demand will increase from a small amount in the early years to a much larger amount in the later years of the period, as the trees grow. Thus, supply may considerably exceed demand in the early years, whereas the supply may not be sufficient in the later years so that N-stress may occur (Miller *et al.,* 1979), particularly if a part of the nitrogen mineralised during the early years is not retained but is lost in drainage waters or as atmospheric emissions.

Once the canopy has closed, at around 18 years, new leaves grow at the top of the tree and on the upper whorls of branches, old needles drop from the lower branches and nutrients *re-circulate* within the stand. The canopy LAI remains at a practically constant value of around 8, requiring *additional* nitrogen only to replace losses to the atmosphere from leaching and redistribution of leaf litter from the site, and to compensate for any immobilisation in the soil of nitrogen released from the decomposing leaves (Miller *et al.,* 1979; Titus and Malcolm, 1999). Possible immobilisation of nitrogen in the litter could lead to undefined, larger requirements in the second half of the rotation than are indicated in Box 3.4.

Nitrogen demand to grow the wood (years 19–40).

The demand for nitrogen is small by comparison with the growth of the canopy, for example, because the wood has a C:N ratio of around 500:1. The estimated total tree dry mass of YC 14 at 40 years is around 460 tonne ha^{-1}. The total mass of the harvested trunk is close to 50% of the total tree mass, with a carbon content of around 50%, i.e. around 115 tonne C ha^{-1}. With a C:N ratio of around 500:1, the total nitrogen requirement to grow the wood is around 230 kg N ha^{-1}, or on average over 22 years, 10 kg N ha^{-1} $year^{-1}$.

Nitrogen supply over the period

Nitrogen is supplied continuously as atmospheric deposition, both gaseous (dry deposition) and in precipitation (wet deposition) (Fowler *et al.,* 1989). For central Scotland, the wet deposition is now about 7 kg N ha^{-1} (Magnani *et al.,* 2007) and the dry deposition probably an additional 30%, adding up to a total nitrogen deposition of around 10 kg ha^{-1}, i.e. sufficient to meet the demand

(Cannell *et al.,* 1998). In addition, nitrogen continues to be available from oxidation of the SOM, as a result of the original site preparation, at an annual rate of up to 120 kg N ha^{-1}.

The requirement for nitrogen is usefully separated in both space (establishment of canopy, fine roots vs wood production) and time (the initial 18 years to canopy closure, and the major wood production period of the rotation. Taking the growth pattern into account, during woodland creation, the nitrogen supply to the trees from soil and atmosphere is more than sufficient to grow a substantial crop of wood, *without addition of nitrogen fertilisers.* How the second rotation fares, however, will depend on how the site is managed.

3.4.5 Disturbance

On undisturbed ground, the soil carbon content maintains a relatively stable state of losses balanced by gains. However, disturbance of the soil has major impacts on both carbon emissions and drainage losses, and overall tends to lead to reductions in carbon stocks (Reynolds, 2007). Catastrophic disturbance such as windthrow that leads to uprooting of trees can, for example, result in immediate annual CO_2 *emissions* from the soil and debris at a rate of at least 20 tCO_2 ha^{-1} year^{-1} (A. Grelle, pers. comm.) and this may continue over several years during reclamation of the site. Such large emissions of CO_2 further compound the economic loss of timber and loss of opportunity for CO_2 removal.

There can be substantial losses of carbon from the soil during the first rotation as a result of site preparation (Figure 3.8) but during the second rotation, the soil carbon content may recover to the extent that the original soil carbon content is restored after 30 years of growth (Zerva *et al.,* 2008). A chronosequence of five stands of Norway spruce (*Picea abies*) in Sweden (18–91 years old) planted onto former agricultural land showed an overall increase in the soil carbon stock reaching 191 tC ha^{-1}, despite initial losses from the mineral soil horizons (Cerli *et al.,* 2006). On that basis, it is to be expected that carbon will continue to accumulate, *provided that the soil does not experience further major disturbance*. Across a landscape, disturbance can be very variable as a result of different intensities of management intervention and the vagaries of catastrophic disturbance from natural events, particularly windthrow. On that assumption, the process of carbon accumulation in successive clearfell rotations on peaty-gley soil can be modelled, taking the stand-scale data from the Harwood age-series (Magnani *et al.,* 2007), and assuming different degrees of disturbance at harvest (Figure 3.9). In the top line, we see the potential of this type of forest to accumulate carbon in the case of no soil disturbance at the end of each rotation. The broken lines show the possibilities with three levels of soil disturbance: mild, moderate and severe, corresponding to an annual loss of carbon as CO_2 of 30, 60 and 90 tC ha^{-1}. Detailed measurement and modelling of the dynamics of carbon in forest soils is challenging, particularly as substantial carbon is sequestered in humic fractions of soil and peat that have a very slow turnover, as compared with the biomass of humus layers. If these fractions change with disturbance (management or windthrow), it will take a longer time (several decades), to restore the stocks. *Because the soil carbon is a large component of the carbon balance of a forest, more attention needs to be paid to establishing a complete carbon balance of soils under different silvicultural practices*.

Management disturbance also has the capacity to stimulate emission of appreciable amounts of CO_2 to the atmosphere. As we have seen, site preparation by ploughing, leads to major CO_2 emissions throughout the rotation. It seems likely that emissions resulting from mounding are less, if only because a much smaller area of ground is turned over, but that remains to be shown.

A commercial thinning causes only a minor perturbation to the net CO_2 uptake lasting no more than two years (Clement, Moncrieff and Jarvis, unpublished results); first because *both* gains and losses of carbon by the trees are reduced concurrently, and second because thinning

Figure 3.8
Changes in soil carbon at a Sitka spruce site in first and second rotation (Zerva *et al.,* 2005). UN is unforested grassland/moorland; CF is clearfell, and remaining bars denote age of the trees at different times in the rotation. The 40-year stand was in the first rotation; 12-, 20- and 30-year stands were in the second rotation.

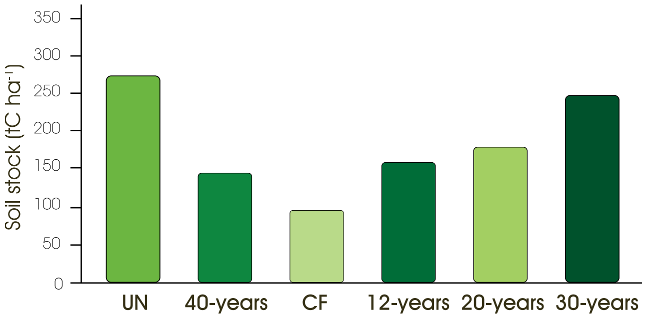
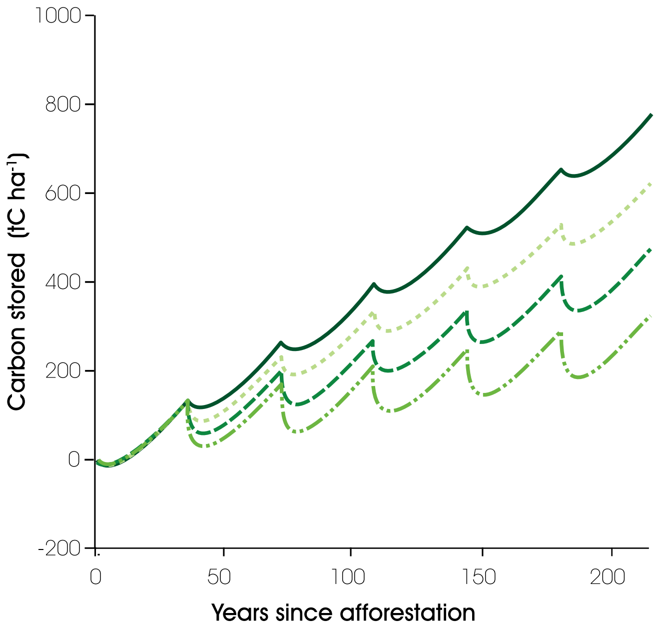


Figure 3.9
Likely changes in the carbon stored in a Sitka spruce plantations on a peaty gley over six rotations. See the text for explanation. The lines show increasing degrees of disturbance at harvest from the top line down.



leads to penetration of solar radiation to greater depths in the canopy, with the result that leaves on the lower whorls of the remaining trees rapidly develop capacity to compensate for loss of leaf area above. Brash mats clearly protect the soil surface during thinning, but their effects on soil CO_2 emissions are not known. However, rapid recovery of NEP to its former level after thinning, suggests that there was little stimulation of soil emissions resulting from thinning at the Griffin forest site (data not shown).

