ECHOES
COST ACTION FP0703

COST action FP0703 – ECHOES

Country report

United Kingdom

5 August 2009

Bill MASON
Maria NIJNIK
Duncan RAY
Mark BROADMEADOW
Bill SLEE

Forest Research

THE MACAULAY LAND USE
RESEARCH INSTITUTE
research today for land use tomorrow

Contents

Acknowledgements and disclaimer

We are grateful to Colin Campbell, Guillaume Pajot, Iain Brown, Robin Matthews, Mike Perks, Helen Sellars and many other colleagues who have found time to review this report and for their comments. The views expressed in the report are our own and should not be taken as an official statement of policy.

INTRODUCTION

Short overview of British forests and forestry

In 2007, the forest cover of the United Kingdom (UK) amounted to 2.85 million hectares or just under 12 per cent of the land area (Forestry Commission, 2007b). There was appreciable variation in forest area between the four countries of the UK: thus in Scotland the percentage cover was 17.5 per cent; in Wales 13.7 per cent; England 8.6 per cent; and in Northern Ireland 6.2 per cent. The species composition of British forests was 58 per cent coniferous and 42 per cent broadleaved, but again there was considerable difference between countries since in Scotland and Wales conifers were more than 80 per cent of the forests whereas in England the comparable figure for broadleaves was nearly 60 per cent. Most of these forests were classed as high forest with only around 1 per cent being managed under coppice systems. 70 per cent of the forests were privately owned while the remainder was owned by the state and managed by the respective country forest services, which in England, Scotland and Wales is the Forestry Commission. About 65 per cent of the forest area of the UK was covered by a management plan or equivalent (MCPFE, 2007) while about 45 per cent, including all publicly owned forests, was certified as being sustainably managed under a FSC-approved scheme.

There was a substantial increase in forest area during the last century through a sustained afforestation programme that was carried out predominantly on marginal agricultural land, particularly in the upland areas of Northern Ireland, Scotland and Wales (Mason, 2007 and references therein). As a result the forest area is dominated by plantations, with the figure of 1.9 million hectares of plantation (67 per cent of forest area) being one of the highest in the EU (MCPFE, 2007). By contrast, the area of semi-natural woodland, whether of a boreal type dominated by Scots pine (*Pinus sylvestris* L.) and birch (*Betula* spp.) or of temperate broadleaves with oak (*Quercus* spp.), beech (*Fagus sylvatica*), ash (*Fraxinus excelsior*) and other species is relatively low.

The main species used in the afforestation programme were conifers, which research trials showed to be more tolerant of the exposed conditions and nutrient poor soils where most of the new forests were created. Early research also indicated that the only native timber producing conifer (Scots pine) was not as productive as a range of non-native conifers. As a result, introduced species such as Sitka spruce (*Picea sitchensis* (Bong.) Carr.), various larches (*Larix* spp.), pines (e.g. *Pinus contorta*, *Pinus nigra*) and Douglas fir (*Pseudotsuga menziesii* Mirb. Franco) are now major components of British forests. A feature of particular importance for carbon management in British forests is that extensive areas of plantation, particularly in Scotland, were established on peaty (organic) soils where soil carbon levels are very high and the carbon content of the soil is often greater than that of the trees (Cannell et al, 1993; Broadmeadow and Matthews, 2003).

The estimated growing stock in 2005 was 340 million m^3 or about 119.5 m^3 ha^{-1} (MCPFE, 2007). The net annual increment was 8.7 m^3 ha^{-1} $year^{-1}$ which was the one of the highest estimates for the EU while the actual timber harvest was around 9 million m^3 $year^{-1}$ for conifers and about 0.4 million m^3 $year^{-1}$ for broadleaves. This output represents just under 50 per cent of the net annual increment and reflects the comparative youth of some of the conifer forests (Mason, 2007) and the fact that many broadleaved woodlands in lowland Britain are unmanaged (Kirby et al. 2005). Estimated carbon stocks in the forests were 115 million tones of carbon (includes above- and below-ground biomass and deadwood, but not soils) (MCPFE, 2007)

Overview of forest policy

Forest management in the UK is governed by the principles first agreed at the 1993 Helsinki Ministerial Conference on the Protection of Forests in Europe (MCPFE) and developed in subsequent conferences to become the 2003 MCPFE criteria and indicators of Sustainable Forest Management (SFM). The approach to implementing these principles in UK forests is laid down in the UK Forestry Standard (UKFS) (Anon., 2004) and a set of supporting guidelines which cover aspects such as the effects of forests on biodiversity, landscape, soils, and water. The UKFS thus sets the context for forestry in the countries of the UK and explains how forestry is regulated. It is a performance standard for the sustainable management, planning and design of all forests in the UK. The guidelines capture the essence of the various elements of forest management in further detail, set out how the requirements can be met, and provide advice on forest management. The UKFS and the guidelines have an important function as the basis of forestry practice in the UK for the certification process carried out through the independent UK Woodland Assurance Standard (UKWAS). A revised version of UKFS is currently out for consultation and should be released in 2009, as well as a new guideline covering forests and climate change.

SFM, as set out in the UKFS, is the fundamental tenet of forestry policy in the UK. Since devolution in 1997, the articulation of forestry policy is devolved to country administrations in the four countries of the UK. Each country has its own forestry strategy setting out policies and priorities for forest creation and management and these strategies are of major importance in determining how the forestry sector will adapt to climate change. Thus the Scottish (Anon., 2006a), English (Anon., 2007), and Welsh (Anon., 2009a) forestry strategies each include sections dealing with the impact of climate change as a major theme or objective, and these are being developed further through specific climate change action plans for forestry in a specific country, as in Scotland (Anon., 2009b). By contrast, the strategy for Northern Ireland (Anon., 2006b) does not yet include explicit reference to climate change. More detailed discussion of the actions proposed to increase the resistance and resilience of British forests to anticipated climate change can be found in the following sections.

Developing awareness of climate change in UK forestry

Because of the history of introducing non-native species into British forestry, there has been a long tradition of assessing the response of species to climate factors such as extreme temperature and drought (e.g. Redfern and Hendry, 2002). However, the tendency was for the effects of such abiotic factors to be studied in isolation and results interpreted on a site or region specific basis rather than as a systematic trend. The first studies that looked at potential health and growth responses of trees in Britain to projected climate change at a country level were undertaken by Cannell and colleagues in the 1980s (e.g. Cannell and Smith, 1986): these culminated in a systematic review (Cannell et al., 1989) which suggested that, *inter alia*, more southerly species and provenances might become more suitable for use In Britain as a consequence of climate warming.

During the following decade, the amount of research undertaken on tree growth and other responses to global warming increased considerably, revealing earlier flushing dates for native tree species (Sparks and Gill, 2002) as well as faster growth in plantation forests (Cannell, 2002). However, awareness of the potential impacts of climate change on British forests was largely confined to the research community until the publication of the first UK Climate Impacts Scenarios in 1998 (Hulme and Jenkins, 1998) which provided regional projections of climate change in 2020, 2050, and 2080. These projections could be combined with the Ecological Site Classification (ESC) predictions of tree species response to climate and edaphic factors (Ray et al., 2002) to show how certain site types or regions of the UK might become marginal for particular species within a few decades. By 2000, increasing awareness of the potential impacts of climate change was reflected by the publication of a UK government strategy on tackling climate (Anon, 2000a) including reference to 'protection and enhancement of forests' as one of the policies to mitigate change. The first major British conference on Trees and Climate change was held in 2000, and the subsequent publication (Broadmeadow, 2002) of the proceedings did much to increase awareness of the issues within the forestry sector.

Subsequent years have seen further development of our understanding of the potential effects of climate change on British forests and there has been a steady flow of publications (e.g. Broadmeadow and Matthews, 2003; Broadmeadow and Ray, 2005) which have sought to increase sector awareness of the need to build such knowledge into future plans. Further conferences have been held to highlight the global dimensions of forestry and climate change (Freer-Smith et al., 2007) and country projections have been provided for forestry in Scotland (Ray, 2008a) and Wales (Ray, 2008b).

Growing attention has been paid to socio-economic aspects of forestry and climate change and to various issues related to rural policy, and land use and landscape changes. The economics of carbon sequestration through forestry based activities and of carbon offsetting (Moran et al., 2008; Nijnik, 2008; Nijnik et al., 2009), social aspects of tackling the changing climate, and institutional settings for implementing relevant policies for forestry and other land use sectors in the UK have been analysed at the Macaulay Institute, in collaboration with other organisations, both in the UK and internationally (Nijnik and Bizikova, 2008; Nijnik in press ; Pajot et al., 2009) (see http://www.macaulay.ac.uk/climatechange/CC_research.php).

The Forestry Commission has produced publicity material to increase general awareness of the impacts of climate change (e.g. Forestry Commission, 2007a) and an authoritative independent statement is under preparation as A National Assessment of UK Forestry and Climate Change (see http://www.forestry.gov.uk/website/forestry.nsf/byunique/infd-7m8ghy) with active contribution from the Macaulay Institute. It is probably fair to say that all parts of the UK forestry sector are now aware of the potential impacts of climate change. The challenge is how to translate that awareness into effective action.

1. Impacts

1.1 Introduction

There is compelling evidence that the climate has changed over past decades in the UK, with nine of the ten warmest years on record having occurred since 1990 and a clear trend of a shift in the seasonality of rainfall (Jenkins et al., 2007). Although it is difficult to prove through empirical evidence that such clear trends are the direct result of anthropogenic greenhouse gas emissions, modelling provides good evidence of the link. Only when greenhouse gas forcing is included in general circulation model (GCM) experiments do the models replicate the climate of the past century adequately (IPCC, 2007a).

The level of climate change observed to date (e.g. 0.8°C to 1°C change in mean UK temperatures from 1961-2003) is small relative to the change that is likely to occur over the course of the 21st century. It is not possible to easily predict how woodlands will be affected, nor is it easy to design or implement adaptation responses to mitigate the future impacts of climate change on without good future climate forecasts. Instead we have developed techniques that involve the use of a biophysical model that shows the site suitability of different tree species, and extended this model into the future climate projected by the United Kingdom Climate Impacts Programme (UKCIP) for a range of greenhouse gas emissions scenarios described by the Intergovernmental Panel on Climate Change (IPCC). Furthermore, for different places in the UK, we can match the future climate of that site to current climates in other parts of Europe. This may help us better understand the likely impacts of climate change on species, from current studies in those climates.

The biophysical-climate space modelling approach is useful in providing a measure of the approximate fit of species to climate and site conditions. However, it does not deal with extreme events. Very recently published data (June 2009) from UKCIP (the UKCP09 projections) provide an opportunity to study the likelihood of climate change, the timing of the advance of thresholds of change, and a simulator to explore the frequency and magnitude of projected extreme events.

1.2 Observed impacts

Summary

- *Phenological records confirm climate change trends, particularly the earlier onset of spring.*
- *Analysis of annual weather patterns over recent decades demonstrates significant trends in the changing climate that match those projected by UKCIP 2002 in the form of increasing mean annual temperature and shifts in the rainfall distribution.*
- *The degree and amount of change varies across the UK. The trend of increasingly warmer growing seasons has increased tree growth in parts of the UK, and some dry summers caused drought stress with reductions in growth.*
- *There is evidence of damage to sensitive tree species in dry summers, e.g. stem lesions on Sitka spruce in eastern Scotland during the hot and dry summer of 2003.*
-

Phenology

Phenology records the timing of natural events, particularly in relation to climate. Many records include the date at which flowering and leafing of plants occur, and often the dates of initiation of insect and bird migration (see Sparks and Gill, 2002). In the UK, phenology has a long history of about 300 years, and in particular the work of Robert Marsham (1708-1798) provides an fascinating insight of the relationship between climate and natural events over a long period. Marsham's work provides a key component of the phenological evidence with the record of 27 indicators of spring dating back to 1736. Records include the first leafing date of 13 tree species, first flowering dates and the arrival dates of some migrant birds.

The date of first leafing of rowan (*Sorbus aucuparia*) is quite sensitive to the mean spring temperature between February and April from the Central England Temperature (CET) record (Figure 1) (Sparks and Gill, 2002). Their data show that rowan responds by producing leaves 6 days earlier for every 1°C increase in the spring temperature. Many species of tree respond in a similar manner, although some are less sensitive to the spring temperature cue and flush in response to changing photoperiod. Another phenological record started by Combes in 1947 shows a change in the flushing date (date of budburst) of several tree species in southern England, in response to warmer mean spring temperature over the last 5 decades (Figure 2 after Sparks and Gill, 2002). The conclusion from these data is that pedunculate oak (*Quercus robur*) budburst advanced by approximately 20 days over the second half of the 20th century in southern England and, with other phenological evidence, it shows that climate change is already having a considerable impact on trees and woodland ecosystems.

Although budburst has advanced for many species of tree as a result of increases in mean spring temperature, there has been little change in stochastic meteorological events. For example, there has been no change in the last date of occurrence of late spring frosts below minus 2°C, at which temperature damage to tender plant tissue can occur. Thus the risk of frost damage has increased slightly over the last 50 years (Broadmeadow *et al*. in prep).

Phenological records relating to plants and dependent organisms, such as the defoliating insect winter moth (*Operophtera brumata)* show synchrony between the emerging foliage and hatching eggs (Buse and Good, 1996) in warmer springs. However, this synchrony is not maintained in some species which have not co-evolved. Winter moth maintains an earlier egg hatch with warmer spring temperatures, even though budburst in spruce does not advance (Watt and MacFarlane, 1991). This suggests that larval survival on some host plants will be reduced as a result of climate change (Evans et al., 2002). It is likely that climate change is exerting, and will continue to exert a complex impact on the synchrony and co-dependence between trees and host organisms. Impacts are difficult to predict since predator-prey relationships will change, and this is likely to cause uncertain effects on interdependencies within the trophic web.

Figure 1 The negative relationship between first leafing date of rowan and mean February-April temperature (^{0}C). The strong negative relationship shows the flushing response of rowan with spring temperature from the Central England Temperature (CET) record (Sparks and Gill, 2002)

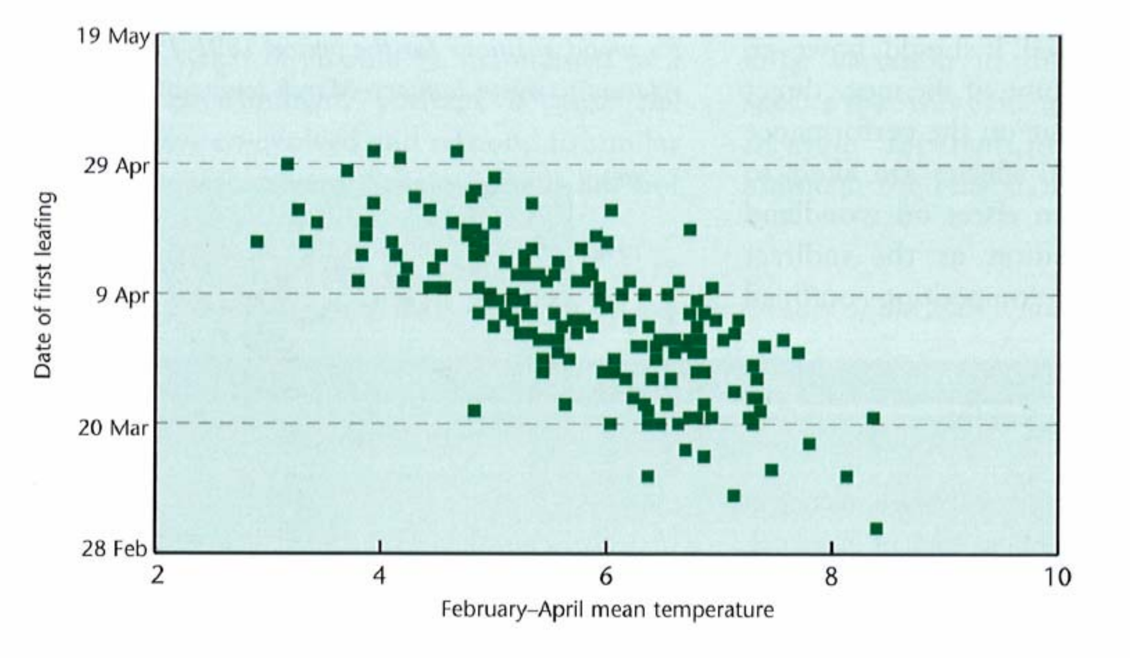


Figure 2 Change in the mean date of budburst over 4 decades in the south of England (after Sparks and Gill, 2002)