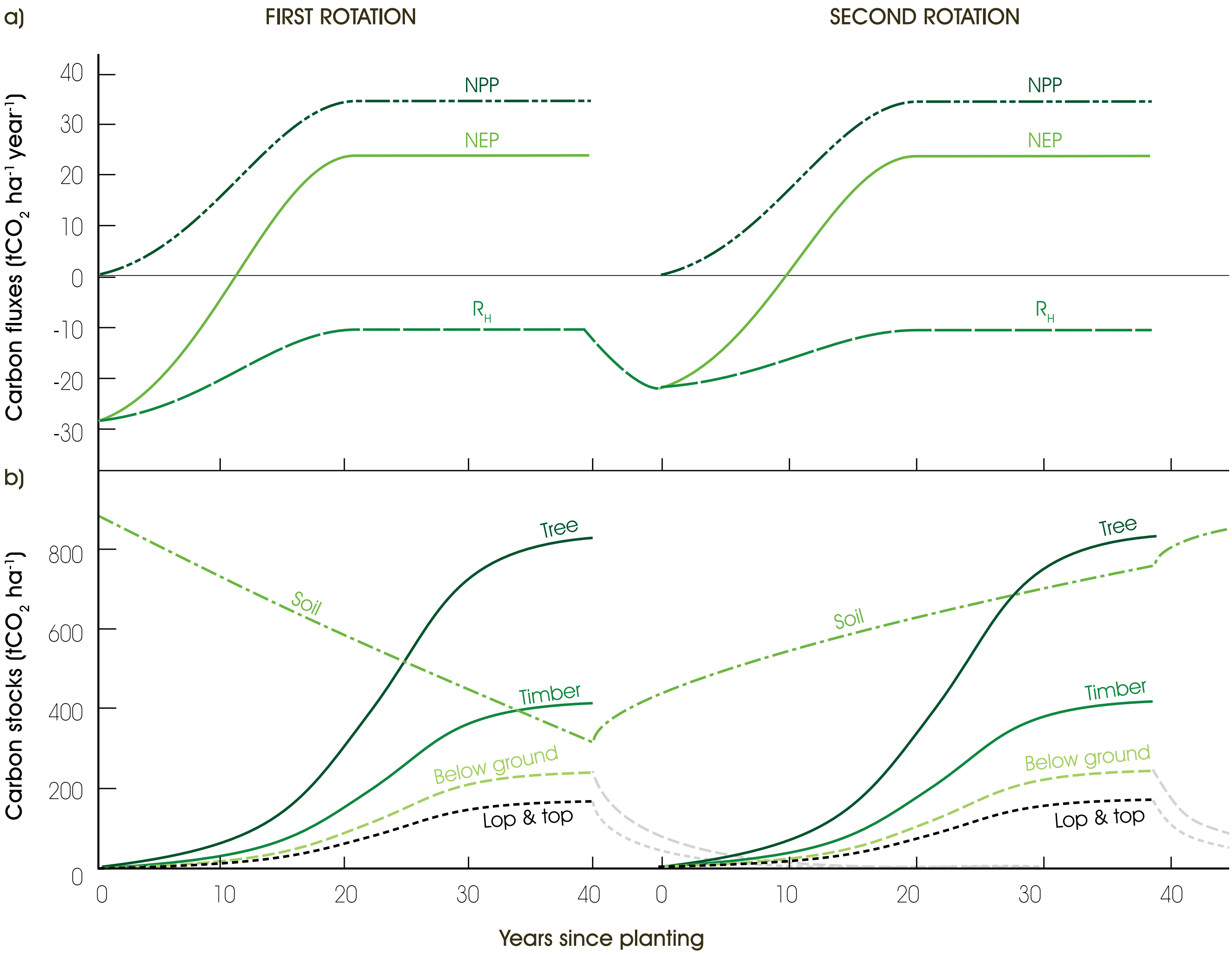
Cropping of forest stands occurs over sequential rotations. The carbon fluxes and stocks through two such rotations of Sitka spruce plantation in Harwood, northern England have been analysed (Figure 3.10a,b). The first rotation was established on a heather moorland, with deep ploughing, so the soil carbon stock declined through the first 40-year rotation as a result of enhanced soil carbon oxidation and mineralisation (Figure 3.10b). Thereafter, during the second rotation there was a compensating recovery of soil carbon stocks but this was dependent on minimising the disturbance involved in replacing the first crop and on leaving the below and above-ground residues (roots, stumps, branches and needles) on site. At the whole stand scale the soil carbon losses during the early years of the first rotation (Figure 3.10b) were sufficient to cause significant negative net carbon gain (NEP, see Figure 3.10a). However, once the canopy closed after around 17 years, CO_2 fixation rates became adequate to yield positive NEP, which reached a plateau of around 24 tCO_2 ha^{-1} $year^{-1}$ at approximately 20 years. CO_2 fluxes were also negative in the early years of the second rotation but they became positive more rapidly as a result of the reduction in loss of soil carbon compared with the first rotation.

Research during the 1970s and 1980s focussed on management effects on nutrient budgets and it became clear that, in general, nutrients should be conserved on site for the following rotation by ensuring that small wood, twigs and leaves in particular, were retained on site (Titus and Malcolm, 1991,1992,1999). Because significant amounts of nutrients are also in the bark, it was also proposed that logs should be barked on site and the bark redistributed, but that proved to be too onerous. Brash is now being put forward as a source of biofuel, and its baling up and removal is being advocated. Nutrients aside (and that issue should be revisited), there is a clear case for ensuring that removal of the coarse brash does not lead to consequent reduction of the soil *carbon* stock.

At time of writing, stump removal is also being advocated on the grounds that stumps are an unused component of the crop that can be exploited as a resource for energy production, and thereby enhance the economic return to the owner. Removal of stumps may also remove pests and certainly can result in a well-prepared level surface for replanting. However, stump removal is tantamount to ploughing a substantial area of the site to a depth of 1 m, and measurements in Sweden have shown consequent annual CO_2 emissions of 25 tCO_2 ha^{-1} $year^{-1}$ (A. Grelle pers. comm., 2008). Since the influence of ploughing in stimulating CO_2 emissions has been found to continue throughout the first rotation, it is likely that the influence of stump removal in provoking CO_2 emissions will continue through the following rotation. Should the enhanced emissions resulting from stump removal continue for no more than 10 years, the gain to the atmosphere from substituting stump-derived chips for fossil fuel will be negated.

Management that leads to ongoing reduction in the soil carbon stock seriously reduces the value of forests as a renewable source for material and energy substitution. As far as the troposphere is concerned, there is little difference between running down the soil carbon and mining coal to burn!

Figure 3.10
A diagram compiled to show measured and inferred carbon fluxes (a) and stock (b), over the first (left) and second (right) rotation of Sitka spruce stands of Yield Class 14–16 $m^3\ ha^{-1}\ year^{-1}$ established on heather moorland in northern Britain. The stocks and fluxes, both presented as CO_2 equivalents, are based on measurements made at the Griffin and Harwood Forests in stands of different ages as part of the EUROFLUX and CARBOAGE programmes. (Further details are given by Zerva and Mencuccini 2005b, Zerva *et al.*, 2005, Ball et al., 2007 and Clement *et al.*, 2003. Conversion factors used and other underlying information are given by Jarvis and Linder, 2007.)



3.5 Spatial carbon dioxide dynamics

3.5.1 Long-term changes in carbon stocks at the forest scale

The long-term trends in carbon stocks of forest biomass associated with land use change may be estimated from the species and age structure of the stands. For conifers in particular, there was considerable planting in the UK from the 1950s to 1990 (see Chapter 1, Figure 1.2). As these 40+ year-old stands are harvested, and other land use changes occur, the carbon stocks inevitably change. The national GHG inventory, based upon this age-structure data, shows a diminishing forest carbon sink from a maximum of 15 Mt CO_2 per year in 2004 to an estimated 10 Mt CO_2 in 2010 (Mobbs and Thomson, 2008). Given a total forest area of 2.84 million hectares (see Chapter 1), this implies an average annual carbon sequestration associated with forested land of 5.4 $tCO_2\ ha^{-1}$ (or 1.4 $tC\ ha^{-1}$). We may compare this with the 'bottom-up' estimates from measurements of carbon fluxes using eddy covariance, as presented in 3.4.3 above. There we showed for Sitka spruce in the UK that the flux averaged over a stand cycle is reduced to about half of that observed when measurements are made on medium-aged forests, and this has also been shown for a number of other species (Magnani *et al.,* 2007). The reduction results from losses of CO_2 at harvesting and planting, and periods of low uptake in the early stages of the management cycle (Magnani *et al.,* 2007). As shown in 3.4.3 above, for Sitka spruce, the *full rotation flux estimate* of a stand of Yield Class 14, based on the Harwood Forest age series of stands, is around 14 tCO_2 ha^{-1}. For integration over the landscape, however, much more work is needed to establish general relationships between Yield Class and size of the carbon sink for a range of species and age distributions, if we are to use that approach to integrate spatially (Cannell and Dewar, 1995).

The national statistics are based on changes in land use and the consequent stock changes, but have not dealt with changes in the soil carbon during the forest cycle. In most forests there is more carbon as soil organic matter than in the form of biomass, and so a proper understanding of the long-term carbon balance of the forest estate requires knowledge of the behaviour of this carbon pool over the cycle of planting and harvesting. Classical soil survey methods do not give a good assessment of the changes in carbon stocks, because often the sampling methodology does not extend to the parent material and does not take into account changes in depth and bulk density, focusing on *concentrations* not *stocks*. Moreover, at a national level, the soils are extremely variable and it is difficult to sample them adequately. Hence, two recent large-scale surveys of the carbon concentrations in UK soils, by different organisations, have produced somewhat different conclusions (Bellamy *et al.,* 2005; Countryside Survey, 2009). Forests usually do accumulate carbon as organic matter in the soil so long as they are not disturbed (Smith *et al.,* 1997; Cerli *et al.,* 2006; Smal and Olszewska, 2008; Stevens and van Wesemael, 2008; Gadboury *et al.,* 2009), although there are notable exceptions to this and reviewers of the topic are not in agreement (see Reynolds, 2007).

With a number of instrumented flux towers within forests, it is possible to integrate removals and emissions of trace gases across compartments of different species, age-class and disturbance. It is also possible to address particular issues at compartment or small forest scale. However, to obtain quantitative estimates of trace gas fluxes at the larger landscape scale, and to monitor how management is influencing the atmosphere, different approaches are required, including the use of taller towers and aircraft.

3.5.2 Long-term changes in carbon stocks at the landscape scale

Tall Towers. In the past five years, it has become possible, through a series of EU-funded projects, including 'Carbo-Europe', to estimate GHG balances at landscape scale by measuring the concentrations of gases at heights of 200–300 m on tall towers. The network currently is not sufficient to cover all the European landscape, and in the UK, there is only one such tall tower that has been instrumented with this capability, whereas at least four such towers are desirable so as to be able to sample the atmosphere, avoiding local sources, when the wind is coming from different directions.

Integrated Carbon Observing System (ICOS). A new European project (ICOS) aims to deliver a denser network which should provide a rich data source on the fluxes of greenhouse gases at national scale as well as at European scale. ICOS has recently been placed on the UK Joint Research Councils Infrastructure Road Map as an 'emerging topic', with the expectation that by 2012 it will be possible to fund four or five such sites in the UK, along with corresponding ecosystem sites, where CO_2 fluxes and soil carbon stocks will be routinely measured and reported (see details online at: http://icos-infrastructure.ipsl.jussieu.fr/ [and] http://www.rcuk.ac.uk/cmsweb/downloads/rcuk/publications/lfroadmap08.pdf).

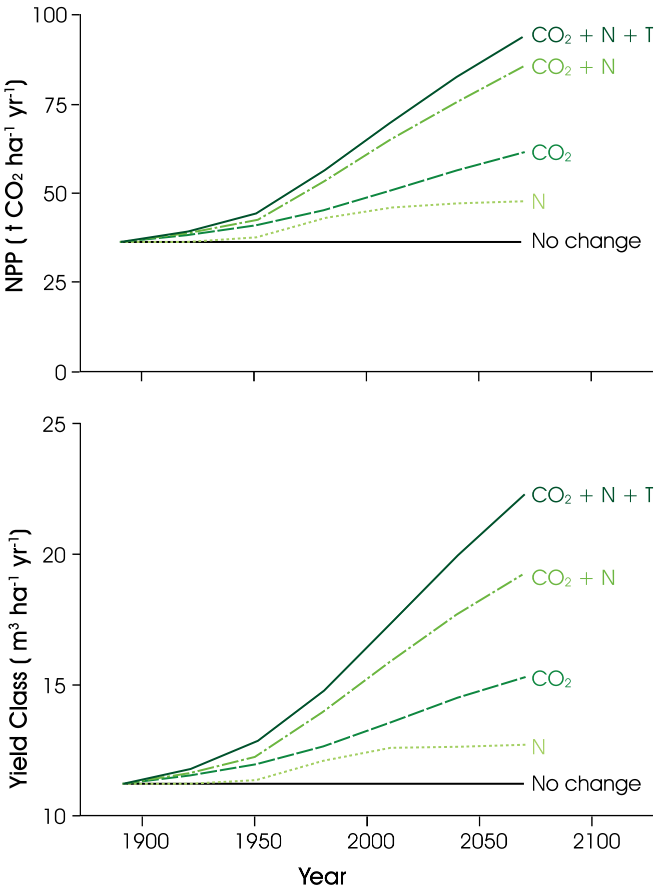
3.5.3 The future carbon sink

The one million hectares of conifers planted between 1950 and 1990 are a major resource today, available as the stands mature for a range of end-uses, including structural timber and other material substitution and fossil fuel substitution. Over a full rotation, these forests remove significant amounts of the predominant anthropogenic GHG, CO_2, from the atmosphere. *With appropriate management*, harvesting and replanting 0.025% (i.e. one-fortieth) of the area annually maintains the standing stock of timber, and continues to remove CO_2 from the atmosphere. Thus, harvesting and replanting sustainably transfers carbon into long-term storage in the soil and into wood products that can be used to substitute for products otherwise derived from fossil fuels. As global CO_2 emissions are increasing rapidly, we need to increase the *area* of actively absorbing and productive forest to access these benefits.

As the climate changes, a key question is whether the forest resource will continue as a significant carbon sink in the UK. Earlier analysis has suggested that the likely increase in temperature will enhance CO_2 emissions to the atmosphere and convert the present UK forest CO_2 sink into a CO_2 source. However, such analysis does not take into account the concurrent increase in atmospheric CO_2 concentration and the likely future availability of both wet and dry nitrogen deposition. When temperature, carbon cycle and nitrogen cycle are included in models, it seems very likely that the current plantations will continue as a significant CO_2 sink (Figure 3.11). *Increasing* the forest area and *minimising* disturbance of the soil will also very likely increase the size of the future UK CO_2 sink; such approaches are imperative to increase carbon sequestration (see also Chapter 8).

Figure 3.11

Rotation mean NPP (above) and yield class (below) predicted by the Edinburgh Forest Model. Each point is the mean at age 30 of a 60-year rotation of Sitka spruce growing in the south of Scotland. The model was run to quasi-equilibrium prior to imposition of increases in temperature (T) of 0.1°C per decade up to 1950 and thereafter at 0.2°C per decade, giving a total of 2.5°C warming; (CO_2) from 290 ppmv in 1900 to 510 ppmv in 2050, to 690 ppmv in 2100; and nitrogen deposition (N) from 5 kg N ha^{-1} year^{-1} in 1940 to 20 kg N ha^{-1} year^{-1} in 1970, and thereafter remaining constant (after Cannell *et al.*, 1998).