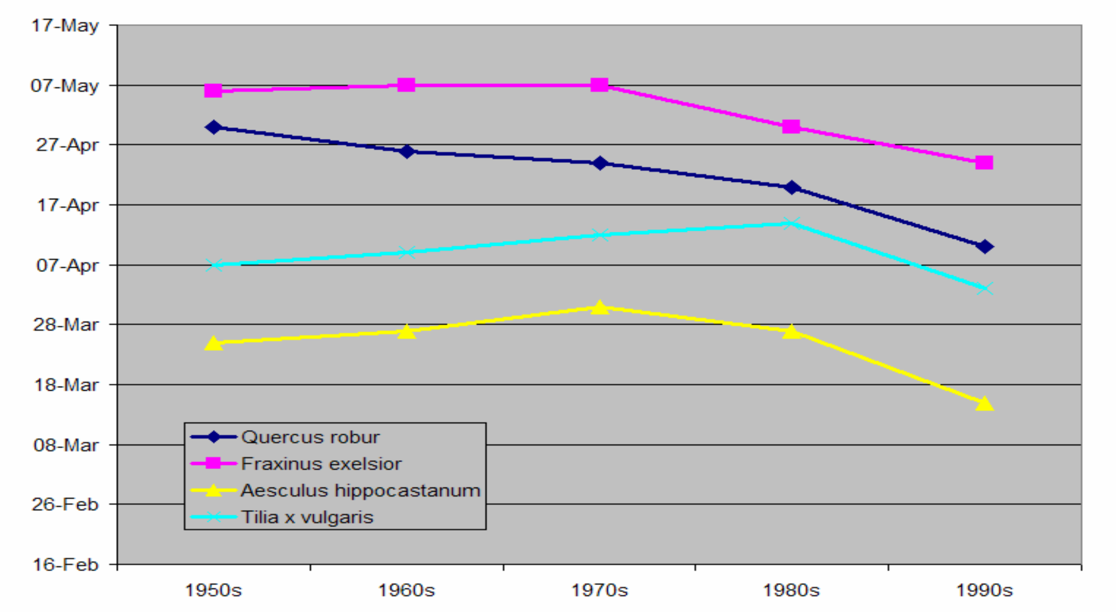
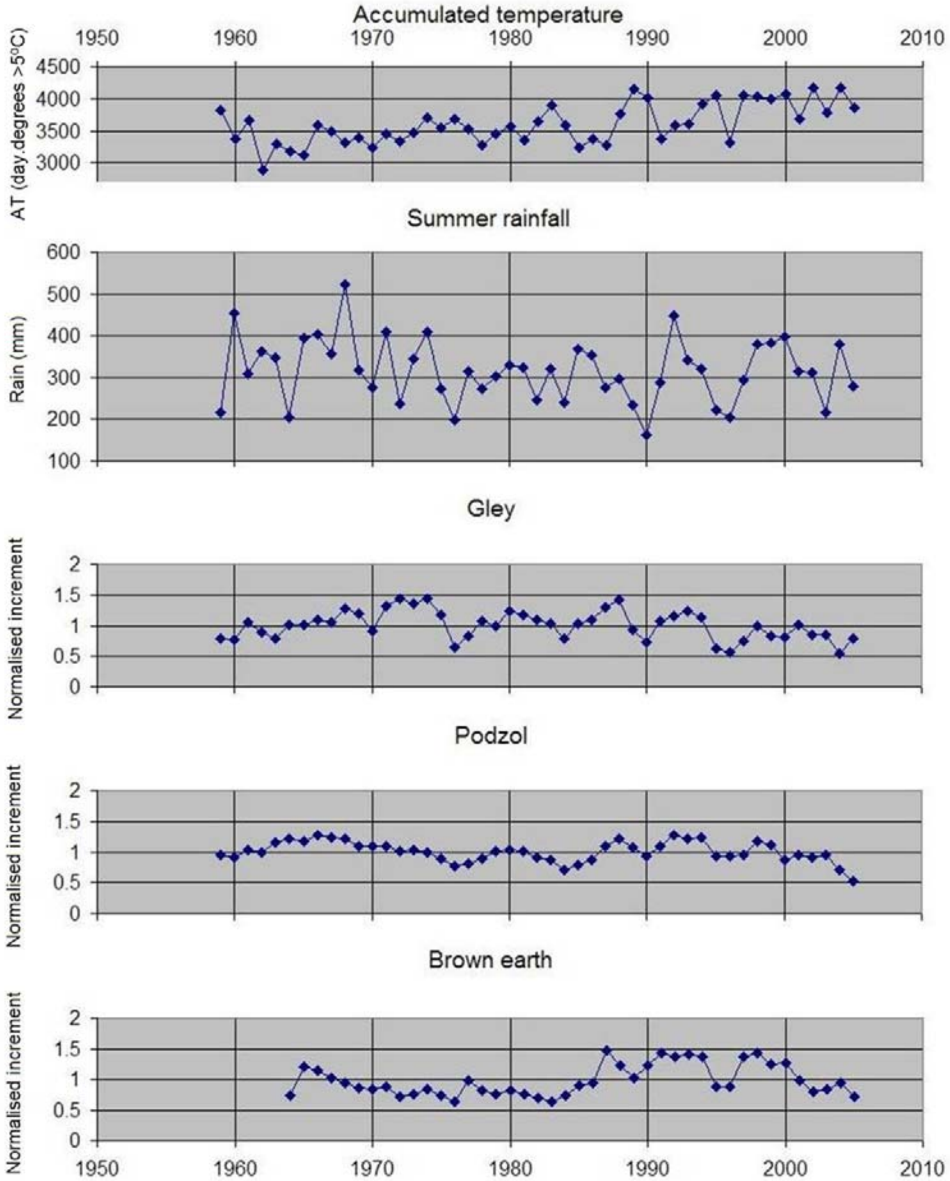


Figure 3 The relationship between warm and dry summers as recorded at Oxford to calculate accumulated temperature and summer rainfall, and the stem diameter increment of beech (Fagus sylvatica) growing on 3 different soil types (surface-water gley, podzol and brown earth) in southern England



Tree growth and timber quality

Increased growth in warmer growing seasons is dependent on sufficient moisture. In dry summers (e.g. 1976, 1984, 1990, 1995, 1996) shown by low summer (April-September inclusive) rainfall (Figure 3) the normalised stem diameter increment for beech was reduced. This was particularly accentuated on trees sampled on surface-water gley soil types (Broadmeadow *et al*. in prep). Surface-water gleys (stagno-orthic gley; Avery, 1990) have a characteristic seasonally fluctuating water table resulting in shallow roots restricted by anaerobiosis, associated with winter water-logging. The restricted rooting depth, and the resulting reduced volume of soil coupled to the root system, may become a particular problem in dry summers. Beech trees sampled on brown earths and podzols, which are types of freely draining soil, showed smaller growth reductions in dry summers.

Dry summers, such as in 2003, have caused serious damage to mature Sitka spruce (*Picea sitchensis*) trees in the form of stem lesions (Figure 4), and internal radial cracking (Figure 5) in the wood. Such cracks render the timber of poor quality and of no structural use. Sitka spruce is a native conifer species of the Pacific northwest coast of North America from southern Alaska in the north to northern California in the south of its range. However, the species is restricted to coastal forests associated with higher rainfall and in particular high humidity, fog and low cloud (Samuel et al., 2007). Consequently, the species is intolerant of high moisture deficits, and is not recommended on sites with moisture deficits in excess of 180 mm in the summer months (Pyatt et al., 2001).

Figure 4 Stem lesion on Sitka spruce in Durris Forest, eastern Scotland, following the dry summer of 2003 - photo B. Rayner, ©Forestry Commission

Figure 5 Radial cracking through the stem of Sitka spruce following dry summer conditions, ©Forestry Commission

Recorded climate change

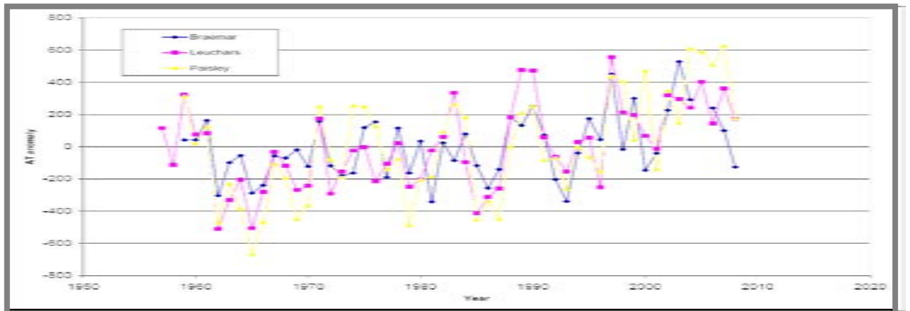
Accumulated temperature provides a good climatic index of warmth, as it expresses the degree to which the photosynthetic rate and particularly the rate of growth occur in plants (Grace et al., 2002) above 5°C. There is a direct relationship between accumulated temperature and yield and, if soil moisture is not limiting, trees will grow faster in a warmer climate. Work by Sing et al (2006), in developing an empirical yield model for Sitka spruce showed a positive relationship between accumulated temperature and yield ($m^3ha^{-1}yr^{-1}$) (Figure 7). A number of studies have reported an increased yield from forests in Britain and Europe, and the effect has been associated with the warming climate, increased nitrogen availability and better silviculture (Cannell, 2002; Magnani et al., 2007; Worrell and Malcolm, 1990).

Figure 6 demonstrates changes in accumulated temperature over the last 50 years. Accumulated temperature has been calculated annually as the number of day-degrees over 5^oC from monthly temperature records over the last 50 year period. A sample of 9 meteorological stations, 3 in each of England, Scotland, and Wales shows that the growing season has become warmer in all regions over the period, based on normalised data – which is the difference from the 50 year mean. Furthermore, accumulated temperature has been steadily increasing over the last 120 years, and Figure 8 shows the long term trend of increasing accumulated temperature over the past 128 years, recorded at Durham in the north-east of England.

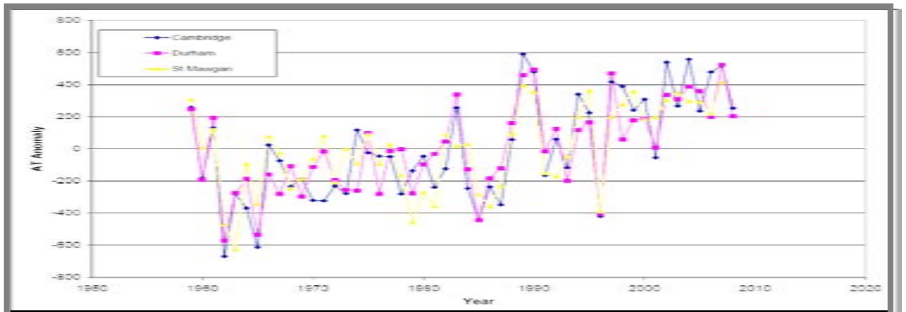
Forest fire

An increasing trend for outdoor ‘grassland’ fires has been observed over recent decades. This contrasts with the number of forest fires (on FC land) which have declined over the period for which data are available (1975 – 2004: FC Annual report 2005). The decline is likely to result primarily from the reduction in the area of thicket stage conifer woodland which is at greatest risk of fire. Cannell and McNally (1997) noted that climate has generally been the catalyst for forest fires but rarely the actual cause, as most fires are human-induced whether intentional or not. The area of woodland burned increased in the well documented ‘drought’ years such as 1976, 1989-90 and 1995, although no increase was evident in 2005.

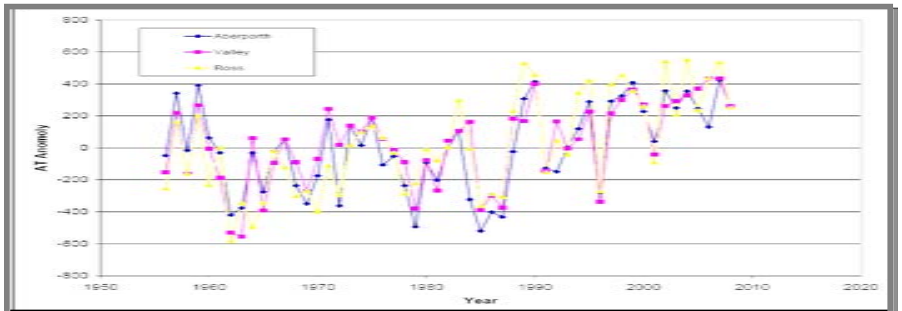
Figure 6 The accumulated temperature anomaly for a 50 years period for 9 meteorological recording stations, 3 in each of the countries England, Scotland, and Wales



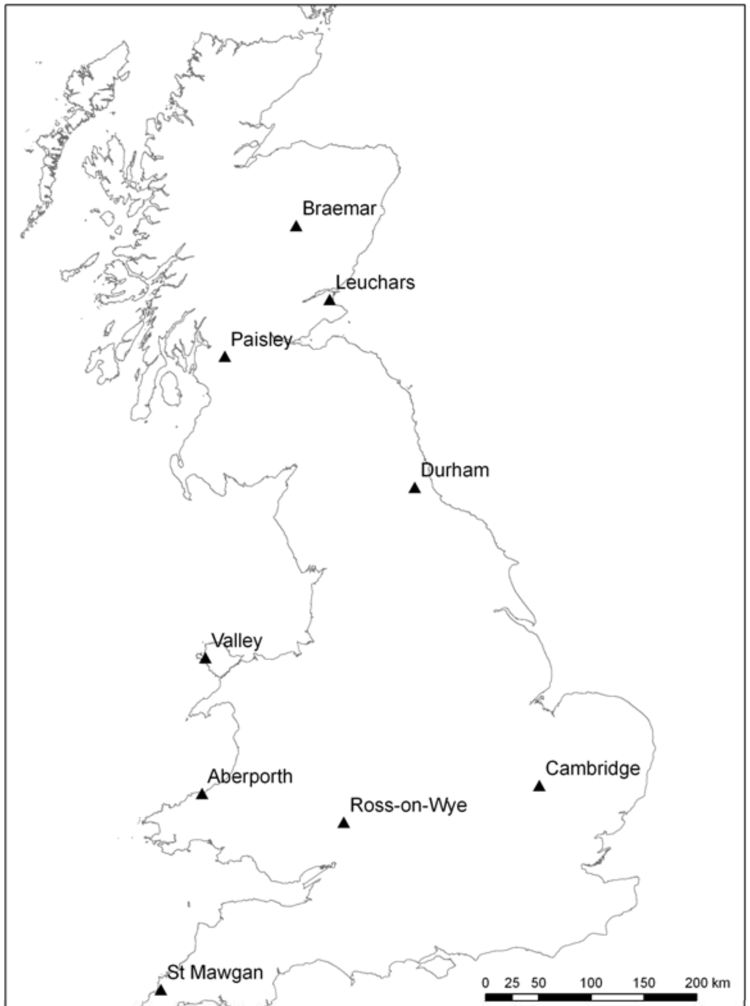
Met Stations in Scotland



Met Stations in England



Met Stations in Wales



Based on Ordnance Survey mapping with the permission
of the controller of Her Majesty's Stationery Office.
© Crown Copyright - Forestry Commission Licence No 100025498

Figure 7 Relationship between accumulated temperature and yield for Sitka spruce in south Scotland (Sing et al 2006)

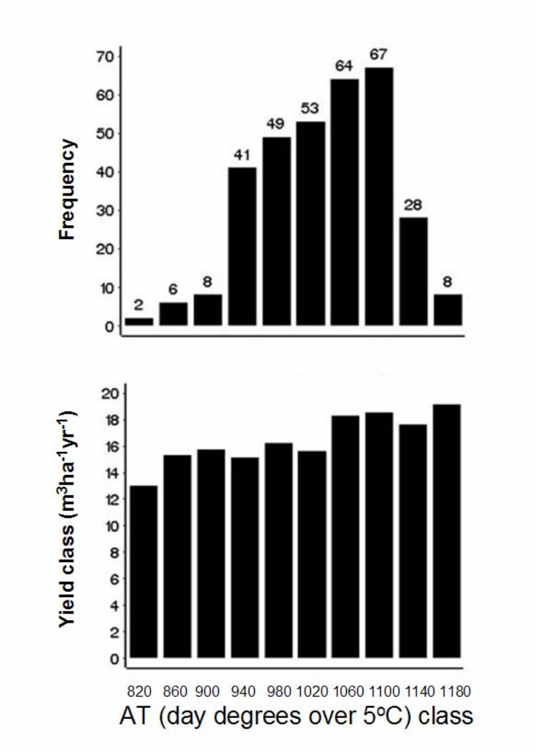
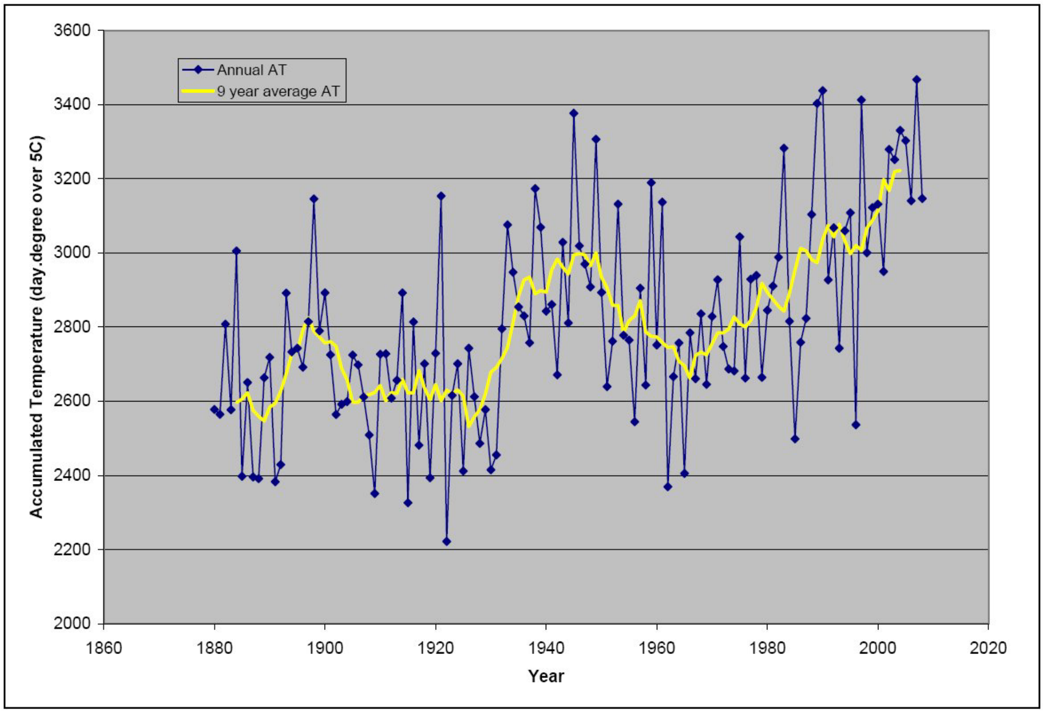