3.6 Interaction of forests with other greenhouse gases

3.6.1 Impact of climate change

In addition to their role in the exchange of CO_2, forests are the source of volatile organic compounds (VOCs) that contribute to the photochemical production of aerosols, and of tropospheric ozone (O_3) (see below); both processes have implications for air quality, and O_3 is a GHG as well as a gas that can damage biological systems. Climate change can also be expected to affect the fluxes of other GHG. Forest soils are sources and sinks of methane (CH_4), and sources of nitrous oxide (N_2O); both of these gases have much higher global warming potentials (GWPs) than CO_2, and their fluxes are strongly affected by temperature and soil moisture status. However, their fluxes usually have a fairly small effect on the overall GWP of a forest system, compared with that arising from CO_2 exchange, but in some circumstances they can make a significant contribution.

3.6.2 Impact of soil physical and nutrient conditions

Land drainage and depth to water table are significant influences on trace GHG fluxes from forest soils, particularly peaty ones. The increased aeration of the surface layers resulting from drawdown of the water table releases more nitrogen by mineralisation that can then act as a substrate for N_2O and NO production. Enhancement of mineral nitrogen by deposition from the atmosphere can have a similar effect. Conversely, improved aeration inhibits the emission, and promotes the microbial oxidation of CH_4 while increased nitrogen availability and soil mechanical disturbance inhibit CH_4 oxidation.

3.6.3 Methane (CH_4)

The relationship between emissions of CH_4 measured at the Harwood forest and soil conditions is shown in Table 3.1. A clearfelled site with the water table close to the surface emitted 6.8–18 kg CH_4 ha^{-1} year^{-1}, whereas the soil under 20- and 30-year-old stands emitted only 0.2–2.8 kg CH_4 ha^{-1} year^{-1}. These trends are in line with previous findings in Finland by Martikainen *et al.*, (1995) and Nykänen *et al.*, (1998), and in Sweden by Von Arnold *et al.*, (2005).

Although peaty soils may turn from being a net source of CH_4 into a net sink after draining, because of microbial oxidation of atmospheric CH_4 in the soil (e.g. Huttunen *et al.,* 2003), generally the CH_4 oxidation rates tend to be low. At Harwood, a maximum sink of 20.8 $\mu g\ CH_4\ m^{-2}\ h^{-1}$ was detected by Zerva and Mencuccini (2005a) from a 40-year-old first rotation site before clearfelling, whereas no detectable consistent sink was found at Harwood by Ball *et al.,* (2005). Earlier data (collated by Smith *et al.,* 2000) showed a range of oxidation rates of 1–9 kg CH_4 ha^{-1} $year^{-1}$ (equivalent to 11.4–103 $\mu g\ CH_4\ m^{-2}\ h^{-1}$) for seven UK forest and woodland sites, with the highest rate being in a 200-year-old deciduous woodland on a sandy lowland mineral soil in East Lothian (Dobbie and Smith, 1996) (Table 3.1). Conversion of forest or woodland to agricultural use reduces the size of the methane sink by two-thirds, on average (Smith *et al.,* 2000) – caused by soil disturbance and/or increased nitrogen availability. After reversion to forest it takes in the order of 100 years for the sink activity to recover fully (Priemé *et al.,* 2007); the reasons for the slowness of the process are still unknown.

Reported impacts of temperature on CH_4 emissions vary. Zerva and Mencuccini (2005a) found an increase in CH_4 efflux with increasing temperature at Harwood, but Ball *et al.,* (2005) did not. The impact of the depth to water table also varies; Ball *et al.,* (2005) found a positive exponential relationship between the efflux and the closeness of the water table to the surface (Figure 3.12), which is consistent with much previous work abroad on wetland soils (e.g. Roulet *et al.,* 1993), but Zerva and Mencuccini (2005a) found a decrease in CH_4 emissions with rising water table, for a newly clearfelled site elsewhere at Harwood. However, they found that the emissions gradually increased over eight months following clearfelling, even although the mean monthly water table depths differed little during this period. Possibly, therefore, the effects of controlling variables such as temperature and/or changes in substrate availability were more important than water table depth in these circumstances.

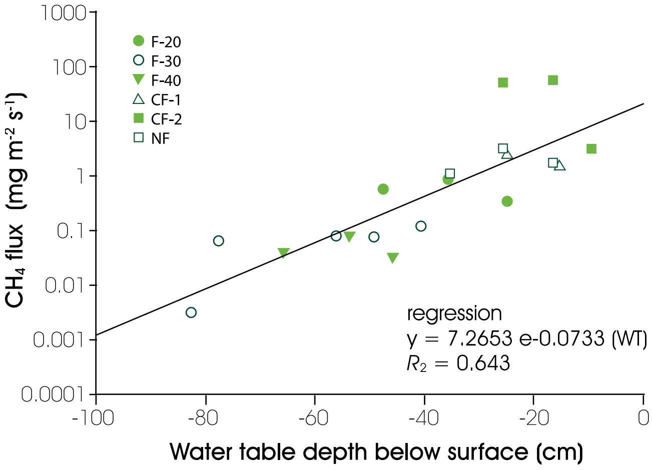
3.6.4 Nitrous oxide (N_2O)

N_2O emissions from a 30-year-old Sitka spruce stand at the Harwood Forest, Northumberland, measured in the field by Ball *et al.,* (2005) were 4.7 and 1.9 kg N_2O ha^{-1} $year^{-1}$ in 2001 and 2002, respectively. At a neighbouring 20-year-old stand, the emissions were 0.2 kg N_2O ha^{-1} $year^{-1}$ in both years (Table 3.1). The results for the more mature stand were very similar to those of Dutch and Ineson (1990) for a Sitka spruce stand in the Kershope Forest (based on soil core measurements in the laboratory), where soil and vegetation are similar to that at Harwood: 4.1 kg N_2O ha^{-1} $year^{-1}$ and 2.0 kg ha^{-1} $year^{-1}$ in a drier year (Table 3.1). Overall, these UK results fit well with those from other northern European forests

Table 3.1
Greenhouse gas fluxes reported for UK forest sites. Negative values indicate uptake by the soil, positive values indicate emissions.

Gas	Emission (kg ha^{-1} $year^{-1}$)	CO_2 equivalent (kg ha^{-1} $year^{-1}$)	Reference
N_2O			
Standing forest			
Glencorse	0.12–0.28	34–83	Kesik *et al.,* 2005
Harwood	0.2–4.7	59–1390	Ball *et al.,* 2005
Kershope	2.0–4.1	592–1214	Dutch and Ineson, 1990
Clearfelled sites (CF)			
Harwood	0.7–2.0	209–592	Ball *et al.,* 2005
Kershope	12—51	3580–15 200	Dutch and Ineson, 1990
CH_4 (emission)			
Harwood CF	6.8–18	156–414	Ball *et al.,* 2005
Harwood (20yr–30yr)	0.2–2.8	4.6–64	Ball *et al.,* 2005
CH_4 (uptake)			
7 UK forest and woodland sites	–1.0 to –9.1 Median: –2.4	–23 to –209 –55	Smith *et al.,* 2000
Harwood	–1.8	–41	Zerva and Mencuccini, 2005a

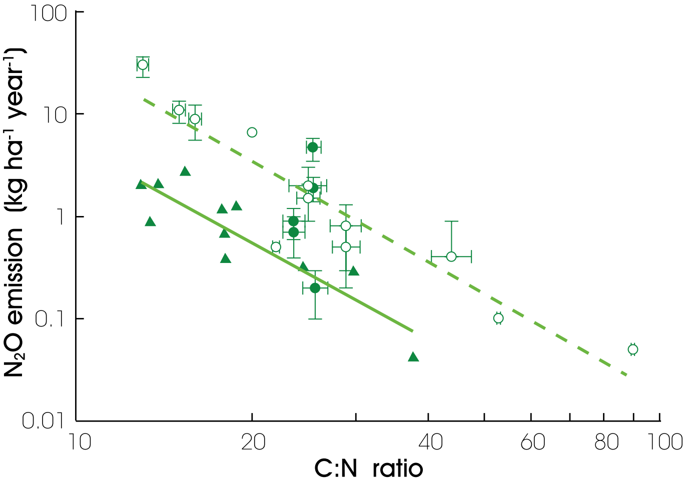
Figure 3.12
Relationship between depth to water table and mean methane emission, the Harwood Forest, 2001–02, from 20-, 30- and 40-year-old Sitka spruce stands (F-20, F-30, F-40), two clearfelled plots (CF-1, CF-2) and adjacent non-forested grassland (NF). (Based mainly on data in Ball *et al.,* 2005).



on organic soils, e.g. those of Martikainen *et al.,* (1993) in Finland, and of Von Arnold *et al.,* (2005) in Sweden. Emissions generally show a logarithmic decrease with increasing C:N ratio in the soil (Figure 3.13), although the absolute values in two data analyses shown in Figure 3.13 differ (Klemedtsson *et al.,* 2005; Pilegaard *et al.,* 2006). The values from the Harwood study are included in Figure 3.1; they fit reasonably within the trend, but with a considerable scatter, probably because of variations in soil wetness and aeration (Jungkunst *et al.,* 2004). Fluctuating aeration regimes may be expected to create partially aerobic conditions in which nitrogen mineralisation can take place (producing the substrate necessary for N_2O production), and anaerobic zones or microsites in which denitrification can occur. These contrasting conditions may occur sequentially at a given depth, or in parallel at different points in the profile. Factors which might be responsible for such a difference include temperature and associated transpiration water demands, and pore size distribution, both of which would affect soil water content at a given height above the water table and the propensity for creation of anaerobic microsites.

Zerva and Mencuccini (2005a) reported an N_2O flux over 10 months at a newly clearfelled site at Harwood of 1.7 kg N_2O ha^{-1} (equivalent to 2.0 kg ha^{-1} year^{-1}), and Ball *et al.,* (2005) measured fluxes of 0.7–0.9 kg N_2O ha^{-1} year^{-1}), on another clearfelled area in the same forest. However, Dutch and Ineson (1990) reported denitrification losses of 10–42 kg N ha^{-1} year^{-1} (the larger part of which was as N_2O) during the first two years after clearfelling. This is an order of magnitude larger than the results of the Harwood studies (see Table 3.1). Huttunen *et al.,* (2003) found average fluxes over three growing seasons after clearfelling on drained peat lands in Finland of 246 and 945 mg N_2O m^{-2} day^{-1}. Assuming a season of five months duration (the longest in their study), and only a small emission (around another 10%) in the colder conditions of the rest of the year, these rates would be equivalent to annual fluxes of around 0.4 and 1.5 kg N_2O ha^{-1}, i.e. very similar to the Harwood results.

Figure 3.13
Relationship between soil C:N ratio and annual N_2O emission, for European forest soils. Data of Klemedtsson *et al.* (2005) (o); Ball et al. (2005) (•); and Pilegaard *et al.* (2006), scaled to the same units (▲). Broken line: regression through Klemedtsson et al. (2005) data; solid line: regression through Pilegaard et al. (2006) data.



For N_2O, it appears that, in general, relatively high soil water contents (but well short of waterlogged conditions), combined with high soil temperatures and a low C:N ratio, give rise to the highest N_2O emissions. Most soils used hitherto for afforestation in the UK are prone to low soil temperatures, because of their upland locations, and generally have fairly high C:N ratios and rates of atmospheric nitrogen deposition much lower than in Central Europe, all of which serves to explain the modest emissions that have been measured. Nonetheless, if there should be a future trend towards afforestation of lowland soils, especially those that have been in previous agricultural use, with C:N ratios of 10 to 15, the average N_2O emissions would likely be much higher, on the basis of the European data available (Kesik *et al.,* 2005; Pilegaard *et al.,* 2006). Additionally, a future general warming of forest soils may be expected to result in significantly larger

N_2O emissions; complex interactions with soil moisture oxygen status render the response to temperature very non-linear, and large increases with temperature have been observed (Brumme, 1995).

3.6.5 Tropospheric ozone, NO, NO_2 and VOCs

Ozone (O_3) is a major GHG in the troposphere and a strong oxidant. As a GHG, O_3 currently ranks as less effective than CH_4, but more effective than N_2O (IPCC, 2007a). O_3 differs in its characteristics from CO_2, in that it is very labile, continuously being formed and decomposed in the troposphere, so that its effectiveness as a GHG cannot be compared relative to CO_2 in the same way as the long-lived GHG, CH_4 and N_2O.

Formation of O_3 in the troposphere is the result of interactions between volatile organic precursor compounds (VOCs) and NO_x (i.e. NO + NO_2). Precursors are varied and may be derived from industrial sources considerable distances away from the forest. However, O_3 may be generated within forests by sunlight-driven chemical reactions between VOCs produced by trees, provided that NO is also present, and within forests the soil can be a significant source of NO.

Emission of NO from a forest soil at Glencorse, near Edinburgh, has been measured as 1.5 µg NO-N m^{-2} h^{-1}, as compared with emission of N_2O of 11.9 µg N_2O-N m^{-2} h^{-1} (Pilegaard *et al.,* 2006). However, at European forest sites with much higher rates of nitrogen deposition, NO emissions are generally much larger than this (Pilegaard *et al.,* 2006). Another major variable affecting NO emission is the wetness of the soil: the NO:N_2O emission ratio decreases exponentially with increasing water-filled pore space. Once emitted to the air, NO oxidises rapidly to NO_2, creating a mixture of NO and NO_2, i.e. NO_x. In the UK and other industrialised countries in Europe, most tropospheric NO_x originates from combustion processes rather than from the soil, but whatever its origin, in sunlight NO_x reacts with VOCs, including those released by forest trees and soil, to form O_3.

In the UK, the VOCs emitted by plantations of Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), birch (*Betula* spp.) and poplar (*Populus* spp.), are mainly isoprene and monoterpenes (Stewart *et al.,* 2003); carbonyl emissions (mainly of acetone) from coniferous trees are also relatively large (Laurila and Lindfors, 1999). Isoprene is produced in sunlight within the chloroplasts in leaves of both broadleaves and conifers, its production increasing with the absorbed solar radiation and with air temperature (Baldocchi *et al.,* 1995). During a day of fine weather, production of isoprene follows photosynthesis, increasing during the morning, peaking in the early afternoon and declining in the evening. Sitka spruce is the dominant emitting species, providing approximately 40% of the annual isoprene and monoterpene fluxes, mainly in the forests in Scotland; poplar plantations in eastern England, and other possible future biofuel species, are also strong isoprene emitters (Kesselmeier and Staudt, 1999). Higher temperatures and possibly sunnier summers resulting from climate change are very likely to make our climate more like that currently in regions much further south in Europe, and it is predicted this will give rise to increased biogenic VOC concentrations, and thus to increased tropospheric O_3 (Bell and Ellis, 2005).

Ozone within the forest environment diffuses into leaves via the stomatal pores in the leaf surfaces and its oxidising properties can do major damage to the physiology of both the guard cells that control the aperture of stomatal pores and the photosynthetic system within leaves (Ashmore, 2005), thus reducing the forest carbon sink and further exacerbating climate change. However, the stomata in many species tend to respond to higher than usual CO_2 concentrations by a reduction in pore aperture, so that internal leaf damage by O_3 may be mitigated to some extent by the concurrent rise in CO_2 concentration. Thus with concurrent increase of both CO_2 and O_3 concentrations, damage caused by O_3 may be limited, but at the expense of a lower rate of removal of CO_2 from the atmosphere (Sitch *et al.,* 2005). Sitka spruce and Scots pine, however, are exceptional in that their stomata are not very sensitive to the ambient CO_2 concentration (see 3.3.2 above). Thus Sitka spruce and possibly other conifers with limited stomatal sensitivity to increasing CO_2 concentration may be more at risk to rising tropospheric ozone concentrations than species with marked stomatal closure at higher CO_2 concentrations.

3.7 Summation of greenhouse gas impacts

Overall, the contribution of the trace GHG to the total global warming potential (GWP, see 3.1 above) of most UK forests and forest soils is generally minor compared with that of CO_2. Relatively high N_2O emissions following clearfelling appear to be fairly short-lived, and when averaged over a rotation of perhaps 40 years, are much less significant. Nonetheless, future patterns of land use, with woodland creation on some lowland former agricultural soils being afforested, combined with increased temperatures, could make the trace gas contribution relatively larger. Also, if the fluxes of the short-lived tropospheric O_3, and its GWP, were to be adequately quantified and included, this would further add to the non-CO_2 component of the total GWP.