Figure 8 Long term trends in accumulated temperature calculated from meteorological data recorded in Durham (see Fig 3) between 1880 and 2008



1.3 Expected impacts

Summary

- *There is a very high likelihood of climate change impacting on drought-sensitive tree species on shallow and/or sandy soils under all future climate scenarios.*
- *By 2080, in southern and eastern England, and in east Wales and eastern Scotland, the High emissions scenario will very likely have a considerable effect on the tree species currently used in British forestry. Less extreme projections would have a lower impact on sensitive sites and the amount of forest land affected.*
- *Biotic impacts are very likely to be more damaging than dry summers for many tree species.*
- *Increased winter waterlogging will render increased areas of upland plantation forest liable to endemic and possibly catastrophic wind disturbance.*
- *It is crucial to ensure the selection of the appropriate species, provenance and management system for each site in order to maintain the quality of the UK timber supply.*
- *Species choice, genetic selection and management system will have as much an influence on the quality of future UK timber supplies as projected climate change.*
- *Forecast changes to the wood properties of the major timber species will not adversely impact on the suitability of future sawn timber supplies to meet existing markets.*
- *Climate change is predicted to increase the growth rate for most species. The impact of this increased growth will vary from species to species, but is not expected to have an impact on the performance of UK timber.*
- *Increased windiness may lead to poorer form on some sites due to increased leader loss. This can be mitigated by appropriate site choice and longer rotations.*
- *Woodland community composition will change with the climate, with readjustments in the dominance of tree, shrub and vascular plant species in response to the site and climatic interactions*
- *Uncharacteristic species will colonise some woodland types, causing changes in the way in which woodland types are classified*
- *There are likely to be changes in the natural disturbance pressure on some native woodlands, leading to more scrubby woodlands from more frequent disturbance from wind and fire*

1.3.1 Projected climate change

Climate projections for Britain published in 2002 (Hulme et al., 2002) show differential changes to the seasonal climate. Comparing different regions, the baseline climate for northern Scotland (Figure 8) shows a relatively high seasonal variation in rainfall and a moderate seasonal variation in temperature. Future projections forecast a small reduction in summer rainfall, a moderate increase in winter rainfall, and a moderate increase in temperature for each season. In comparison, the baseline climate of southern England shows a moderately high temperature range between summer and winter but a very low range in seasonal rainfall. Future projections forecast an increase in the seasonal temperature range with much warmer summers and milder winters, and an increase in the seasonal rainfall distribution, with wetter winters and much drier summers. The climate projections for Northern Ireland and Wales are intermediate between north Scotland and southern England in response.

UKCIP climate projections have been used to adjust accumulated temperature (AT) and moisture deficit (MD), two of the climate factors in the ESC model (Broadmeadow and Ray, 2005; Ray et al., 2002) with dynamic linking between climatic moisture deficit and summer soil moisture regime. The data and ESC model have provided a low resolution, strategic planning tool to indicate the kinds of changes that may occur in the climatic factors used to specify tree species suitability and site yield potential.

By 2080, both the Low emissions scenario (IPCC-B1) and High emissions scenario (IPCC-A1FI) are projected to have a profound effect on accumulated temperature and moisture deficit (Figure 9a & b) in Britain. High emissions projections show accumulated temperature could increase by as much as 40-50% in south Wales and central Scotland, and by as much as 60% in south-east England. In Britain's relatively cool climate, large increases in accumulated temperature occur due to small increases in the mean daily temperature above 5°C. Two reasons account for this - warmer seasonal temperatures, and a longer growing season. Moisture deficits are also likely to increase. Increases of up to 40% may occur in eastern and southern Wales and central Scotland, and increases of 50% are likely in south-east England. This would cause forest soils in affected parts of Britain to be depleted of soil moisture on freely draining and shallow soils, and would be a problem for species that are sensitive to drought conditions in excess of about 180-200 mm (e.g. Sitka spruce, beech). Indeed, on such sensitive sites the High emissions scenario projections of frequent and extreme moisture deficit would seriously reduce the growth for many species of tree currently grown in Britain.

Figure 8 Monthly and seasonal changes, of monthly mean temperature and total monthly rainfall in different parts of the UK, in the baseline climate (grey), the projected climate in the IPCC B1 scenario (light green) for 2080, and the IPCC A1FI scenario (black) for 2080 (after Hulme et al. 2002)

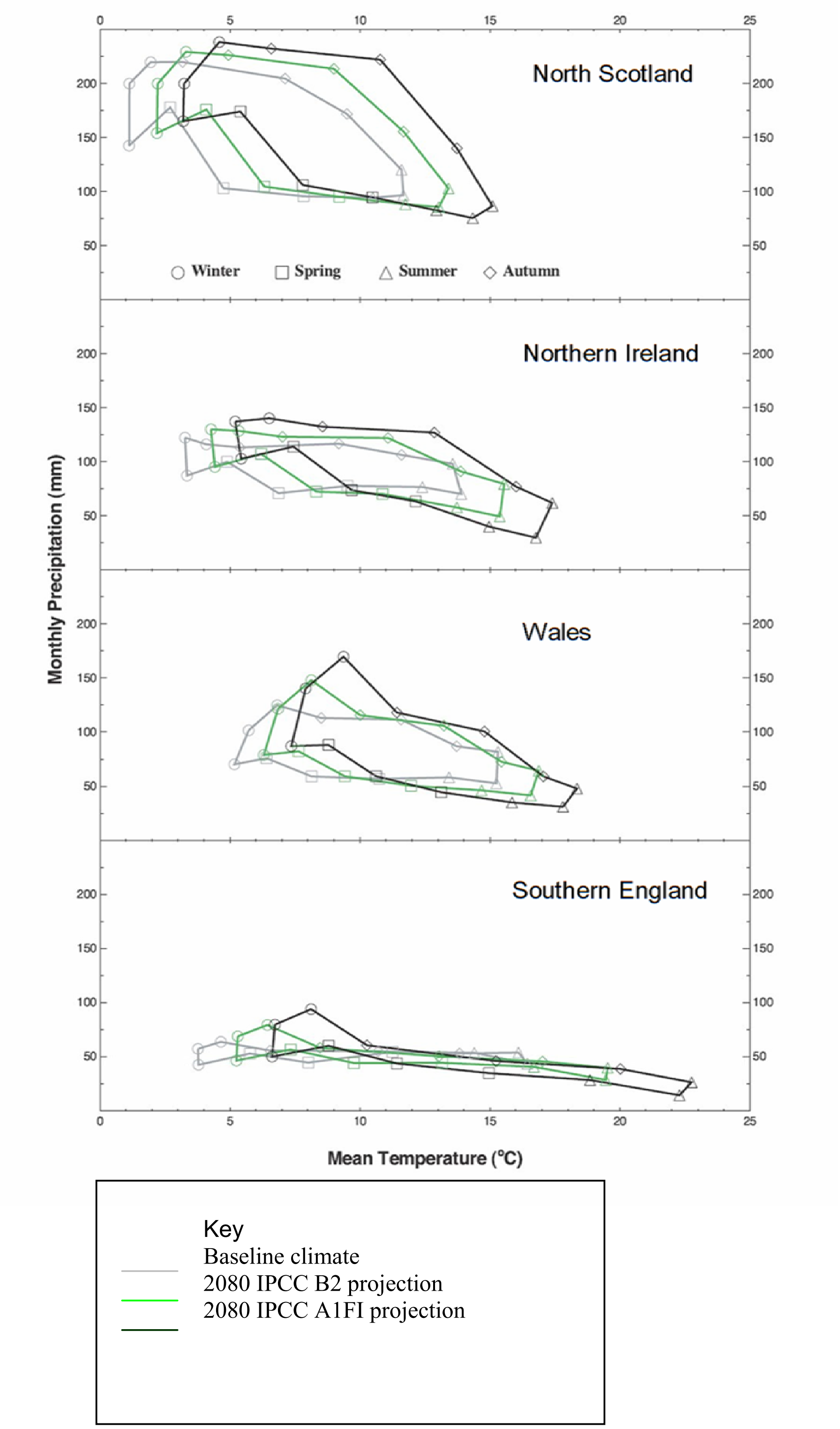
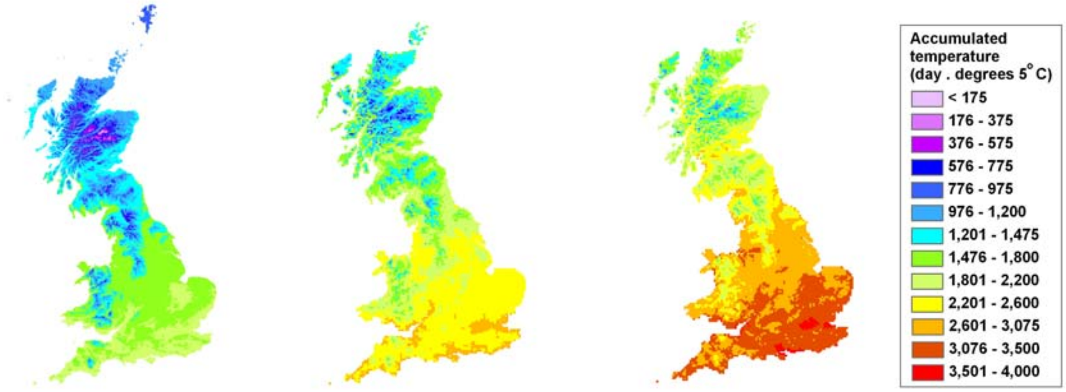


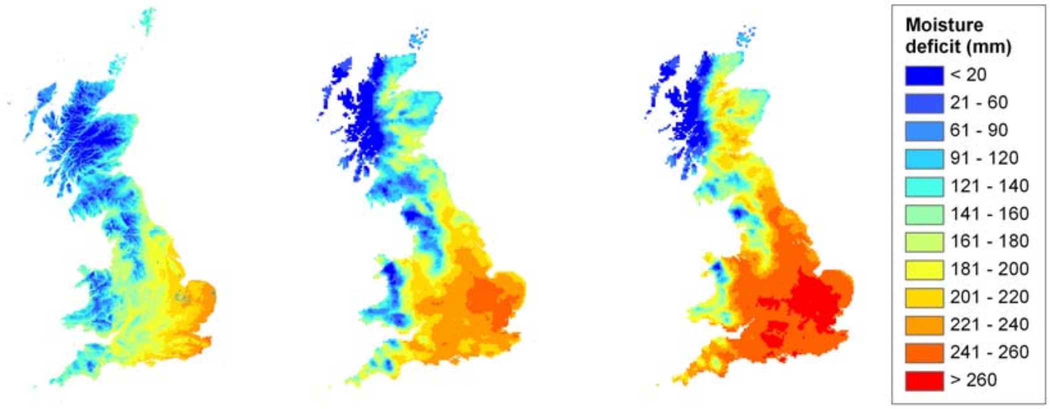
Figure 9 Projected changes in a) accumulated temperature and b) moisture deficit for future climate projections in Britain (Note ESC projections not available for Northern Ireland) simulating the Low (IPCC B1) and High (IPCC A1FI) emissions scenarios

a)



a) Baseline climate 1961 - 1990 b) Projection for 2080 low c) Projection for 2080 high

b)



a) Baseline climate 1961 - 1990 b) Projection for 2080 low c) Projection for 2080 high

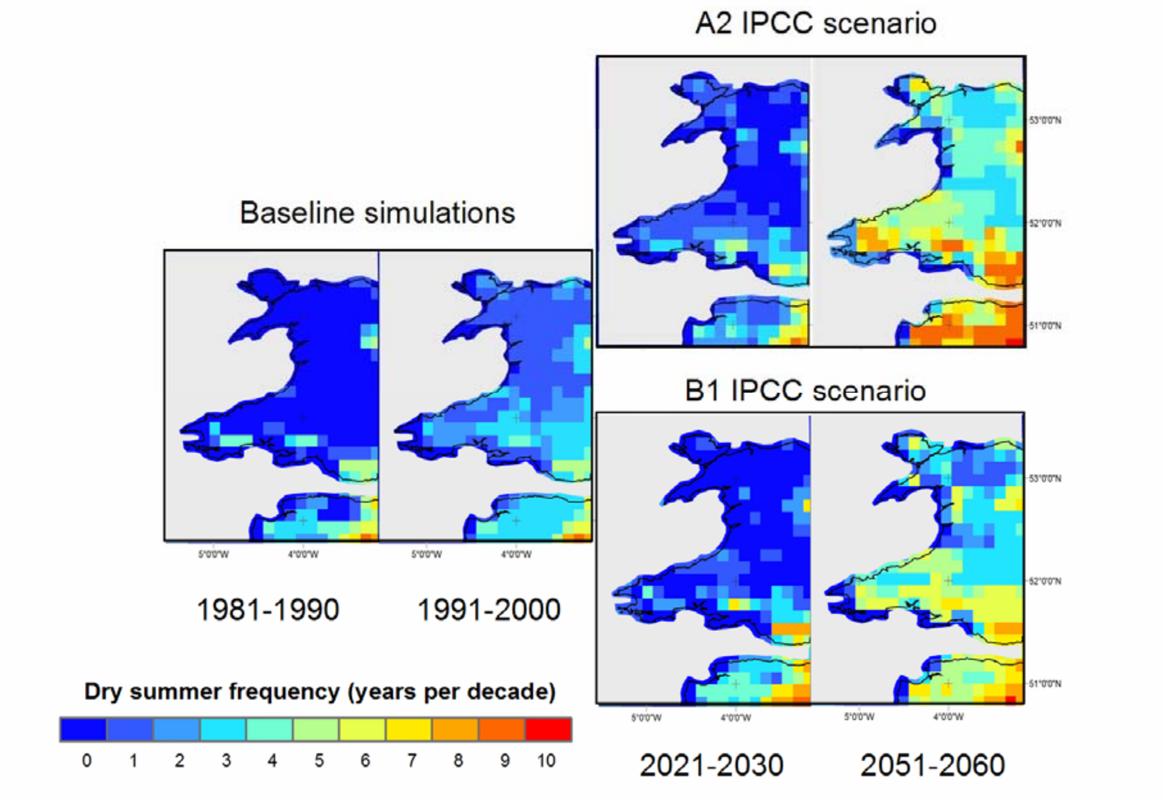
Frost

On sites that can maintain adequate soil moisture during dry periods, for example, on deep, loamy textured, freely draining soils perhaps at the base of hill slopes, with a percolation from above, the warmer summers will stimulate increased growth. Although the mean temperature is projected to increase, the likelihood of early autumn frost, and late spring frost will remain. Therefore, considering the effect of increased mean temperature producing a longer growing season for most species, the effect is an increased risk of frost damage in the future.

Seasonal changes in rainfall

Many regional climate models (RCM) projections suggest greater year to year variability in seasonal rainfall, so that both drier summers and wetter winters will occur more frequently. Taken over a thirty year climate period, the result is a mean increase in MD (Figure 9) calculated from projected climate variables, which suggests an increase in the frequency of dry summers for all emissions scenarios, to a lesser or greater degree. The change in frequency of dry summer events has been calculated for Wales from C4I data published by Met Eareann in Ireland. The simulated daily meteorological variables were used to calculate MD on a daily basis. MDs were accumulated annually and summarised on a decadal basis. A sample of 4 decadal periods, 2 from the climatic baseline period, and one for the 2020s and 2050s, are presented in Figure 10. They show the frequency of MD in the decade of the 2020s to be similar to the 1990s, and a higher frequency of dry summers than in the baseline period are projected for the 2050s for both the IPCC B1 and A2 emissions scenarios.