In the UK context, GHG other than CO_2 may become more important. Disturbance, especially afforestation of gleyed soils can strongly influence GHG flux. For example, lowering of water table can lead to a reduction of CH_4 emissions whereas the application of fertiliser can increase nitrous oxide fluxes. The capability to measure methane and nitrous oxide fluxes on a continuous basis by eddy covariance is only now developing, with the advent of appropriate laser-based instruments that can be mounted on towers alongside the current CO_2 sensors and sonic anemometers. This will enable a major step forward in our understanding of the overall significant GHG fluxes associated with forests throughout the production cycle.

Research priorities

1. Upgrade and ensure the future of the Straits, Griffin and Harwood research sites. Enhance the radiation budget measurement by adding measurements of upward and downward components of both short-wave (solar) and long-wave (thermal) radiation. Increase the focus on energy partitioning and direct transfer of sensible heat to the atmosphere. Add above-canopy, continuous net flux measurements of CH_4 and N_2O, as fast gas measuring sensors become generally available.
2. Increase the number of similar, comparable, long-term GHG measurement sites in our forests to cover geographical locality, species, stand age, yield-class and management operations, such as thinning. Select sites on the basis of production potential and ecological significance.
3. Develop and utilise moveable low-level, flux systems to investigate the impacts at compartment scale on net emissions/removals of CO_2, CH_4 and N_2O consequent on natural events that result in site disturbance, particularly of the soil, such as windthrow, and management operations, such as ploughing, mounding, clearfell and stump removal.
4. Evaluate the role of the GHG gas ozone (O_3) within our forests. Initiate a programme on natural emissions within forests of isoprene, monoterpenes and other VOCs from trees that may lead to generation of the GHG, ozone (O_3) within forests.
5. Support programmes for using instrumented aircraft to evaluate emissions and removals of trace gases across landscapes to define major sources and sinks of GHG in relation to forestry, agriculture and other land uses, at district and regional scales.
6. Stimulate collaboration with CEH, SEPA and Defra for instrumentation of tall towers (400 m) to measure concentrations of GHG and other trace gases continuously, so as to define daily and seasonal sources and sinks of forested landscapes at regional scales.

References

ÅGREN, G.I., BOSATTA, E. and MAGILL, A.H. (2001). Combining theory and experiment to understand effects of inorganic nitrogen on litter decomposition. *Oecologia* **128**, 94–98.

ASHMORE, M.R. (2005). Assessing the future global impacts of ozone on vegetation. *Plant*, *Cell and Environment* **28**, 949–964.

BALDOCCHI, D., GUENTHER, A., HARLEY, P., KLINGER, L., ZIMMERMAN, P., LAMB, B. and WESTBERG, H. (1995). The fluxes and air chemistry of isoprene above a deciduous hardwood forest. *Philosophical Transactions of the Royal Society of London, Series A* **350**, 279–296.

BALL, T., SMITH K.A. and MONCRIEFF, J.B. (2005). Effect of stand age on greenhouse gas fluxes from a Sitka spruce [*Picea sitchensis* (Bong.) Carr.] chronosequence on a peaty gley soil. *Global Change Biology* **13**, 2128–2142.

BEADLE, C.L., JARVIS, P.G. and NEILSON, R.E. (1979). Leaf conductance as related to xylem water potential and carbon dioxide concentration in Sitka spruce. *Physiologia Plantarum* **45**, 158–166.

BELL, M.L. and ELLIS, H. (2005). The impact of biogenic VOC emission on tropospheric ozone formation in the mid-Atlantic region of the United States. In: Brebbia, C.A. (ed.) *Air pollution XIII*. WIT Press, Southampton. pp. 89–95.

BELLAMY, P.H., LOVELAND, P.J., BRADLEY, R.I., LARK R.M. and KIRK, G.J.D. (2005). Carbon losses from all soils across England and Wales 1978–2003. *Nature* **437**, 245–248.

BERNHOFER, C., AUBINET, M., CLEMENT, R., GRELLE, A., GRUNWALD, T., IBROM, A., JARVIS, P., REDMAN, C., SCHULZE, E.D. and TENHUNEN J.D. (2003). Spruce forests (Norway and Sitka spruce, including Douglas fir): Carbon and water fluxes and balances, ecological and ecophysiological determinants. In: Valentini, R. (ed.) *Ecological studies*: *fluxes of carbon water and energy of European forests*. Springer, Berlin. pp. 99–123.

BLACK, K., BYRNE, K.A., MENCUCCINI, M., TOBIN, B., NIEUWENHUIS, M., REIDY, B., BOLGER, T., SAIZ, G., GREEN, C., FARRELL, E.T. and OSBORNE, B. (2009). Carbon stock and stock changes across a Sitka spruce chronosequence on surface water gley soils. *Forestry* **82**, 255–272.

BRUMME, R (1995). Mechanisms of carbon and nutrient release and retention in beech forest gaps. III. Environmental regulation of soil respiration and nitrous oxide emissions along a microclimatic gradient. *Plant and Soil* **169**, 593–600.

BYRNE, K.A. and FARRELL, E.P. (2005).The effect of afforestation on soil carbon dioxide emissions in blanket peatland in Ireland. *Forestry* **78**, 217–227.

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.

CANNELL, M.G.R., DEWAR, R.C. and PYATT, D.C. (1993). Conifer plantations on drained peatlands in Britain: a net gain or loss of carbon. *Forestry* **66**, 353–369.

CANNELL, M.G.R., MILNE, R., SHEPPARD, L.J. and UNSWORTH, M.H. (1987). Radiation interception and productivity of willow. *Journal of Applied Ecology* **24**, 261–278.

CANNELL, M.G.R., THORNLEY, J.H.M., MOBBS, D.C. and FRIEND, A. D. (1998). UK conifer forests may be growing faster in response to increased nitrogen deposition, atmospheric CO_2 and temperature. *Forestry* **71** (Suppl.), 277–296.

CERLI, C., CELI, L., JOHANSSON, M.B., KOGEL-KNABNER, I., ROSENQVIST, L. and ZANINI, E. (2006). Soil organic matter changes in a spruce chronosequence on Swedish former agricultural soil. I. Carbon and lignin dynamics. *Soil Science* **171**, 837–849.

CLEMENT, R., MONCRIEFF, J.B. and JARVIS, P.G. (2003). Net carbon productivity of Sitka spruce forest in Scotland. *Scottish Forestry* **57**, 5–10.

DOBBIE, K.E. and SMITH, K.A. (1996). Comparison of CH_4 oxidation rates in woodland, arable and set aside soils. *Soil Biology and Biochemistry* **28**, 1357–1365.

DUTCH, J. and INESON, P. (1990). Denitrification of an upland forest site. *Forestry* **63**, 363–378.

FOG, K. (1988). The effect of added nitrogen on the rate of decomposition of organic matter. *Biological Reviews* **63**, 433–462.

FOWLER, D., CAPE, J.N. and UNSWORTH, M.H. (1989). Deposition of atmospheric pollutants on forests. *Philosophical Transactions of the Royal Society, London, Series B*, **324**, 247–265.

GADBOURY, S., BOUCHER J.F., VILLENEUVE, C., LORD, D. and GAGNON, R. (2009). Estimating the net carbon balance of boreal open woodland afforestation: a case-study in Quebec's closed crown boreal forest. *Forest Ecology and Management* **257**, 483–494.

GRACE, J. *et al.* (2003). *Final Report to the European Commission of the CARBO-AGE Project, a component of CARBOEUROPE.* Online at: www.bgcjena.mpg.de/public/carboeur/

HARGREAVES, K.J., MILNE, R. and CANNELL, M.G.R. (2003). Carbon balance of afforested peatland in Scotland. *Forestry* **76**, 299–316.

HUTTUNEN J.T., NYKÄNEN H., MARTIKAINEN P.J. and NIEMINEN M. (2003). Fluxes of nitrous oxide and methane from drained peatlands following forest clear-felling in Southern Finland. *Plant and Soil* **255**, 457–462.

HYVÖNEN, R., ÅGREN, G.I., LINDER, S., PERSSON, T., COTRUFO, M.F., EKBLAD, A., FREEMAN, M., GRELLE, A., JANSSENS, I.A., 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 $[CO_2]$, nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: a literature review. *New Phytologist* **173**, 463–480.

JARVIS, P.G., with an appendix by WANG, Y.P. (1986). Coupling of carbon and water in forest stands. *Tree Physiology* **2**, 347–368.