Figure 10 Simulated decadal frequency of dry summers (MD>=200mm) for 2 decades in the climate baseline period, and 2 decades in the future for IPCC emissions scenarios A2 (Medium-High) and B1 (Medium-Low). Data courtesy of C4I, Met Eareann, Dublin



In addition to more dry summers, the indications are that UK forests will experience much wetter winters. This will have a serious impact on soil wetness and exacerbate summer water availability. Wetter soils will cause shallower rooting, reducing the anchorage of trees in winter gales and consequently tree stability, so exacerbating the potential for windblow. The future wind projections are rather uncertain, although UKCIP reports suggest that the frequency and intensity of winter gales will increase. Windthrow may become a much more serious impact in the windy climate of the UK. This will require greater attention in planning to manage the increase in the risk of windthrow as a result of intervention. As a result, the exposure limit for productive coniferous stands in the UK may need to be revised.

1.3.2 Changing productive species suitability

General

The changing suitability of productive tree species in future climates are projections developed through the application of the model Ecological Site Classification (Broadmeadow and Ray, 2005). Figure 11 provides a regional projection of change in suitability for 5 species in the 2050 and 2080 climates for Low and High emission scenarios. The bars represent the potential suitability of the woodland area for the given species. This does not mean that a species occurs in the woodland area, but its suitability has been tested for the woodland sites in the region, for the baseline and future climate projections.

Beech

The natural range of beech (*Fagus sylvatica*) extends across southern England, through France and Germany to central Poland and northwards again to southern Sweden. The species is found at higher elevation as far south as the Pyrenees and the mountains bordering the Mediterranean, and as far east as mainland Greece. In England, it is particularly associated with chalk and limestone geologies, but also occurs on sands and loams that provide deep rooting and adequate moisture reserves. The species grows well up to an AT of approximately 3000 day-degrees, but is less tolerant of high MD, as evidenced by drought stress in dry summers (a MD of 240 mm is probably the upper limit for suitable). The warmer and drier climate predicted in southeast England is likely to become unsuitable for beech due to high MD, particularly for the 2080 High emissions scenario. Except for the 2080 High emissions scenario, both east and west Scotland, Wales, and northern England may be a part of Britain where beech suitability increases. In the west Midlands, and western peninsula of England beech suitability is likely to decline, therefore becoming unsuited to the projected climate of a 2080 High emissions scenario.

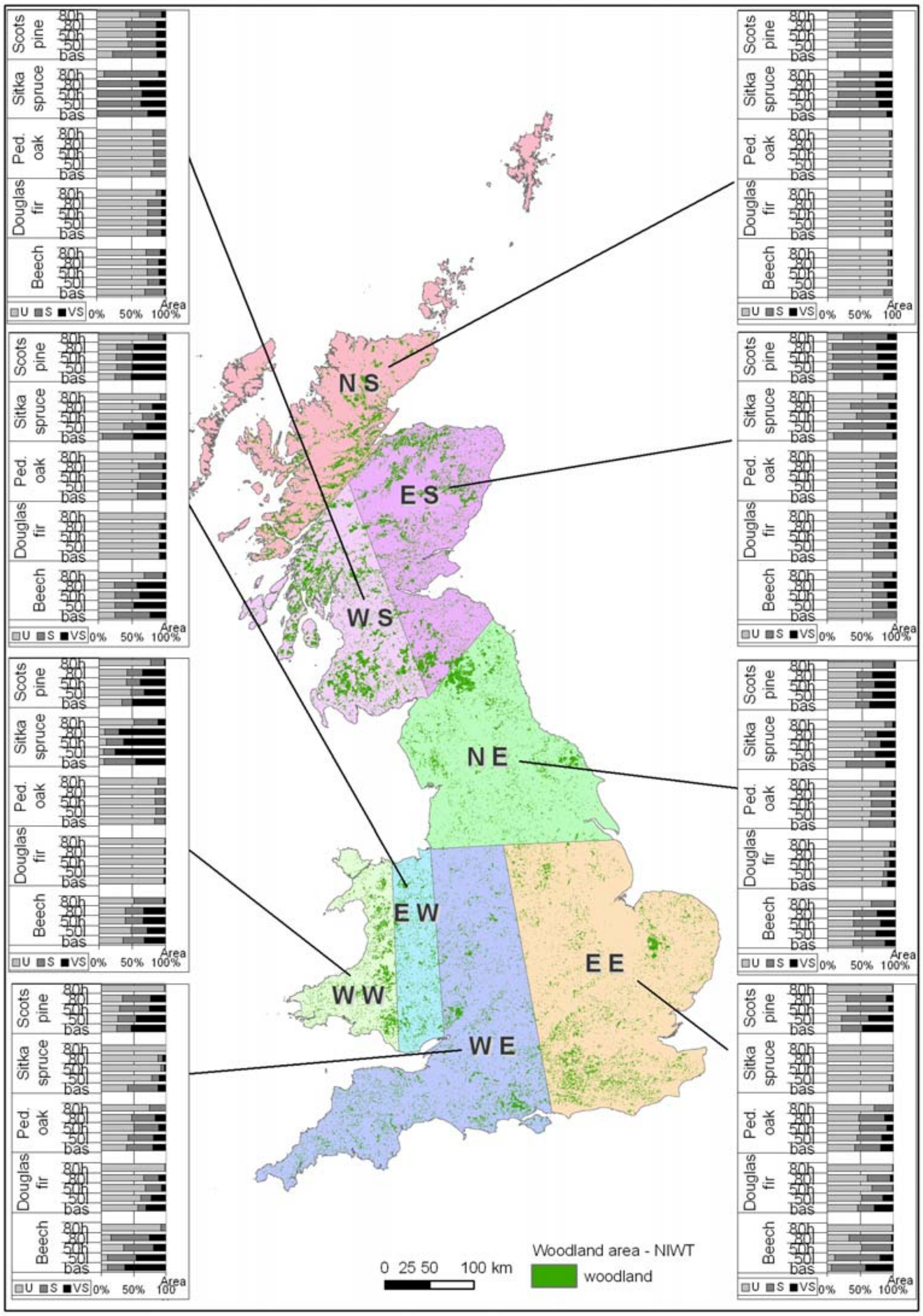
Douglas fir

Douglas fir (*Pseudotsuga menziesii*) occurs along almost the entire length of the western mountain ranges of North America from southern British Columbia to New Mexico. The seed sources of Douglas fir grown commercially in Britain, from Oregon and Washington, are adapted to higher summer temperatures and more severe moisture deficits than currently occur in Britain. The species will therefore tolerate the predicted warmer and drier climate remaining suitable in most of southern and eastern England and very suitable in western England and Wales, except for the 2080 High emission scenario. The climate is predicted to become more suitable for Douglas fir throughout Scotland, particularly in the east.

Pedunculate oak

The natural distribution of Pedunculate oak (*Quercus robur*) is from the Atlantic in the west to continental central Russia in the east. The southern extent of its natural range is northern Spain and Portugal (38°N), although it has been planted further south in the Mediterranean region. To the north, the species is found naturally in southern areas of Scandinavia (about 61°N) in southern Norway and Sweden. It is considered a more continental species than sessile oak (*Quercus petraea*), and tolerates rich heavy soils and a fluctuating water table, whereas sessile oak is more suitable on freely draining soils.

Figure 11 Suitability of 5 tree species, described as the proportion of the current woodland area that is unsuitable (U), suitable (S) or very suitable (VS) for that species in 8 regions of Britain, and simulated for the baseline climate (bas), and the future climate scenarios 2050 Low (50l), 2050 High (50h), 2080 Low (80l) and 2080 High (80h)



Sitka spruce

Sitka spruce (*Picea sitchensis*) is a native of the moist oceanic climate of the Pacific Northwest, extending from Alaska to northern California in a narrow coastal strip. In the climate of the late 20th century it was best suited to the western regions of Britain. Two main provenances, from the Queen Charlotte Islands (QCI) and Washington are planted according to climatic warmth, respectively in the northwest and southwest of Britain. It is regarded as Unsuitable within the drier northeast, East Midlands and the southeastern counties of England, where the moisture deficit exceeds about 180 mm. The extension of a warm dry climate westwards across central and southern England is likely to make the currently Suitable areas of the West Midlands and southwest England Unsuitable by the 2050s. In the southwest peninsula and west Wales, the AT increase is substantial whereas the MD increase is marginal, and here Sitka spruce should remain at least Suitable. In the cooler uplands of Scotland and northern England, land currently Suitable for Sitka spruce will become Very Suitable by the 2080s, as a result of the increase in AT and a decrease in MD. The temptation may be to plant the Washington provenance in areas where the Queen Charlotte Islands provenance is currently recommended, but the incidence of spring and autumn frost damage is likely to continue to be a major constraint.

Scots pine

This is the most extensive species in the genus, straddling an east west distance of about 14,000 km, from Scotland and Spain in the west to Kamchatka in the east. The north south range extends across about 3000 km, from northern Norway to the Sierra Nevada in Spain (Anon, 2000b). The species is also highly tolerant of site types, growing at sea level in sand dunes, at the tree line, and in bogs, on podzolised mineral soils and planted on cultivated soils. The species tolerates a moderate amount of drought of up to 2 months without summer rain, and in climates with as little as 200 mm of rainfall. However, a regular supply of summer rainfall is required for Scots pine to remain a productive species in Britain. The ESC suitability model shows that Scots pine remains suitable as a productive species in Scotland for most climate scenarios, but becomes unsuitable in England and Wales in the 2080 High emissions scenario.

1.3.3 Timber Quality

Site selection

A key factor in maintaining the quality of timber is to choose, wherever possible, the species or provenance well suited to the site type. In Sitka spruce, during dry summers water stress on soils with limited moisture retention can result in cracking and ring shake in mature trees. Conversely, Scots pine can produce poor form and lower timber quality because of forking and heavy branching, on sites that are too wet, usually where winter water-logging is a problem. Although sites in eastern areas of the UK, and sites in south and eastern Wales will have a greater risk of drought induced cracking in Sitka spruce, the problem may occur in other parts of the UK in the future. In the current climate, a 1 in 40 year drought (2 dry months) might be considered the limit of risk for a Sitka spruce site. However, in the future, a shift in the seasonal distribution of rainfall is predicted, and 2 dry months will occur more frequently in the UK.

Frost and winter cold

As the winter climate becomes milder over most of the UK, some species may not enter dormancy until late in the winter, and the degree of winter hardening may be reduced. For the main conifer species (Sitka spruce, Norway spruce, Scots pine, Japanese larch, European larch, Douglas fir) day-length (photoperiod) is the critical factor which triggers the onset of dormancy. This is a function of provenance with northerly provenances entering dormancy earlier. With milder winters it will still be important to pay careful attention to provenance choice and use material that is not at risk from autumn frosts.

The time of flushing in the spring is controlled by temperature and photoperiod and there is less variation between provenances. Milder winters will encourage earlier flushing and make trees vulnerable to late spring frosts. Knowledge of the variation in temperature at a specific location and the correct species/provenance choice will be important for minimising the impact of any frost damage.

Many tree species are able to take advantage of warm late summer and autumn periods by producing lammas growth beyond the terminal bud set at the end of the main part of the growing season. Tender shoots formed in this way are especially vulnerable to early autumn frost, with damage leading to stem forking. Additionally, the lammas apical shoots set a second whorl on the stem leading to increased knottiness in sawn timber.

Growth rate

The most important climatic variable for plant growth is temperature, and when water and nutrients are not limiting, most species will produce increased growth (height or diameter or both) in warmer growing seasons. It has been suggested that the rising CO_2 concentrations and climate warming will result in an increase in the general yield productivity by $2\ m^3\ ha^{-1}\ yr^{-1}$ for most species (e.g. from YC 6 to YC 8 for oak; from YC 14 to YC 16 for Sitka spruce).

Table 2. Comparison of Sitka spruce timber quality properties with yield class

		Yield Class		
Property	**Unit**	**14**	**16**	**18**
Average wood density (12% moisture content)	kg/m3	424.9	421.6	419.6
Average between whorl spacing	m	0.45	0.50	0.55
Average knot size for whorl with biggest branches	cm	3.40	3.65	3.90
Knot surface area ratio on outside of logs	none	0.01	0.01	0.01

With increasing growth rate, there will be changes in the wood properties of importance for timber performance. Table 2 shows the change in four important criteria affecting timber strength as the yield class increases for Sitka spruce (holding site and tree spacing factors constant) as predicted by the FR timber quality model (A. Achim, personal communication). For a change of 1 yield class (e.g. 14 to 16) the model predicts a reduction in wood density by between 0.5-0.7%, an increase in whorl spacing of around 10%, a 7% increase in knot size and no change in the knot area ratio. Interpreting these results in Table 2 using predictions of Maun (1992) suggests that due to climate change an increase in the growth rate of Sitka spruce of $2\ m^3\ ha^{-1}\ yr^{-1}$ will have no impact on the stress-graded batten recovery of Sitka spruce in the UK.

Although conifers such as the spruces and firs tend to have reduced wood density with increased growth rate, the pines, larches and Douglas fir show little or no reduction in wood density with faster growth. Therefore, for these species there is also likely to be no change in the timber performance with increased growth rates resulting from climate change.

Stem form

Stem form (straightness and taper) is a phenotypic attribute described as a function of the genotype combined with the biophysical factors of a site (environment). The British wind climate has an important influence on the loss of leaders during strong storms. Leader loss leads to crooked stems as one of the side-branches takes over apical dominance from the lost leader. This poorer stem form in turn leads to a lower recovery of desirable straight ‘green’ logs for construction grade timber. However, with time, trees recover straightness as the initial bend following leader loss is subsumed within the tree and, therefore, increased rotation length can be an important factor in improving tree form. Background wind loading can cause coniferous trees to produce compression wood and broadleaved trees to produce tension wood. Both these types of wood lead to increased difficulties in processing and poorer performance in service and their incidence could rise in a windier climate.

1.3.4 Native Woodland communities

General

Recent policy in each of the devolved countries has sought to increase the area of woodland comprised of ‘native’ species. Seven native woodland types are recognised by the UK Biodiversity Action Plan (Anon, 1995). The impact of climate change on each of these is summarised below:

Lowland mixed deciduous woodland

This woodland type covers a broad range of species and woodland types on heavier soils. The majority of native tree species will persist, although there will clearly be differential effects of climate change resulting in changing competitive advantage and a shift in species composition. In particular, sycamore and beech may tend to increase at the expense of oak and ash (Ray, 2008a). Bramble, nettle and other ‘rank’ vegetation may become more dominant on the heavier, rich soils that are characteristic of the habitat, at the expense of forbs and grasses. Although it is impossible to be precise, the habitat is likely to continue as a functional habitat across the United Kingdom, but the woodland community will change. The greatest threat to the habitat, in common with other habitats, probably comes from the potential impacts of pest and disease outbreaks, particularly where species diversity is limited, and possibly from fire, as public access increases in a warmer and drier summer climate.

Lowland beech and yew woodland

The impacts of drought on beech are well documented (Mountford and Peterken, 2003) and a number of studies (Berry et al., 2002; Broadmeadow and Ray, 2005; Harrison et al., 2006) have suggested that the species will struggle for climate space, or as a commercially viable species. However, the natural distribution of the species coupled to more recent modelling results suggest that beech and yew will persist across southern England. Soil type, aspect, slope and soil depth will be key determinants of beech survival. Although the individual species of tree are likely to persist as climate change progresses, beech will be challenged on some sites, particularly those with free-draining shallow soil profiles. Ash and, in time, oak will colonise and the nature of the woodland community will change. The woodland type will also extend beyond its naturally occurring range (Wesche et al., 2006).

Upland mixed ashwood

There is little evidence to suggest that upland ashwoods will be negatively impacted by climate change with the main species (ash, hazel, oak, birch) highly likely to persist in the wetter north and west where the habitat occurs. However, the species composition may change, suggesting that the northward movement of small-leafed lime may be a possibility. (Ray, 2008a) highlights the particular importance of the habitat in Wales (25% of the semi-natural woodland area) and concludes that the habitat, in both Wales and Scotland (Ray, 2008b) may show slower changes in species composition than other habitats because of the ability of ash to regenerate in dense shade.

Upland oakwood

The tree species components are unlikely to be affected by climate change as the woodland type has a distribution restricted to high rainfall areas. However, the community is highly valued for its fern, bryophyte and lichen flora which are highly sensitive to changes in rainfall and humidity. Ray (2008a) also notes the possibility that more frequent disturbance events coupled to the changing climate may allow other species such as birch, hazel and rowan to colonise Atlantic oakwoods. Of particular concern in this context is the potential for beech to colonise upland oakwoods with the deeper shade cast by the species impacting negatively on the ground and epiphytic flora.

Wet woodland

The persistence of wet woodland will depend on local factors rather than regional climate change. In this context, Ray (2008a&b) highlights the role that wet and riparian woodland might play in flood risk management and the maintenance of freshwater temperature to protect fisheries. The extent of the habitat may therefore increase as a response to climate change. In southern England, the increasing frequency and severity of summer drought represents a threat to the habitat, but this may be countered by increased winter rainfall maintaining ground water supplies through the early part of the summer. If individual sites do become drier, ash may colonise at the expense of alder, the dominant species of many sites. Ray (2008a&b) suggests that water supply is unlikely to limit the habitat in Scotland and Wales, and that wet woodland might expand into upland mires and flushes as a result of changes in climate and land management. The greater fluctuations in water levels that would be expected to result from climate change could enhance the risk of significant dieback of alder through Phytophthora infection (Lonsdale and Gibbs, 2002).

Native pine woodlands

The persistence of the principal species of tree, Scots pine, is unlikely to be affected by climate change. However, the composition of the ground flora is likely to be affected with plant communities associated with the drier sub-communities of the east and central Highlands favoured (Ray, 2008a). There may also be colonisation by other tree and shrub species (e.g. oak, birch, rowan) and the appearance of flora not generally associated with native pinewoods. Disturbance through fire may represent an enhanced risk, particularly in woodlands used extensively for recreation. Where grazing levels permit, there may be colonisation by scrub (juniper, and montane willows), and ultimately pine, above the current tree line.

Upland birchwoods

The persistence of birch in upland birchwood habitats is unlikely to be challenged by climate change as currently projected. However, Ray (2008a) notes the recent planting and limited tree species diversity that might render these woodlands vulnerable to pest/disease impacts or the effects of extreme climatic events. On drier sites, silver birch may become more competitive at the expense of downy birch.

1.3.5 Biotic impacts

Invertebrates

Climate change will influence the distribution and abundance of many pests and pathogens. A reasonable assessment of impact can be made based on the present knowledge of key pests and pathogens and the role played by environmental factors in their life cycle and population dynamics. For insect pests, one of the more general predictions for temperate regions of the northern hemisphere is that under climate change, ranges are likely to extend northwards and to higher elevations.

For insects, simple responses to rising average temperatures include an increase in the development rate and in the number of generations per year. For example, semi-voltine insects may become uni-voltine, whereas those with a uni-voltine life-cycle have the potential to become multi-voltine. Other direct effects include the influence of winter temperatures on survival and of rainfall on mortality of vulnerable feeding stages. Examples of indirect effects include loss of phenological synchrony due to differential effects of temperature on host and insect development and the effects of drought or waterlogging on tree susceptibility. A summary of impacts is provided in Table 3.

Pathogens

Foliar pathogens which infect the leaves and needles of trees are likely to be most directly affected by climatic change and already show marked fluctuations each year depending on weather conditions. Overall however, there is a high probability that many pests and diseases will become more prevalent in Scotland under a climate with milder winters, and more frequent droughty summers. Milder conditions are particularly likely to present pathogens with longer periods of activity, closer to their optimum temperature for growth, while the increased frequency of drought will stress tree species not well suited to the site conditions, which in turn will encourage pest and pathogenic attack. The major impacts are summarized in Table 4.

Table 3 Summary of potential climate change impacts on woodland invertebrate pests (after Broadmeadow and Ray 2005). Current status is given as a subjective assessment of the impact of a given pest on tree mortality, defoliation and amenity value, modified by its geographical extent. Key for current status: S=serious; M=minor; A=generally absent; T=affects timber value.

Insect species	Climatic driver	Current	Likely trend	Comments
Elatobium abietinum	Milder winters	S		Commercial spruce crops only.
Hylobius abietis	Hotter summers	S		Small felling coupes in CCF may moderate increase in activity.
Dendroctonus micans	Summer drought	S	(or ↓)	Principal predator may benefit more from a warmer climate.
Ips acuminatus	Summer drought	M		Currently a secondary agent; may be primary agent in drought conditions.
Ips cembrae	Summer drought	A		Currently limited to Scottish borders; could cause serious damage to larch.
Agrilus pannonicus	Rising temperature	M		May be associated with oak decline; may be primary or secondary agent.
Platypus cylindricus	-	T	-	Secondary pest affecting timber value; more impact if tree mortality increases.
Longhorn beetles	Summer drought	T		Affect dead trees; under extreme drought may attack living trees.
Tortrix and winter moth	Rising temperature	M	↓	Climate warming could affect synchrony between emergence and budburst.
Cameraria ohridella	Hotter summers	M		Hotter summers will increase the number of generations per year and hence the amount of damage / a warmer climate will extend geographic range northward.
Agrilus planipennis	Hotter summers	A		Hotter summers will increase the number of generations per year and hence the amount of damage / a warmer climate will extend geographic range northward. Currently absent from UK but recent exotic pest in USA and Canada (from China).
Anoplophora glabripennis	Rising temperature	A		If introduced into woodland environment would benefit from climate warming. Absent from UK, but has been intercepted in imported wood packaging materials.
Ips typographus	Summer drought	A		Summer drought likely to increase tree susceptibility to the pest and to increase the number of generations. Absent from UK, but intercepted frequently in wood imports.

Table 4 Summary of potential impacts of climate change on fungal diseases of trees (after Broadmeadow and Ray, 2005)

Disorder/pathogen	Predicted effect of climate change on prevalence
Phytophthora root diseases	Likely to become more prevalent and damaging, especially those which have higher growth temperature optima (28-30°C) such as *P. cinnamomi.*
Oak and beech decline	The incidence of these complex disorders is likely to increase because of the predicted increase in the frequency and severity of summer drought stress.
Damage to timber caused by blue stain fungi	Will increase as the bark beetle vectors are likely to favoured by longer, hotter summers (more generations per year). The causal agents also have growth temperature optima of 25°C and above.
Foliar diseases	The incidence of most foliar diseases will increase if climate change leads to wetter, warmer springs. This would apply to needle pathogens such as *Dothistroma* and shoot and foliar pathogens such as *Malamspora*, *Venturia* and *Marssonia*. However, the three foliar pathogens identified could become less prevalent as a result of reduced rainfall and lower relative humidity in summer. The planting of more Corsican pine would also contribute to an increased incidence of *Dothistroma septosporum* if, as predicted, climate change increases its productive range.
Brunchorstia infection of Corsican pine	Likely to become less prevalent as a result of hotter, drier summers. This would have the effect of expanding the potential range of Corsican pine northwards and westwards.
Dutch elm disease	Higher summer temperatures likely to encourage more Dutch elm disease. Disease development is correlated with high temperatures, and activity of vector beetles is also likely to increase.
Latent invaders or diseases	Disorders such as *Hypoxylon* (strip cankers) and *Cryptostroma* (sooty bark disease) are likely to be expressed more frequently because of increases in summer temperatures. For example, each consecutive summer month that has a mean maximum temperature of 23°C increases the likelihood of damaging outbreaks of sooty bark disease in the UK.
Facultative pathogens	Climatic changes will encourage activity of facultative pathogens if trees are under stress.

Deer

Long-term studies of the impacts of annual weather variability on deer (Irvine et al., 2007) show that in upland areas, milder winters and warmer and wetter spring weather has influenced earlier calving, faster juvenile growth rates and increased juvenile and adult survival, leading to higher population growth rates. In addition, the cohorts of calves born in warm springs appear to be favoured throughout their lives, with more animals surviving there first winter, maturing and calving earlier and also have longer life spans (Albon et al., 1987). As well as red deer, there is evidence that the abundance of other species is increasing, with the largest increases likely in Muntjac and Sika deer (Irvine et al., 2007).

1.3.6 Impact monitoring guidance

Currently, 6 important forestry-related monitoring networks and reporting protocols are in place in the UK. These are:

1. Indicators of climate change in the UK developed within the UK Environmental Change Network - http://www.ecn.ac.uk/iccuk/. The indicator of the health of beech trees in Britain was discontinued in 2002.

2. Environmental Change Network (http://www.ecn.ac.uk/aboutecn.htm) is the UK's long-term integrated environmental monitoring and research programme, started in 1992 and led by CEH on behalf of the Natural Environment Research Council (NERC) and supported by all of the UK government agencies. Monitoring of climate change, water quality and biodiversity are providing environmental indicators of the effects and impacts of climate change. Seven of the 29 sites are forest, and these have shown a significant warming trend of 0.9°C in the average annual temperature, and an increase in the total amount of rainfall, over the 15 year period.

3. UK Phenology Network (http://www.naturescalendar.org.uk/) is supported by the Woodland Trust and the Centre for Ecology and Hydrology, and uses a large network of volunteers throughout the UK to observe and record the onset of natural events. There are a few events that have been monitored for a long period (up to 2 centuries), but the application of the work to impact studies is limited by a relatively short duration of wide-spread records.

4. Countryside Survey (http://www.countrysidesurvey.org.uk/index.html) is a large and complete survey of vegetation and land-cover in the UK. It provides snapshots of the extent of change in the land-cover between survey points, which have been carried out at regular intervals since 1978. Land-cover maps were produced from remote sensing imagery in 1990, 2000, and the 3rd will shortly be available for 2007. The field survey part of the data allows a comparison of samples from 600 1 km squares for different times since 1978. The field survey includes soil and vegetation assessments and so provides a useful national assessment of changes in certain physical and biological components of the UK countryside though time.

5. Forest Health Survey/Forest Condition Survey was established in 1986 (http://www.forestresearch.gov.uk/fr/INFD-5W3M9C) to assess the crown condition of five different species: oak, beech, Scots pine, Sitka spruce and Norway spruce. Crown condition and masting was assessed on about 350 sites between 1986 and 2006, when the survey was suspended at the end of the ICP forest survey.

6. A National Forest Inventory has been developed from earlier National Inventory of Forest and Tree surveys in the Britain (NIWT). A number of forest surveys have been undertaken in Britain over the last 80 years. The last survey occurred in 2002, and the new inventory survey will be implemented every 5 years. The inventory examines the extent of all woodland with and interpretation of forest type. It also samples about 0.5% of the forest resource for structural and composition elements.

1.3.7 Impact management guidance

The devolved administrations of the UK are currently engaged in developing impact information, guidance and support for forestry in their countries. Current information and guidance is based upon the projected climate impacts published by UKCIP in 2002 (Hulme et al., 2002). However, in June 2009 the UK Government, through UKCIP, published revised projections of climate change in the UK. New information includes probabilistic climate change projections based on an ensemble of RCM and General Circulation Model (GCM) outputs. The information will help in understanding the degree of likelihood of certain change thresholds. This will improve our understanding of when impacts will occur and therefore when adaptation must begin. A daily time step weather simulator is now available and will help scientists to determine the extent and frequency of extreme events that often cause abiotic damage to trees.

The new climate change projections will be used to extend a number of management tools to help forest managers plan and manage climate-related impacts. These will help managers continue to adapt forest management to maintain resilient forests and woodlands and provide guidance on when to adapt in a timely manner to lessen the impacts in the future.

Current information on climate change impacts is shown below. In addition, the Forestry Commission Bulletin 125 “Climate Change: Impacts on UK Forests” is a primary source of information about the likely impacts. Bulletin 125 will be superseded later in 2009 with the publication of the “National Assessment of UK Forestry and Climate Change” (Forestry Commission, 2009). Climate change policy is currently being clarified in the UK Forestry Standard, and overarching guidance on managing forests in a changing climate is incorporated in the Climate Change Guidelines (currently available for public consultation) (Anon., 2009e).

At the operational level, the Forestry Commission has a number of decision support tools which are being extended to help manage impacts and plan adaptation. These tools include:

Ecological Site Classification (ESC) www.forestry.gsi.gov.uk/esc

ForestGALES www.forestry.gsi.gov.uk/forestgales

Establishment Management Information System (EMIS)
http://www.forestresearch.gov.uk/fr/HCOU-4U4JE4

Conifer Timber Quality Model http://www.forestry.gov.uk/fr/HCOU-4U4JEQ

Broad level forest management guidance related to climate change has been written for Scotland and Wales. A Research Note is currently being developed for England. Recent guidance on climate change impacts include:

Forestry Commission Research Information Note 69.

http://www.forestresearch.gov.uk/pdf/fcin069.pdf/$FILE/fcin069.pdf

Web page resources on initial impact and adaptation guidance in Scotland and also Forestry Commission Scotland Research Note 001.

http://www.forestresearch.gov.uk/fr/INFD-79RD4S

Web page resources on initial impact and adaptation guidance in Wales and also Forestry Commission Wales Research Note 001.

http://www.forestresearch.gov.uk/fr/INFD-7FXBYQ

2. Adaptation

2.1. Vulnerability of forests and forestry

From the 1950s onwards, British foresters became increasingly aware of the potential vulnerability of the new plantation forests to the impacts of climatic factors and particularly wind damage. Thus there were major storms in 1953 (north-east Scotland), 1968 (central and south Scotland), 1976 (Wales and central England), 1987 (south England) and 1998 (Wales and south-west England), all of which caused severe damage to forests in particular regions and disruption to wood supply chains. In addition, plantations on more exposed sites were at risk of ‘endemic’ windthrow once the trees had reached the vulnerable height of 10-12 m (Miller, 1985).

The need to be able to classify sites and stands in terms of their vulnerability to windthrow led to the development of a ‘Windthrow Hazard Classification’ (WHC) (Miller, 1985) whereby sites were graded from I-VI in terms of increasing wind risk. Silvicultural practice was adapted to the guidance provided by this system in that thinning was normally confined to WHC classes I-III and many stands in the higher classes were managed under a non-thin regime which was considered less risky for stand stability (Savill, 1983). The system was a deterministic classification which assumed that the risk of windthrow was driven by a combination of site and wind climate and made no allowance for effects of management, for example the higher wind stability found in self-thinning mixtures of Sitka spruce and pines. This lack of flexibility resulted in the development of the wind risk model ForestGALES (Gardiner et al., 2004) which provides a probabilistic approach to the prediction of wind damage including the possibility of predicting extreme winds (Quine, 2000). The importance of the latter was shown by the impacts of the 1987 storm which caused severe damage to forests and woods in areas of the UK which would have been considered a low risk under the WHC system.

By contrast with the systems for predicting vulnerability to wind damage, there have been no national systems developed and applied to assess the impacts of other abiotic or biotic factors. The effects of frost are known to be species and site dependent (Redfern and Hendry, 2002), but guidance is based on general principles such as replacing Sitka spruce by the later flushing, and thus less frost sensitive, Norway spruce (*Picea abies*) in low lying ground at risk from spring frost. Two major droughts, in 1976 and 2003, have affected British forests and have caused dieback and death of vulnerable species (e.g. beech and birch in 1976; Peterken, 1996) or loss of timber quality through drought crack (Sitka spruce in 2003; Ray, 2008a). The latter paper identified eastern Scotland as being an area where forests could be particularly vulnerable to the impacts of summer drought, and guidance is available which grades the soils low, medium or high in terms of their susceptibility to drought and makes recommendations on appropriate species and/or native woodland communities. Although country guidance is available via the ESC system to assess the vulnerability of species to climate change (Ray et al., 2002), this guidance has still be made operational at a forest planning level.

A number of pests and pathogens currently influence the health of British forests and hence their vulnerability to climate change. For instance, the fungus red band needle blight (*Dothistroma septosporum*) has caused high levels of needle loss and tree death in pine plantations, particularly of Corsican pine (*Pinus nigra* var. *laricio*), such that there is presently a moratorium on planting this species (Brown and Webber, 2008). The increased incidence of this disease in British forests may well be a consequence of the warmer and wetter springs that have occurred as part of global warming, mediated by a silvicultural history of delayed or no thinning. The American grey squirrel (*Sciurus carolinensis*) is an introduced species which has become established throughout lowland Britain and which can cause extensive bark stripping damage in woodlands, particularly to thin barked species such as beech and sycamore (*Acer pseudoplatanus*) (Mayle et al., 2007; Rayden and Savill, 2004). Other studies have shown that death of mature trees caused by drought can result in increased squirrel damage to regenerating beech (Mountford, 2006). Similar interactions between climate change, species vulnerability and the impact of pests and pathogens can be expected in the future.

At time of writing, no systematic assessment of the vulnerability of British forests to climate change has been undertaken, although many prerequisites for such an exercise are available. The combination of ForestGALES and ESC provide a basis for evaluating the risks from wind damage and any potential changes in growth or species suitability as a consequence of projected changes. At least for the Forestry Commission estate, there is spatial information on species distribution and age classes which would allow evaluation of different sensitivity over time. Similar information should be available in due course for private woodlands through the new National Inventory. However, the lack of comprehensive soils data for many British forests limits the ability to carry out a national assessment, and instead the best way forward seems to be to identify areas that may be particular sensitive to projected changes and concentrate a vulnerability assessment in such locations (e.g. Ray, 2008a).

In the absence of a national assessment, we have attempted to rank the vulnerability of British forests on a low, medium, or high scale using information on the age structure of the forests at the beginning of the century (Table II.A.). This shows almost all the conifer forest to be less than 50 years of age, whereas over half the broadleaves are more than 50 years old, with an appreciable amount being over 100 years.

Table II.A. Area ('000 ha) of conifer and broadleaved high forest by four age class groups and percentage distribution (parentheses) in 2000 (adapted from Mason, 2007).