JARVIS, P.G. (1994). Capture of carbon dioxide by coniferous forest. In: Monteith, J.L., Scott, R.K. and Unsworth, M.H. (eds) *Resource capture by crops*. Nottingham University Press, Loughborough. pp. 351–374.

JARVIS, P.G. (ed.), assisted by Aitken, A., Barton, C.V.M., Lee, H.S.J. and Wilson, S. (1998) *European forests and global change: the likely impacts of rising CO_2 and temperature*. Cambridge University Press, Cambridge.

JARVIS, P.G. and FOWLER, D.G. (2001). Forests and the atmosphere. In: Evans, J. (ed.) *The forests handbook, Vol. 1.* Blackwell Science, Oxford. pp. 229–281.

JARVIS, P.G. and LEVERENZ, J.W. (1983). Productivity of temperate, deciduous and evergreen forests. In: Lange, O.L., Nobel, P.S., Osmond, C.B. and Ziegler, H. (eds). *Encyclopedia of plant physiology*, new series, Physiological plant ecology IV, Vol 12D. Springer-Verlag, Berlin. pp. 233–280.

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.

JARVIS, P.G. and MCNAUGHTON, K.G. (1986). Stomatal control of transpiration: scaling up from leaf to region.

Advances in Ecology Research **15**, 1–49.

JARVIS, P.G., STEWART, J.B. and MEIR, P. (2007). Fluxes of carbon dioxide at Thetford Forest. *Hydrology and Earth Systems Science* **11**, 241–255.

JUNGKUNST, H.F., FIEDLER, S. and STAHR, K. (2004). N_2O emissions of a mature Norway spruce (*Picea abies*) stand in the Black Forest (southwest Germany) as differentiated by the soil pattern. *Journal of Geophysical Research* **109**, Art. No. D07302 doi:10.1029/2003JD004344.

KARNOSKY, D.F., TALLIS, M., 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. 136–142.

KESSELMEIER, J. and STAUDT, M. (1999). Biogenic volatile organic compounds (VOCs): an overview on emission physiology and ecology. *Journal of Atmospheric Chemistry* **33**, 23–88.

KESIK, M., AMBUS, P., BARITZ, R., BRUGGEMANN, N., BUTTERBACH-BAHL, K., DAMM, M., DUYZER, J., HORVATH, L., KIESE, R., KITZLER, B., LEIP, A., LI, C., PIHLATIE M., PILEGAARD, K., SEUFERT, S., SIMPSON, D., SKIBA, U., SMIATEK, G., VESALA, T AND ZECHMEISTER-BOLTENSTERN, S. (2005). Inventories of N_2O and NO emissions from European forest soils. *Biogeosciences* **2**, 353–375.

KLEMEDTSSON, L., VON ARNOLD, K., WESLIEN, P. and GUNDERSEN, P. (2005). Soil CN ratio as a scalar parameter to predict nitrous oxide emissions. *Global Change Biology* **11**, 1142–1147.

LANDSBERG, J.J., PRINCE, S.D., JARVIS, P.G., MCMURTRIE, R.E., LUXMOORE, R. and MEDLYN, B.E. (1996). Energy conversion and use in forests: an analysis of forest production in terms of radiation utilisation efficiency (ε). In: Gholz, H.L., Nakane, K. and Shimoda, H. (eds) *The use of remote sensing in the modeling of forest productivity at scales from the stand to the globe*. Kluwer Academic Publishers, Dordrecht. pp. 273–298.

LAURILA, T. and LINDFORS, V. (eds) (1999). *Biogenic VOC emissions and photochemistry in the boreal regions of Europe*. Air Pollution Research Report 70. Commission of the European Communities, Luxembourg.

LINDER, S. (1985). Potential and actual production in Australian forest stands. In: Landsberg, J.J. and Parsons, W. (eds) *Research for forest management*. CSIRO, Melbourne. pp. 11–51.

McNAUGHTON, K.G and JARVIS, P.G. (1983). Predicting effects of vegetation changes on transpiration and evaporation. In: Kozlowski, T.T. (ed.) *Water deficits and plant growth*, Vol VII. Academic Press, New York. pp. 1–47.

MAGNANI, F., MENCUCCINI, M., BORGHETTI, M., BERBIGIER, P., BERNINGER, F., DELZON, S., GRELLE, A., HARI, P., JARVIS, P.G., KOLARI, P., KOWALSKI, A.S., LANKREIJER, H., LAW, B.E., LINDROTH, A., LOUSTAU, D., MANCA, G., MONCRIEFF, J.B., RAYMENT, M., TEDESCHI, V., VALENTINI, R. and GRACE, J. (2007). The human footprint in the carbon cycle of temperate and boreal forests. *Nature* **447**, 848–850.

MARTIKAINEN, P.J., NYKÄNEN, H., CRILL, P. and SILVOLA, J. (1993). Effect of a lowered water table on nitrous oxide fluxes from northern peatlands. *Nature* **366**, 51–53.

MARTIKAINEN, P.J., NYKÄNEN, H., ALM J. and SILVOLA J. (1995). Change in fluxes of carbon dioxide, methane and nitrous oxide due to forest drainage of mire sites of different trophy. *Plant and Soil* **168**, 571–577.

MEDLYN, B.E., BADECK, F.W., DE PURY, D.G.G., BARTON, C.V.M., BROADMEADOW, M., CEULEMANS, R., DE ANGELIS, P., FORSTREUTER, M., JACH, E., KELLOMÄKI, S., LAITAT, E., MAREK, M., PHILIPPOT, S., REY, A., STRASSEMEYER, J., LAITINEN, K., LIOZON, R., PORTIER, B., ROBERNTZ, P., WANG, K. and JARVIS, P.G. (1999). Effects of elevated [CO_2] on photosynthesis in European forest species: a meta-analysis of model parameters. *Plant, Cell and Environment* **22**, 1475–1495.

MEDLYN, B.E., BADECK, F.W., DE PURY, D.G.G., BARTON, C.V.M., BROADMEADOW, M., CEULEMANS, R., DE ANGELIS, P., FORSTREUTER, M., JACH, E., KELLOMÄKI, S., LAITAT, E., MAREK, M., PHILIPPOT, S., REY, A., STRASSEMEYER, J., LAITINEN, K., LIOZON, R., PORTIER, B., ROBERNTZ, P., WANG, K. and JARVIS, P.G. (2000). *Effects of elevated [CO_2] on biomass increment in European forest species: a meta-analysis of model parameters. Biomass growth and carbon allocation of young trees in response to elevated CO_2 concentrations.* Unpublished Final Report to the European Union of the 'Ecocraft' Project, 1993 to1999.

MEDLYN, B.E., BARTON, C.V.M., BROADMEADOW, M., CEULEMANS, R., DE ANGELIS, P., FORSTREUTER,M., FREEMAN, M., JACKSON, S.B., KELLOMÄKI, S., LAITAT, E., REY, A., ROBERNTZ, P., SIGURDSSON, B.D., WANG, K., CURTIS, P.S. and JARVIS, P.G. (2001). Stomatal conductance of forest species after a long-term exposure to elevated CO_2 concentration: a synthesis. *New Phytologist* **149**, 247–264.

MILLER, H.G. (1979). The nutrient budgets of even-aged forests. In: Ford, E.D., Malcolm, D.C. and Atterson, J. (eds) The ecology of even-aged forest plantations. *Proceedings of Division I. International Union of Forestry Research Organisations,* Edinburgh, September 1978. pp. 221–256.

MILNE, R., SATTIN, M., DEANS, J.D., JARVIS, P.G. and CANNELL, M.G.R. (1992). The biomass production of three poplar clones in relation to intercepted solar radiation.

Forest Ecology and Management **55**, 1–14.

MOBBS, D.C. and THOMSON, A.M. (2008). Inventory and projections of UK emissions by sources and removals by sinks due to land use, land use change and forestry. *Annual Report by CEH to Defra*.

MONTEITH, J.L. (1977). Climate and efficiency of crop production in Britain. *Philosophical Transactions of the Royal Society of London, Series B,* **281**, 277–294.

MONTEITH, J.L. and UNSWORTH, M.H. (1990). *Principles of environmental physics.* 2nd edn. Edward Arnold, London.