Woodland type	**Age class (years)**			
	<15	**15-50**	**51-100**	**>100**
Conifers	219.5 (16)	1067.8 (77)	73.0 (5)	19.1 (1)
Broadleaves	57.9 (7)	269.6 (31)	376.9 (43)	176.3 (20)

Our ranking distinguishes between conifer and broadleaved forests because of differences in both age structure (younger conifers, older broadleaves) and regional distribution (broadleaves found in southern lowland zones, conifers in upland oceanic zones). We have assumed 'business-as-usual' forest management for the two types which implies limited and small scale management for broadleaves on long rotations (100 years or more), as against intensive management of conifers based either on clear-felling on 40-50 year rotations or on continuous cover forestry with 'rotations' of perhaps 70-80 years (Mason, 2007).

Table II.B. Assessment of the potential vulnerability of British forest types to projected climate change for three time periods assuming ‘business-as-usual’ forest management (see text for details).

Forest type	Period	Vulnerability	Notes
Conifers	Until 2020	Low (Medium)	Assumes many stands reach maturity, are felled, and replanted with better site adapted species if necessary. Higher vulnerability if storm frequency and intensity increases.
	2020-2050	Medium	More sites become marginal (e.g. increased drought risk) and require species changes
	2050-2100	Medium (High)	Ranking depends upon the magnitude of change and the extent to which sensitive sites were identified and remedial action taken during first part of century.
Broadleaves	Until 2020	Medium	Older stands become increasingly vulnerable to disturbance/death from drought, pests, and diseases.
	2020-2050	Medium-High	As 2020, but increasing need for species and provenance changes.
	2050-2100	High	Many stands in critical condition because of lack of management and/or age.

This evaluation is clearly superficial in that little allowance is made for regional variation or the effects of country policies. However, it does indicate a general trend that older and less managed stands are those which seem less resistant to climate change, while younger plantation stands have more flexibility and hence more resilience to future conditions (Nabuurs et al., 2007). In the following sections, we illustrate how management could be used to increase the adaptive capacity of British forests.

2.2 General adaptation strategy

UK government policy on adaptation is expressed through the mechanisms developed under the Climate Change Act (CCA) of 2008, which sets binding targets of reducing carbon emissions over a 1990 baseline of 26 per cent (for 2020) and 60 per cent (for 2050). Amongst the mechanisms relevant to adaptation are the requirements to carry out a UK wide Climate Change Risk Assessment (CCRA) every five years, and the establishment of an independent committee on climate change (www.theccc.org.uk). The functions of this committee include the creation of an ‘adaptation sub-committee’ which examines the CCRA and has oversight of the development of the first national adaptation programme for England due to be prepared by 2012.

Policies on adaptation are devolved to the four countries of the UK, but all are informed by the UK Climate Projections whose most recent findings (Anon., 2009d – a.k.a. UKCP09) were published in June 2009. In Scotland, a Climate Change Adaptation Framework is being prepared, and the second consultation document (Anon., 2009c) refers to the way in which Scottish forests are being adapted to climate change and notes (p. 22):

> ‘A key basis for risk planning and management of the [forestry] sector is diversification; from broadening the choice of genetic material, mixing tree species, to varying management systems and timing of operations. Increasing the functional connectivity of forest habitat networks should also help improve the resilience of woodland ecosystems to climate change.’

In Wales, a Climate Change Strategy is being developed which will cover adaptation measures and consultation on the content and direction of this strategy is in progress. Northern Ireland is also aiming to produce an adaptation plan whose recommendations will be aided by an existing report (Arkell et al., 2007) on preparing for climate change. This report highlights both threats (e.g. increasing risks from pests and forest fires) and opportunities (e.g. higher productivity of forests, greater opportunity for tree planting as part of a mitigation strategy) arising from climate change. In England, many actions to implement adaptation policy will be implemented at a regional level (there are 10 regions within the country) and these will be developing Regional Climate Change Partnerships.

In all countries of the UK, the way in which the forestry sector links with national adaptation strategy is through the forest polices of the different countries and the measures set in place to implement these. This aspect is considered in more detail in the following section.

2.3. Forest adaptation measures

2.3.1. Policies

In the Introduction to this report, we highlighted that in Scotland (Anon., 2006a), England (Anon., 2007), and Wales (Anon., 2009a), though not yet Northern Ireland, the forestry strategies each include sections dealing with the impact of climate change as a major theme or objective, and these are being developed further through specific plans for forestry in a specific country, as in Scotland (Anon., 2009b). Although all three policy documents cover adaptation, the degree of detail and prioritisation varies.

There are seven objectives listed in the Forestry Commission Scotland’s Climate Change Action plan for 2009-2011 (Anon., 2009b), one of which is:

- ‘adapting [Scottish forests] to climate change by planning and managing forests and woodlands in a way that minimizes future risks from climate, for example through the creation of forest habitat networks, and using different timber species, including hardwoods, or silvicultural systems (p.7).’

Four main areas of activity are proposed under the adaptation objective, namely: facilitating ecological adaptation (with 6 priorities for action); to consider the threats to forests from pests, diseases, and weather (4 priorities); silviculture and forest operations (3 priorities); and environmental protection (4 priorities).

The corresponding document for England is the 2008-2012 Delivery Plan for England’s Trees, Woods and Forests (Anon., 2008a), where three of the objectives supporting the climate change component of the strategy are relevant to adaptation. These are: increasing the resilience of trees and woodlands (5 areas of activity); increasing the role of trees and woodlands in adapting the rural landscape (2 areas); and enhancing the role of street trees and urban woodland in adapting the urban environment (3 areas).

‘Responding to climate change’ is identified as one of the four strategic themes of the Welsh woodlands strategy (Anon., 2009a), but the main outcome relevant to adaptation is located in the ‘foundation’ section of the strategy covering Welsh woodlands and trees. Outcome 2 in this section specifies that ‘woodland ecosystems are healthy and resilient’ and the supporting text emphasizes the need to diversify woodlands in Wales, particularly non-native plantations. Diversification is understood to involve the use of a wider range of species and the development of more mixed forests. This approach is also seen to be a means of reducing the potential risks from pests and diseases. Five actions will be taken to help deliver this outcome, namely: manage the public sector woodlands to increase their resilience, and use advice and incentives to encourage private woodland owners to do the same; review and improve the ability to deal with pests and diseases; develop guidance for diversifying plantation woodlands; provide guidance on improving genetic diversity; and develop a strategy for dealing with increasing numbers of deer and grey squirrels.

A review of the opportunities and challenges posed by climate change carried out for the Confederation of Forest Industries in the UK (Prebble, 2008), identified that forestry and trees could help society adapt to climate change through aspects such as protecting soils and biodiversity, and moderating temperatures in the urban environment. The need for better research to inform long-term forestry planning was highlighted since changes in the species planted and in the prevailing silvicultural systems could all influence the products harvested and affect the viability of the processing sector. However, it was recognised that changes in British forests needed to be set in a European context since forests in other countries might be more severely affected by climate change, which could provide opportunities for British growers and processors.

2.3.2. Management measures

At time of writing, there are no specific measures in place in either public or private forests to implement an agreed process of adaptation. Instead, there is general guidance available from documents such as the consultation draft of the Forest and Climate Change Guidelines (FCCG) (Anon., 2009e – see Introduction for details of the framework linking the UK Forestry Standard and the supporting guidelines). The FCCG lists 18 key points for forest managers to consider as part of a planned or anticipatory adaptation strategy (see Box 1).

Box 1: A list of the key points or Climate Change Guidelines (CCG) forest managers should consider as part of process of adapting their forests to projected climate change (from Anon., 2009e)

Forest Design and Planning
- **CCG14 - Aim to diversify age and species composition at the forest level**
- **CCG15 - Review species suitability (see below) over time in Forest Plans**
- **CCG16 - Consider alternatives to clearfell systems such as continuous cover where suitable sites and species combinations allow**
- **CCG17 - Aim to establish a range of stand structures and silvicultural approaches over time**
- **CCG18 - Develop contingency plans for wind, fire, pest and disease outbreaks, appropriate to scale of forest**
- **CCG19 - Consider projections of changes to rainfall patterns when specifying culvert and road design**

Adaptive Forest Management
- **CCG20 - Review rotation lengths in response to changing productivity and wind risk.**
- **CCG21 - Review planting seasons in response to changing conditions and establishment success and promote natural regeneration**
- **CCG22 - Consider augmenting natural regeneration through planting where species diversity and potential adaptability is likely to be limited**
- **CCG23 - Consider the susceptibility of forests to forest pests and pathogens and strategies for protection; review practice as further evidence becomes available**

Species Selection
- **CCG24 - Consult the relevant climate change guidance on species choice and the risks of new pests and pathogens when selecting species**
- **CCG25 - Diversify the range of species planted to meet management objectives wherever soil conditions and predicted climate allow**

- **CCG26 - Select planting material that is locally native and well adapted to the planting site, and consider supplementing this with a proportion of nonlocally native material to increase the resilience of woodlands to climate change**
- **CCG27 - In new native woodlands, consider a proportion of non-local native species; restrict choice to continental European origin and take advice from Joint Nature Conservation Committee and/or Forest Research**

Adaptation and Landscape Ecology

- **CCG28 - Avoid fragmenting existing priority habitats and consider the impacts of new woodland on the ecology of adjacent sites**
- **CCG29 - Improve the ecological connectivity of the landscape for woodland species by extending and linking woodland habitats**
- **CCG30 - Aim to control or remove populations of non-native species that are invasive and problematic from woodlands and their surroundings as opportunities to do so arise**
- **CCG31 - Take opportunities to extend existing semi-natural woodland**

These guidelines are supported by recommendations available in a number of documents including those reviewing the potential impacts of climate change on forestry in different countries of the UK (e.g. Ray et al., 2008), by the Actions proposed to support the delivery plan in England (Anon., 2008b) or an examination of possible adaptation strategies (Kirby et al., in press). In Table II.C., we examine how the measures noted in these documents relate to the categories of silvicultural and forest management response identified within the ECHOES action.

Table II.C. A comparison of the adaptation measures identified in a sample of recent UK documents against the categories of silvicultural and management measures defined in ECHOES. For the FCCG, we list the number of the guideline (see Box 1) against the category – note that a guideline can appear more than once. For the other three documents, we have scored the frequency of mention of a measure in the text as follows: '+++' = frequent mention; '++' = regular mention; '+' = occasional mention; '-' = no mention.

	Document listing possible adaptation measures				
Echoes category	**CCG (Anon., 2009e)**	**Ray et al., 2008**	**Anon., 2008b**	**Kirby et al., in press**	**Notes**
Forest regeneration, including species/ provenance/genotypes	14,15,21, 22,24,25, 26,27	+++	+++	+++	
Tending and thinning of stands, including silvicultural systems	16,17,20	++	++	++	The ECHOES category has been widened to include silvicultural systems
Harvesting	20	+	-	-	
Forest protection	18,23,24, 30	++	++	+++	
Management planning	17,18,20, 28,29,31	+	++	++	
Infrastructure and transport	19	-	-	-	
Nurseries and forest tree breeding	21,26,27	++	-	+	References are generally to nurseries rather than tree breeding
Higher level adaptation options in risk management and policy.	18	+	+++	+++	

The categories that are covered most often are forest regeneration, including species/provenance choice, forest protection, and management planning while aspects such as harvesting and infrastructure receive comparatively little attention. Given that one aspect identified as a key component of adaptation is an overall increase in management intervention in British forests (Kirby et al., in press), it may be necessary to give more emphasis to the thinning, harvesting and transport categories in future management guidance. Thus increasing the amount of thinning in British forests, possibly as part of a transformation to continuous cover forestry (Mason and Kerr, 2004), can be problematic on wetter soils because the amount of woody brash available to protect soils against machine damage is less under thinning regimes than under patch clear felling.

One other essential aspect of adaptation at the forest level is the need to ensure that the skills of the forest managers and work force are sufficient to diagnose stands or sites which are more sensitive to climate change and where adaptation measures should be urgently taken. The guidance that is available through projections such as UKCP09 (Anon., 2009d) and assessments of risk provided by ESC and other decision support tools (Ray, 2008a) will need to be validated at a stand or forest level by operational foresters. Training of the type currently being developed by the Forestry Commission for its own staff will need to be expanded to encompass parts of the sector if effective adaptation measures are to be put in place.

2.4 Research studies of adaptation

As yet there has been little systematic research in Britain on adaptation of silviculture or forest management to climate change. The knowledge that has been obtained is largely derived from studies of the potential impacts of projected changes on aspects such as species growth and survival (e.g. Ray et al., 2002) and then providing guidance on measures that might be taken to compensate for such changes. Such measures could include the use of more southerly provenances of both native species (Broadmeadow et al., 2005) and of major plantation conifers such as Sitka spruce (Samuel et al., 2007). The knowledge base to underpin such recommendations is supported by a long history of tree species and provenance trialling in Britain (Macdonald et al., 1957) informed by more recent detailed studies of species sensitivity to cold temperatures (e.g. studies on *Alnus rubra*, *Nothofagus* spp., and *Eucalyptus* spp. cited in Cannell et al., 1989). Hubert and Cottrell (2007) provide an overview of the role of genetic resources in helping forest managers adapt to climate change. They distinguish three strategies, namely: maintaining genetic variation by the use of natural regeneration; planting a mixture of provenances where local stock are admixed with more southern material expected to be better adapted to a future climate; and planting more southerly provenances or species. The preferred option will depend upon site and management objectives, but the last option of deliberately planting a more southerly provenance (or species) is thought to be particularly relevant in southern Britain where the English Channel and southern North Sea form a barrier to the natural spread of southern gene complexes.

By contrast, the guidance on desirable stand management practices such as greater use of mixed species stands or the conversion to continuous cover forestry is not based on as comprehensive research. While both these approaches can be considered to ‘spread the risk’ associated with single species plantation stands, the evidence that these will necessarily prove more resilient to climate change is lacking. The transformation of even-aged plantations to irregular structures can increase the risk of windthrow during the transformation phase (Mason and Kerr, 2004), while it is possible that heavier thinning to reduce canopy leaf area may be as effective in maintaining viable stands on sites of marginal soil moisture as trying to foster a mixed species stand. There is a need for better understanding of the interaction between stand management and vulnerability and how this may vary with region of the country, projected climate change, and site conditions. For instance, scenario modelling is currently underway using the ForestGALES model (Gardiner et al., 2004) to see how the windthrow risk to the Forestry Commission forests in Scotland will change if the frequency and/or intensity of severe gales were to increase.

As part of the UK Assessment of Forestry and Climate Change, a number of research priorities were identified which are relevant to the adaptation of British forests to climate change (Kirby et al., in press; Mason et al., in press). These are summarised in Box 2 below.

Box 2: A list of some of the most important research questions relevant to adaptation of British to climate change as identified in the UK Assessment of Forestry and Climate Change

1. Develop methodologies to help forest managers identify sites and stands most vulnerable to climate change;
2. Development of data-bases/knowledge on how different species are expected to respond to climate change (e.g. climate envelope modelling) matched by studies on how their populations and distributions are actually changing;
3. Improved understanding as to which environmental factors will become limiting for which species at a regional level;
4. Trialling of species that may be suitable for the current and projected British climate;
5. Improved understanding of how climate change factors will change disturbance regimes of wind, fire, pests and diseases;
6. Improve predictions of changes in wind climate and adapt existing wind risk models to predict vulnerability of more varied stand structures;
7. Adaptation of growth models developed for single species even-aged forestry to more diverse forest types and/or provision of more flexible models;
8. Improved understanding of appropriate decision-making methods– including methods of dealing with uncertainty and the integration of multiple societal values;

A number of new research initiatives have been established which may help provide answers to these questions. These include a new Forest Research programme on ‘Forestry Climate Change Adaptation Strategies’ (http://www.forestresearch.gov.uk/fr/INFD-7K9DDV) which has two main aims of:

- assessing the impacts of climate change on British forests and the opportunities for managing adaptation to it in multi-functional forestry,
- and to investigate how to increase adaptive capacity.

The intention is to seek to develop understanding of the factors influencing adaptive management in response to climate change by concentrating upon a number of case study sites distributed throughout the United Kingdom. Some of these case studies are already being developed as part of recently established EU projects such as:

- ForestClim (http://www.forestclim.eu/) which investigates forest management strategies in response to regional climate change impacts and where a case study forest is located in the Scottish Borders;
- Reinfforce (http://www.iefc.net/index.php?page=bdd/annuaire/annuaire_update.php?id_contact=1136381437) which examines adaptation to climate change impacts on Atlantic forests and which will involve establishment of new species trials in various parts of western Britain.
- Motive which focuses on the role of stand growth and other models in helping the development of adaptive forest management strategies in the light of climate change.

We envisage that the findings from the case studies will be helpful in supporting the final UK country report to Echoes at the end of this Action. For the meantime, we agree with the conclusions of Kirby et al. (in press) in their evaluation of adaptation for the UK Assessment of Forestry and Climate Change, namely that:

> ‘Adaptation needs to be an ongoing process, with continuing testing of orthodoxies and re-calibration of experience, which have often been based on a static view of the natural and social environments, a focus on preservation of past structures, communities, systems or markets. Equally, views on climate change and its impacts will evolve. Incentives, controls, education and knowledge transfer need to be kept in line with progress on adaptive measures. Ultimately, it will be case of accepting the impacts and changes we can make little difference to; concentrating effort on those which can be changed; and having the wisdom to separate the two.’