MORISON, J.I.L. and JARVIS, P.G. (1983). Direct and indirect effects of light on stomata. I. Scots pine and Sitka spruce. *Plant, Cell and Environment* **6**, 95–101.

NEILSON, R.E. and JARVIS, P.G. (1975). Photosynthesis in Sitka spruce (*Picea sitchensis* (Bong.) Carr.) VI. Response of stomata to temperature. *Journal of Applied Ecology* **12**, 879–889.

NEILSON, R.E., LUDLOW, M.M. and JARVIS, P.G. (1972). Photosynthesis in Sitka spruce (*Picea sitchensis* (Bong.) Carr.) II. Response to temperature. *Journal of Applied Ecology* **9**, 721–745.

NORMAN, J.M. and JARVIS, P.G. (1974). Photosynthesis in Sitka spruce (*Picea sitchensis* (Bong.) Carr.) III. Measurements of canopy structure and interception of radiation. *Journal of Applied Ecology* **11**, 375–398.

NYKÄNEN, H., ALM, J., SILVOLA, J., TOLONEN, K. and MARTIKAINEN, P.J. (1998). Methane fluxes on boreal peatlands of different fertility and the effect of long-term experimental lowering of the water table on flux rates. *Global Biogeochemical Cycles* **12**, 53–69.

PILEGAARD, K., SKIBA, U., AMBUS, P., BEIER, C., BRUGGEMANN, N., BUTTERBACH-BAHL, K., DICK, J., DORSEY, J., DUYZER, J., GALLAGHER, M., GASCHE, R., HORVATH, L., KITZLER, B., LEIP, A., PIHLATIE, M.K., ROSENKRANZ, P., SEUFERT, G., VESELA, T., WESTRATE, H. and ZECHMEISTER-BOLTENSTERN, S. (2006). Factors controlling regional differences in forest soil emission of nitrogen oxides (NO and N_2O). *Biogeosciences* **3**, 651–661.

PONTAILLER, J.Y., BARTON, C.V.M., DURRANT, D. and FORSTREUTER, M. (1998). How can we study CO_2 impacts on trees and forests? In: Jarvis, P.G. (ed.) *European forests and global change: the likely impacts of rising CO_2 and temperature*. Cambridge University Press, Cambridge. pp. 1–28.

PRICE, D.T. and BLACK, T.A. (1990). Effects of short-term variation in weather on diurnal canopy CO_2 flux and evapotranspiration of a juvenile Douglas-fir stand. *Agricultural and Forest Meteorology* **50**, 139–158.

PRICE, D.T. and BLACK, T.A. (1991). Effects of summertime changes in weather and root-zone water storage on canopy CO_2 flux and evapotranspiration of two juvenile Douglas-fir stands. *Agricultural and Forest Meteorology* **53**, 303–323.

PRIEME, A., CHRISTENSEN, S., DOBBIE, K.E. and SMITH, K.A. (1997). Slow increase in rate of methane oxidation in soils with time, following land use change from arable agriculture to woodland. *Soil Biology and Biochemistry* **29**, 1269–1273.

REY, A. and JARVIS, P.G. (1997). Growth response of young birch trees (*Betula pendula* Roth.) after four and a half years of CO_2 exposure. *Annals of Botany* **80**, 809–816.

REYNOLDS, B. (2007). Implications of changing from grazed or semi-natural vegetation to forestry for carbon stores and fluxes in upland organo-mineral soils in the UK. *Hydrology and Earth Systems Science* **11**, 61–76.

ROULET, N.T., ASH, R., QUINTON, W. and MOORE, T. (1993). Methane flux from drained northern peatlands: effect of a persistent water table lowering on flux. *Global Biogeochemical Cycles* **7**, 749–769.

ROYAL SOCIETY (2001).*The role of land carbon sinks in mitigating global climate change*. Policy Document 10/01. Royal Society, London.

ROYAL SOCIETY (2008). *Ground-level ozone in the 21st century: future trends, impacts and policy implications*. Policy document 18/08. Royal Society, London

SANDFORD, A.P. and JARVIS, P.G. (1986). The response of stomata of several coniferous species to leaf-to-air vapour pressure difference. *Tree Physiology* **2**, 89–103.

SATTIN, M., MILNE, R., DEANS, J.D. and JARVIS, P.G. (1997). Radiation interception measurement in poplar: sample size and comparison between tube solarimeters and quantum sensors. *Agricultural and Forest Meteorology* **85**, 209–216.

SITCH, S., COX, P.M., COLLINS, W.J. and HUNTINGFORD, C. (2007). Indirect radiative forcing of climate change through ozone effects on the land-carbon sink. *Nature* **448**, 791–794.

SMAL, H. and OLSZEWSKA, M. (2008). The effect of afforestation with Scots pine (*Pinus silvestris* L.) of sandy post-arable soils on their selected properties. II. Reaction of carbon, nitrogen and phosphorus. *Plant and Soil* **305**, 171–187.

SMITH, K.A., DOBBIE K.E., BALL, B.C., BAKKEN, L.R., SITAULA, B.K., HANSEN, S., BRUMME, R., BORKEN, W., CHRISTENSEN, S., PRIEME, A., FOWLER, D., MACDONALD, J.A., SKIBA, U., KLEMEDTSSON, L., KASIMIR-KLEMEDTSSON, A., DEGORSKA, A. and ORLANSKI, P. (2000). Oxidation of atmospheric methane in Northern European soils, comparison with other ecosystems, and uncertainties in the global terrestrial sink. *Global Change Biology* **6**, 791–803.

SMITH, P., POWLSON, D.S. and GLENDINING, M.J. (1997). Potential for carbon sequestration in European soils: preliminary estimates for five scenarios using results from long-term experiments. *Global Change Biology* **3**, 67–79.

STEVENS, A. and VAN WESEMAEL, B. (2008). Soil organic carbon stock in the Belgian Ardennes as affected by afforestation and deforestation from 1868 to 2005. *Forest Ecology and Management* **256**, 1527–1539.

STEWART, H.E., HEWITT, C.N., BUNCE, R.G.H., STEINBRECHER, R., SMIATEK, G. and SCHOENEMEYER, T. (2003). A highly spatially and temporally resolved inventory for biogenic isoprene and monoterpene emissions: model description and application to Great Britain. *Journal of Geophysical Research* **108**, Art. No. 4644, doi:10.1029/2002JD002694.

TITUS, B.D. and MALCOLM, D.C. (1991). Nutrient changes in peaty gley soils after clearfelling of Sitka spruce stands. *Forestry* **64**, 251–270.

TITUS, B.D. and MALCOLM, D.C. (1992). Nutrient leaching from the litter layer after clear felling of Sitka spruce stands on peaty gley soils. *Forestry* **65**, 389–416.

TITUS, B.D. and MALCOLM, D.C. (1999). The long-term decomposition of Sitka spruce needles in brash. *Forestry* **72**, 207–221.

VON ARNOLD, K., WESLIEN, P., NILSSON, M., SVENSSON, B. and KLEMEDTSSON, L. (2005). Fluxes of CO_2, CH_4 and N_2O from drained coniferous forests on organic soils. *Forest Ecology and Management* **210**, 239–254.

WANG, Y. P. and JARVIS, P.G. (1991). Influence of crown structural properties on PAR absorption, photosynthesis and transpiration in Sitka spruce: application of a model (MAESTRO). *Tree Physiology* **7**, 297–316.

WANG, Y.P., JARVIS, P.G. and BENSON, M.L. (1990). The two-dimensional needle area density distribution within the crowns of *Pinus radiata* trees. *Forest Ecology and Management* **32**, 217–237.

WANG, Y.P., JARVIS, P.G. and TAYLOR, C.M.A. (1991). PAR absorption and its relation to above-ground dry matter production of Sitka spruce. *Journal of Applied Ecology* **28**, 547–560.

WANG, Y.P., REY, A. and JARVIS, P.G. (1998). Carbon balance of young birch trees grown in ambient and elevated atmospheric CO_2 concentrations. *Global Change Biology* **4**, 797–807.

ZERVA, A. and MENCUCCINI M. (2005a). Short-term effects of clearfelling on soil CO_2, CH_4, and N_2O fluxes in a Sitka spruce plantation. *Soil Biology and Biochemistry* **37**, 2025–2036.

ZERVA, A. and MENCUCCINI, M. (2005b). 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., 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.