3. Mitigation

The role of forestry to mitigate climate change is especially important in countries which have a substantial potential for forestry development (Krcmar et al., 2003; Van Kooten, 2004; Nijnik and Bizikova, 2008). Therefore, carbon inventory and monitoring, the economics of afforestation and forest management, social acceptability of various carbon sequestration options, existing challenges and opportunities of woodland development on high carbon soils, using wood in renewable energy projects, and in wood products, are highly pertinent in the United Kingdom. Carbon sequestration through afforestation is commonly considered as clean (it may concurrently provide other ecosystem services), proven (the country has a legacy of tree-growing), effective in the short-term, providing almost immediate effect after tree-planting, cheap (cost-efficient), and as a less resource and energy consuming climate policy measure. It can be incorporated in multifunctional forest use to simultaneously enlarge timber production and bring a variety of other benefits, and it can provide economic incentives for sustainable forestry development (The Royal Society, 2002; Nabuurs et al., 2007).

Mitigation can take place either through managing existing forests differently, such as lengthening rotations, or alternatively can be achieved by new planting. A country like the UK with low levels of forest cover may have greater potential than already heavily forested countries. However, the extent to which new planting is contemplated is likely to be heavily constrained by the operation of the farm policy support rules of the European Union.

It is anticipated that forestry-based activities could help reduce CO_2 concentrations in the atmosphere by increasing biotic carbon storage, decreasing emissions and producing biomass as a substitute for fossil fuels. Increasing forest regeneration, agroforestry, using more of wood products as substitutes of carbon intensive materials, especially in construction, improving forest and land-use management, and growing and utilizing of energy crops are considered in the UK as important policy measures of coping with the changing climate (IPCC, 2007b).

3.1 Carbon accounts

3.1.1 Kyoto Protocol and the UK position

In the light of the Kyoto Protocol (KP) to the United Framework Convention on Climate Change, the Parties have committed themselves to stabilizing of atmospheric Greenhouse Gas (GHG) concentrations, including those of Carbon Dioxide (CO_2). The overall reduction target of 8% was distributed on a differentiated basis to individual Member states (UNFCCC, 2004; EC, 2002a). This target is to be achieved by reducing emissions (reduction of sources) and removing GHG from the atmosphere (enhancement of sinks). Article 3.3 of the KP states that biological sources and sinks enhanced through afforestation[1], reforestation and the decreasing of deforestation rates since 1990 should be used for meeting the commitments during the stipulated period. Since the Conference of the Parties (COP-7 in 2001), afforestation, reforestation, forest management and soil carbon have become eligible climate change mitigation policies.

The United Kingdom has one of the best records in the world in reducing direct GHG emissions within its territorial boundaries. In 2005, UK GHG emissions were reported to be 15.3% below base year levels, with CO_2 emissions having fallen by 6.4% (DEFRA, 2007a). The future commitment of the UK under the EU burden-sharing target is 12.5% GHG emissions reduction for 2008–2012, relative to the base year. Further, a domestic goal of a 20% reduction of CO_2 emissions by 2010 was introduced (EC, 2002a). A series of targets for reducing CO_2 emissions have been set out (DEFRA, 2007b) - including making the net UK carbon account for the year 2050 at least 80% lower than the 1990 baseline (OPSI, 2008). The goal is to increase the use of renewable energy to 10% of total (currently, c. 3%) and pay more attention to the expansion of forest and short rotation forestry, in combination with further use of timber as a construction material (ECCP, 2004).

The principal forest policy measures that increase carbon sinks are recognized as maintaining and enlarging existing carbon pools by improving existing forests, the protection and sustainable management of these forests, expanding forest area through afforestation, replacing fossil fuels with fuel wood from sustainable managed forests, and replacing high energy products with industrial wood (EC, 1998; Forestry Commission, 2008b).

The UK is on track to meetits Kyoto targets. Its emissions in 2010 are predicted to be 23.6% below base year levels, 11.1% lower than required (DEFRA, 2007b). The Stern Review (2006) examined the evidence on the economic impacts of climate change and explored the economics of stabilising GHG in the atmosphere. The UK Climate Change Act (DEFRA, 2008) - the first of its kind in any country - set out a framework for moving the UK to a low-carbon economy with a target of 80% emissions reduction by 2050.

The Climate Change Programme (DEFRA, 2006), which is under the responsibility of the devolved governments, sets out policies and priorities for action. It elaborates the framework of carbon sequestration opportunities for forestry and advocates co-operation across regions of the country and between different sectors of the economy. The targets are linked across climate policy objectives, such as those of carbon sequestration forestry projects, of the increased use of renewable energy, an increase in energy efficiency and short rotation forestry. The documents demonstrate the UK's desire to deal effectively with climate change, and emphasize an importance of investment in low-carbon fuels and in terrestrial carbon capture and storage (DEFRA, 2007c).

---

[1] Afforestation is an expansion of forest on land, which more than 50 years ago was covered by forests, but was later converted to other use. Reforestation is a restoration of degraded or recently (20-50 years ago) deforested lands (IBN-DLO, 1999). In this paper, we do not make this distinction.

3.1.2. Forest carbon accounts in the United Kingdom

The UK has one of the lowest percentages of wooded land (11.8%) in Europe compared with the EU average of 38%, but it has significantly expanded its wooded cover in the last hundred years (currently 2.85 Mha, FAO, 2005). The dynamics in sources and sinks from forestry and land use changes (LUC) in the UK are summarized in Table 1. Both on private (64% of forests) and on publicly owned forest land climate change mitigation through carbon sequestration is becoming increasingly recognized (Nijnik, 2009).

Table 1 Changes and predicted trends in emissions due to forestry and LUC

Millions tC/year	1990	1995	2000	2005	2010	2015	2020
Forest sink (a)	2.6	2.8	2.9	3.2-3.3	3.1-3.4	2.7-3.0	2.4-2.8
from planting since 1990 (b)	0	0.2	0.3	0.5-0.6	0.6-0.8	0.9-1.2	1.2-1.6
Emission from LUC (c)	8.7	7.3	6.5-8	4.9-7.8	4.1-8.2	2.8-8.4	1.4-8.3

Source: DEFRA (2002) a – C accumulation in biomass, soil, litter and in wood products; b – entries from woodlands planted since 1990, excluding in timber products; c – net emissions caused by LUC. The trends do not consider possible effect of CC on forest productivity.

The maximum rate at which the forests expanded in the UK during the 20th century was about 40kha/yr in the early 1970s, primarily in the uplands (Cannell and Dewar, 1995; Mason, 2007). However, the establishment of 1.3Mha of mainly monoculture conifer plantations met with considerable objection due to their impact on visual, ecological and environmental components of landscapes (Cannell, 2003). Partly as a result of this, and also because of low forest profitability and uncertainty over CAP reform, the average rate of forest expansion went down to about 19 kha/yr in the 1990s, and over the following decade to 10 kha/yr (Forestry Commission, 2008a). The age structure of forests and declining availability of land suitable for afforestation, as well as public preferences for multifunctional land use, suggest that the net rate of carbon uptake in British forests may have peaked in 2005 (Tipper et al., 2004). Planting targets under the current Scottish Rural Development Plan look unlikely to be met at current rates of planting.

Currently, about 3MtC is sequestered annually by forests in the UK, with 0.5Mt C from trees planted since 1990 (DEFRA, 2001). Carbon sequestration rates per hectare are comparable with those in other countries in Europe. Annual carbon uptake in excess of 4tC/ha can be attained mainly in fast growing conifer stands and short rotation plantations (Nijnik et al., 2009). Concerning broadleaved species - an example of carbon exchange (and therefore sequestration) associated with oak forest in England of general yield class $6m^3 ha^{-1} yr^{-1}$ and gross primary productivity of c. $14.0t ha^{-1} yr^{-1}$ is shown in Figure 1. This figure explains the exchange of carbon between the atmosphere and all carbon pools in forest (above ground biomass and roots, and forest soil and litter) and shows the mitigative capacity of the forest.

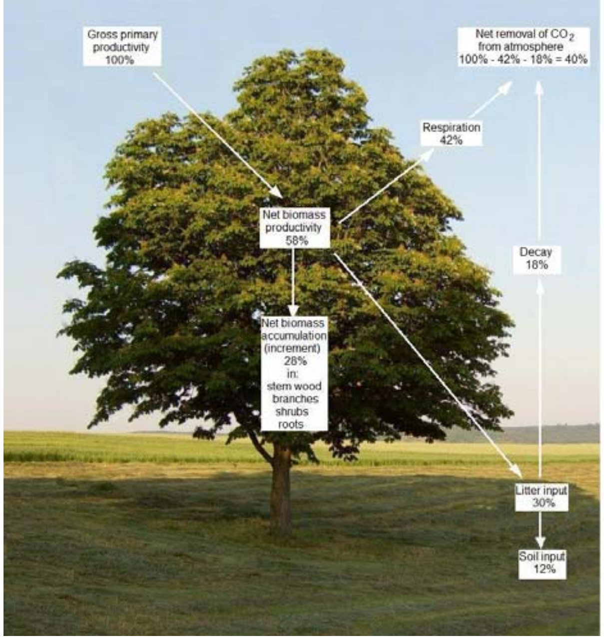


Figure 1 Representation of carbon exchange associated with forest components

Source: Nijnik (2009) adapted from Broadmeadow and Matthews (2003).

The rate, dynamics and patterns of carbon sequestration in forest depends on tree species and their characteristics, and naturally on tree-growing conditions, particularly on temperature, CO_2 concentration and forest management alternatives. Estimates of possible carbon stocks (t CO_2eq ha^{-1}) and annual rates of sequestration (t CO_2eq ha^{-1} yr^{-1}) that apply to each alternative forest management in the UK are shown in Table 2.

Table 2. Indicative estimates of whole tree carbon stocks (t CO_2eq ha^{-1}) and annual mid-rotation rates of carbon sequestration (t CO_2eq ha^{-1} yr^{-1}) that may apply to a range of forest management alternatives in the UK

	Forest Management Alternative				
	Unmanaged forest nature reserve	Close to nature forestry	Combined objective forestry	Intensive even-aged forestry	Wood biomass production
Carbon stocks	800	260	(200)	180	(90)
Annual rates	4	(11)	(16)	22	29

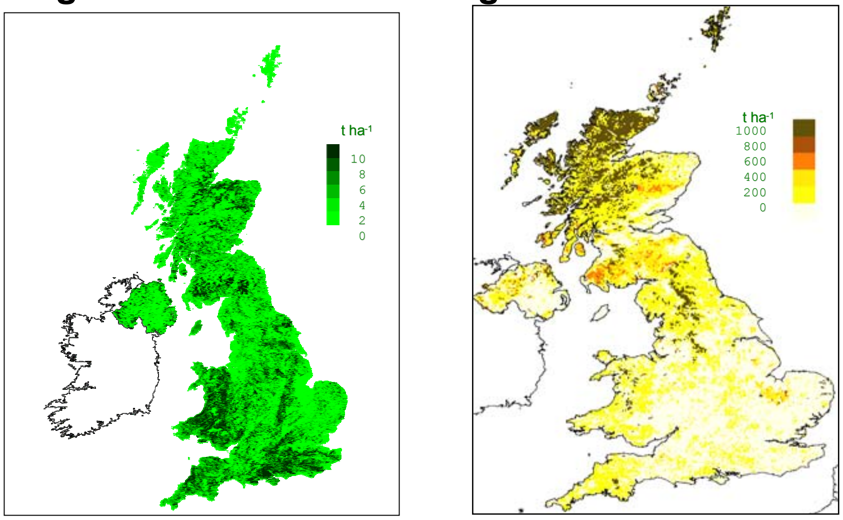
Source: Mason et al., (in press). Notes: Values in parentheses are extrapolated from other measures - see notes for further detail. Sitka spruce is assumed as the species.

1. Principal data sources used are Morison et al. (2009) for carbon stocks, Jarvis and Linder (2000 and 2007) and Luyssaert et al. (2008) for rates.

2. Extrapolations are based on the assumptions that: a) carbon stocks in wood biomass production will be a function of the shorter rotation – half or less that of intensive even-aged forestry; b) carbon stocks in combined objective forestry are higher than intensive even-aged forestry because of a longer rotation, but the amount of increase is reduced because of likely admixture with less productive species; c) similarly rates in close to nature and combined objective forestry are likely to be lower than for intensive even aged forestry because of the greater age of the trees and the presence of less productive species mixtures.

Research carried out at the Macaulay Institute, Forest Research, Aberdeen University, and the Centre of Ecology and Hydrology suggests that although carbon stocks in forest vegetation are high, with more than 95 Mt of carbon stored in above ground biomass of UK woodlands (as seen in Table 3), the largest carbon pools in this country are in soils and litter (in Figure 2). This is in part a function of major reserves of peat in the UK.

Figure 2: UK C stock in vegetation and soils



Vegetation Carbon

Soil Carbon

Source: Milne (2002).

They together store about 10 Gt C (Chapman *et al*., 2001; Smith *et al.,* 2006). Forest soils, particularly the peat-based soils in the uplands contain much more carbon than the trees (Forestry Commission, 2008b).

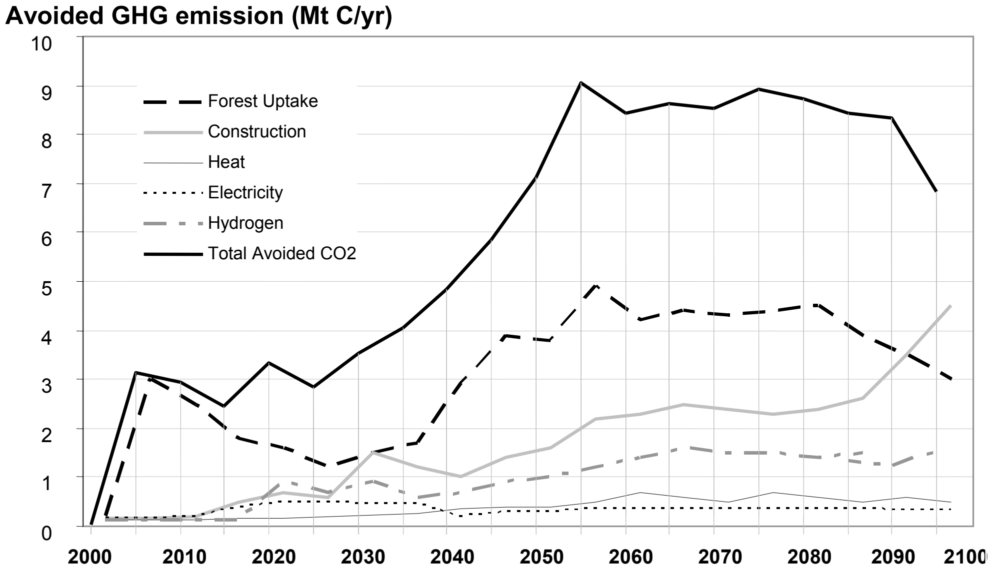
Table 3 Stock of carbon in vegetation in the UK

UK	Vegetation carbon (Mt)	%	% area
Semi-Natural	12	10	32
Agriculture	12	10	47
Woodlands	95	80	11
Other	0	0	9
TOTAL	119	100	100

Source: Milne (2002)

The projections indicate that an increase of woodlands at a rate of 10kha/yr of conifers and 20kha/yr of broadleaved would allow forest to sequester 3.1MtC/yr in 2020, storing over the two decades an extra 50MtC (DEFRA, 2001). The potential for carbon savings from forestry, timber production and bio-energy could enable avoidance of emissions of about 8MtC/yr in fifty years from now (Figure 3). This estimate comes close to 10% of the amount that is needed to halve UK emissions by the year 2050.

Figure 3 Carbon savings of forest cover increase to 25%, plus the promotion of bioenergy and of substitution of carbon intensive materials with wood



Source: Tipper *et al.* (2004).

To reach this target, the UK would require an expansion of woodlands towards 25% of land cover, in combination with use of timber for construction and wood for energy. Higher estimates of the physical potential for land-based carbon sequestration are available in the literature (Cannell, 2003). These projections are largely based on the assumptions that concern the maximum possible expansion of forest cover. They do not account for technical, institutional and economic constraints of a large scale afforestation, as well as for a broad range of uncertainties, associated with forest sink and soil carbon estimates, and with the rates of possible carbon uptakes or losses etc. According to Tipper et al. (2004), the target of woodland expansion (6.2Mha, 50% broadleaved and 50% conifer) by itself could provide a carbon sink of about 4MtC/yr for most of the second half of this century.

3.2 Political processes, instruments and strategies for mitigation

The carbon sequestration land use activities in Europe are supported by afforestation schemes and rural development regulations (EC, 1992). The policy of woodland development is supported by financial instruments which vary across the territory. In England, the Forestry Commission (FC) administers the English Woodland Grant Scheme (EWGS) (Forestry Commission, 2008a). Payments differ depending on localities and land categories, tree species (£1800 /ha for broadleaves, £1200/ha for conifers) and the likelihood of social benefits. Woodland creation grants also encourage farmers to convert productive land into forest and receive compensation to offset the foregone agricultural income (Forestry Commission, 2008a). In Scotland, as part of the Rural Development Programme (RDP), new grants have been introduced aiming to deliver targeted environmental, social and economic benefits from forests. The RDP brings together a range of formerly separate support schemes, including those covering the farming, forestry and primary processing sectors, rural enterprise and business development, diversification and rural tourism. Grant support will be delivered through a number of forestry-specific (e.g. short rotation coppice crops of willow or poplar) and non-specific (e.g. support for renewable energy – forestry) options, including those of climate change mitigation. Some of these options require a five year commitment, others are one year. They are non-competitive and open to all managers with land in Scotland (Forestry Commission, 2008a).

The potential to mitigate climate change through new forest planting is not only shaped by climate and forestry policies. Also, various cultural values affect the propensity to plant trees and develop forest-based activities to tackle climate change. Afforestation can be inhibited where farm policy subsidies are capitalised in land values, and where farm subsidies are lost to the occupier, if grant-aided farm woodland planting occurs. The rules relating to loss of farm subsidies have been modified in the summer of 2009 and this inhibitory factor will now disappear. Land use decisions are shaped less by market signals and more by the distortions generated by public policy measures. Agri-environmental policies (e.g. farm subsidies) on land allocation decisions and the general tax and monetary policies on agricultural land prices have had a significant impact on forestry (Guyomard et al., 2006; RSE, 2008). Also, any policy support for renewable energy is likely to increase the demand for wood energy, as should any tax on non-renewables. There is an increasing policy support for the development of woody biomass, with grant aid (DEFRA Energy Crops Scheme) available in some part of the UK (LUPG, 2004).

Forestry measures to mitigate climate change require a long-term perspective. The optimum policies, therefore, tend to link long-term carbon sequestration in forestry with the long-term substitution of wood in construction and in renewable energy projects (Cannell, 2003). A systematic promotion of renewable energy highlighted in the 2005 EU Biomass Action Plan offers opportunities for innovation, development of energy markets, with locally and regionally oriented value chains and thereby provides new employment opportunities (EC, 1997). Importantly, national programmes supporting carbon sequestration forest-based activities in the UK focus largely on remote rural areas. These programmes (DEFRA, 2006) are embodied in regional policies, and some of the available options provide multiple benefits. The effective measures aim for "win-win" situations to benefit rural development, people, the economy and the environment and both at a national level and internationally (Rollinson, 2007; Forestry Commission, 2008a). One measure that can be used to encourage new planting would be to provide land owners and investors with 'carbon credits' for woodland creation schemes. The Forestry Commission has just released a draft code of good practice (Anon., 2009f) as a means of developing the UK's forest carbon sector.

3.3 Forestry as a source of bio-energy

Biomass is increasingly recognised as a renewable energy source with low GHG emissions (Elsayed et al., 2003; RCEP, 2004; Matthews and Robertson, 2003) that can make a valuable contribution to the UK objective of tackling the drivers of climate change (Andersen et al., 2005). The forestry section of the UK Biomass Strategy (DEFRA, 2007d) highlights that the forest sector can increase the resource for energy generation by 1Mt of dry wood that are expected to be recovered from currently unmanaged woodlands in England, an increased recovery of wood energy from managed woodlands and other sources of wood waste products in the UK. Overall, it is deemed that the UK has a significant biomass resource of c. 20Mt/yr (Biomass Task Force Report, 2005), but only a fraction of this is effectively captured for energy, contributing approximately 4.1 % to its heat and electricity production (DEFRA, 2007d). To capture this potential more fully, and use wood for fuel more effectively and efficiently are among the most important climate policy objectives pertaining to the forestry sector.

At the devolved level, the Scottish Biomass Action Plan (Scottish Executive, 2007) details the following objectives:

- to generate 18% of Scotland's electricity from renewable sources by 2010, rising to 40% by 2020;

- to exceed the Scottish share of the UK's carbon savings by 1Mt in 2010, totaling 2.7Mt carbon per year;
- to increase the percentage of transport fuels from renewable sources to 5% by 2010 (see Renewable Transport Fuel obligation set at the UK level);
- to set a Renewable Heat Action Plan.

On the supply side of bio energy development, forestry is supposed to play a major role. The 20% renewable energy target is acknowledged in the Forestry Commission Scotland Climate Change Action Plan for 2009-2011 (Anon., 2009b) which develops the Scottish Forestry Strategy (2006) where tackling climate change was one of the highest priorities for the forest sector (mitigation and adaptation perspectives). It says that the forest cover in this part of the UK should be increased from 17.1% to 25% with a rising importance of using wood as a source of energy. In the Climate Change Programme for Scotland (Scottish Executive, 2006), it is pointed out that forests in Scotland provide 350kt of green wood used for energy systems, and that, with various measures in support of energy systems based on biomass, this should rise by 750kt of dry wood by 2010 and 1Mt by 2020. The Northern Irish Forest Strategy (Anon, 2006) also plans to increase forest cover and highlights an important role for forests as a source of renewable energy.

In addition to the utilizing of wood waste products and to afforestation, new woody fibre based crops grown for energy are under development in the UK. Biomass is also viewed as an environmentally beneficial land use alternative to conventional food crop production. Greater use of forest-derived biomass for energy is seen as a means of improving woodland management and stimulating rural development (SDC, 2005). The Bioenergy Infrastructure Scheme funded by the DEFRA and administered by the Forestry Commission was set up to provide grants to farmers, foresters and businesses to help in developing the supply chain required to harvest, store, process and supply energy crops and wood fuel to end-users.

Forestry's potential role in mitigating climate change through wood energy is still impeded by high capital costs of wood boilers compared to gas or oil alternatives. Significant capacity in producing pellets and chip now exists but the future expansion of the industry depends on increasing demand for wood energy in domestic, public sector and industrial markets. To date the public sector has played a leading role in developing workable supply chain models. If a case for support via capital grants can be made based on carbon savings, an increased uptake of wood energy would be probable. However, the major push towards wood energy will be contingent on higher oil prices, as much as on lowering the capital costs of moving to wood energy systems.

3.4 Using wood to substitute for carbon intensive materials

The rising importance of using wood in wood products can be explained by the fact that the avoidance of carbon release when using wood to replace energy intensive materials is repeatable, as long as a continual process of tree growing, harvesting and regeneration, with the use of harvested timber, is maintained. Therefore, the social benefits of substitution projects are likely to be higher, in the long run, than under the strategy of carbon fixation in trees alone (Van Kooten, 2004).

Research has been undertaken in the UK to assess the contribution of wood products to climate change mitigation goals. Bateman et al. (2003) estimate "carbon release curves" for different types of products with varying lifetimes, based on UK timber production and its allocation to various types of products. These curves have been adapted by Brainard et al. (2009) to take into account various yield classes, in an attempt to estimate the social value of carbon sequestered in UK forest trees, forests soils and forests products. The wood products pool in the UK is estimated to be 80 MtC stored and growing at 0.44 MtC per year (Broadmeadow and Matthews, 2003). Wood products in a medium growth scenario have the potential to store an estimated additional 10 TgC in the UK's new and refurbished homes (Forestry Commission, 2008a).

Carbon stored in wood product sinks is not considered under Article 3.4 of the Kyoto protocol to the UNFCCC, and accounting for carbon storage in wood products needs to be resolved. This policy option could provide multiple benefits by enlarging the supply of wood and adding to the total carbon sink. Wood is a substitute for various raw materials implicated in GHG releases and can be used in construction, engineering and production of household goods. In all these cases, and especially in construction and packaging, wood acts as a sink of carbon (beyond its storage in trees), and with the duration of the sink equivalent to the life of the goods. Managing the wood products pool by increasing the volume of wood products in construction by building more timber rich houses and by increasing the service life of wood products are considered as valuable contributions to reducing carbon impacts.

3.5 Research studies of mitigation

The last few years have seen an upsurge in the number of papers in the UK addressing the role of forestry to mitigate climate change (Adams et al., 1999; Bateman and Lovett, 2001; Broadmeadow and Matthews, 2003; Cannell, 2003; Matthews and Robertson, 2003; Rollinson, 2007; Brainard et al, 2008; Moran et al., 2008; Nijnik and Bizikova, 2008; Nijnik et al., 2009). They indicate that the extent to which the mitigative role of forests can be enhanced by new planting or forest management (IPCC, 2007b) is mediated by externalities and uncertainties, and shaped by a range of environmental, economic and policy drivers, market signals, institutions and governance, and public attitudes and behavioural patterns.

The Stern Review (2006) increased the awareness about climate change mitigation, placing the scientific observations in a conventional economic framework. The Carbon Trust (2005) published recommendations on how best to deliver carbon emission reductions for the UK and on the economics of different climate change mitigation options. Among the key research projects on forestry and climate change in the UK is the independent "National Assessment of UK Forestry and Climate Change" that has been initiated by the Forestry Commission (2009), with active involvement from the Forest Research, the Macaulay Land Use Research Institute and a number of British Universities.

Information about Macaulay Institute Climate Change research is available at:
http://www.macaulay.ac.uk/climatechange/MLURICCresearchoverview.pdf and
http://www.macaulay.ac.uk/climatechange/index.php
http://www.macaulay.ac.uk/climatechange/CC_research.php

More specific reports have assessed the importance of climate policies in setting business strategies, and manifold implications of climate policy decisions (ENDS, 2007); the GHG impacts of different bioenergy systems (Elsayed *et al*, 2003) and the environmental impacts of biofuel crop systems (Turley *et al*., 2004). The UK Biomass Study (2007) called for expansion of wood use for fuel. The Renewables Energy Strategy stressed a significant gain yet to be taken from the use of wood biomass in energy production. Assessment of UK forest biomass resource for bioenergy has been made by McKay et al (2003) and DEFRA (2007d). The reports by the Sustainable Development Commission (2005), by Rippengal (2005) and by the Fraser of Allander Institute (2006) have provided information on the potential of the wood fuel market for heat and on competitiveness of different wood fuel scenarios. The potential of biomass for renewable heat was reviewed in a report of AEA Technology (2005). An analysis of biomass production and consumption of most relevance to Scotland was published by SEERAD (Towers *et al*., 2004; Galbraith, 2006). A report by Bauen et al. (2004) proposed a strategy for the generation of electricity from biomass sources up to 2020. The reports provide a broad picture concerning technological aspects, GHG life cycle emissions, air pollution impacts of biomass production and consumption in the UK, as well as socio-economic aspects of using wood for biofuel.

Research studies on climate change mitigation published in the UK in recent years also address political processes, instruments and strategies for climate change mitigation through forestry based activities (Freer-Smith et al., 2007; ICF, 2008; Nijnik and Bizikova, 2008; Nijnik, in press), as well as the economics of climate change mitigation policy options (Nijnik et al., 2009). The report "UK marginal abatement cost curves for the agriculture and land use, LUC and forestry sectors out to 2022, with qualitative analysis of options to 2050" was published by the Committee on Climate Change (Moran et al., 2008). The project "Forestry and Climate Change: a Socio-Economic Perspective" to the "National Assessment of UK Forestry and Climate Change" is under development. These, and other projects addressing the economics of climate change mitigation through forestry that are carried out at the Macaulay Institute and other collaborating research organizations, highlight that socio-economic issues are important in determining the range of land types available for woodland development in the UK, and that comparative indicators of the cost-effectiveness of climate strategies are needed (Nijnik, in press; Galbraith et al., 2006; SNIFFER, 2008).

Numerous studies also show that the public value forests for more than carbon sequestration and that multiple ecosystem services are to be taken into account when carbon sequestration strategies are implemented (Nijnik and Mather, 2008; Nijnik et al., 2008). Documents reinforce that it is a good practice to consult the public (Forestry Commission, 2008a; Forestry Commission, 2008b), and public attitudes to forestry in the UK are assessed in biennial surveys carried out on behalf of the Forestry Commission (Grant et al., 2007). There are also several climate change surveys of public opinion in the UK (DEFRA, 2005; UKRC, 2007), including those carried out for research purposes, e.g. at the Macaulay Institute. However, the relation between attitudes to forestry and climate change taken together is largely unexplored.

Participation of landowners and farmers in afforestation is crucial as they are directly involved in the process of converting land to forests. However, there is evidence that farmers attribute a high value on their independence and their ability to make their own decisions (Shucksmith et al., 1993). This could be an obstacle to grant-conditioned afforestation as it could may also give rise to a distaste for monitoring. Towers et al. (2006) highlight that farmers perceive themselves as "stewards of the countryside", and in a way, afforesting land may not seem right to them in this role.

Research studies on mitigation indicate that afforestation may also be seen as a threat to the social aspects of farming. Cosgrove et al. (1996) suggest that large-scale afforestation may alter farmers' way of life. There is some evidence that farmers are aware of such potential impacts. For example, Mather and Thompson (1995) observed that in some areas where the forest extent exceeds 30 per cent "the social character of farming has been transformed" and some farmers noted this social change as a reason for selling up and relocating to other parts of the country. Studies suggested that there is a general reluctance in the farming community to large-scale afforestation.

The economics of afforestation is not the only obstacle and there are also psychological, cultural and institutional barriers. In particular, it is argued that the UK has a weakly developed forest culture (Mather et al., 2006; Nijnik and Mather, 2008). The issue of land tenure was also mentioned as a barrier to afforestation (Warren, 2002; Towers et al., 2006). However, research is currently underway at the Macaulay Institute to investigate the issue of offsetting GHG emissions from farming through forestry with the focus of afforestation being small-scale, “localized” afforestation. Cooperation and institutional arrangements between farmers representing different types of farm (for which cost effectiveness of carbon sequestration is different) have also been examined as part of a research program (Pajot et al., 2009).

To conclude, through the analysis of biogeochemical processes involved, and by assessing the opportunities and challenges for forestry to sequester and store carbon, it is now becoming possible to suggest more effective, efficient and socially desirable climate policies and measures, and to advise on their proper sequencing in space and in time.

3.6 Research Needs

The cost-effectiveness of afforestation in different locations, social acceptability of carbon forestry options, challenges and opportunities of woodland development on carbon rich soils, using wood for energy and in wood products projects, are important topics for future research (Cannell, 2003; SDC, 2005; Smith et al., 2006; Nijnik and Bizikova, 2008). As identified by Nijnik et al. in the report to the UK Assessment of Forestry and Climate Change:

- The socio-economics of carbon sink forestry scenarios is highly topical in the UK, because the choice of location for forestry development, and of management regimes to be applied are important factors in raising the effectiveness of mitigation and saving economic costs.
- New tree-planting is deemed to be economically viable either when afforestation provides multiple environmental and/or social co-benefits or when short rotation plantations are established for bio-energy. It is therefore important to determine a particular agenda for bioenergy forest policy by addressing economic, social and environmental factors (e.g. biodiversity and landscape values), and to define where to place biomass production in the general context of (multifunctional) land use, where reform of CAP (EC, 2002b) and contemporary rural change will also likely be influential.
- Adaptation and mitigation activities are linked together, and the knowledge built up in the UK and internationally should be used to facilitate more successful mitigation – adaptation interactions in the forestry/LU sectors and in the wider context of sustainable development and rural livelihoods.
- Trade-offs between mitigation and adaptation efforts also necessitate evaluation of costs (forest damages/losses versus benefits) due to the changing climate. Research on investment, economic incentives, and institutional and governance capacities of climate change mitigation through forestry is required.
- Among motivating research topics are: who is responsible for carbon sinks after the Kyoto commitment period of 2012; what is the value of a temporary terrestrial carbon, and how it will change, as markets develop and institutions evolve to handle uncertainty aspects affecting terrestrial carbon offsetting and trading.
- Major problems with the inclusion of carbon offsets from forestry into regulatory emission trading schemes are caused by temporary nature of terrestrial carbon sinks, and by “leakages”, double-counting and too high transaction costs associated with measuring, assessing and monitoring of carbon. Opportunities to increase the cost-efficiency of climate change mitigation are in finding of solutions of these problems.
- Studies to identify and explain the attitudes of various groups of people towards the role of forests in adaptive and mitigative measures, particularly concerning afforestation and short rotation plantations has started at the Macaulay Institute but merit further attention.

- Decisions to change behavioural patterns in the area of climate change mitigation and adaptation will be influenced by price and economic incentives. However, behaviours are also shaped by citizenship values, and the drivers of change are thus many, and varied. There is therefore a need for consultation with stakeholders on climate change mitigation policy options (within the forestry sector and beyond, and across various regions in the UK) and to encourage the public to be more actively involved in tackling of climate change.

4. Conclusions

As should be evident from the preceding sections, there is now good evidence to show the potential impacts of climate change on forests in the UK, the need to adapt the forests to such changes, and the valuable role that British forests can play in mitigating some of the effects. We have noted several times that the knowledge base about climate change is considerable and awareness of its effects is increasing within the forestry sector, but as yet we can find little indication of systematic changes in silvicultural practice or wider forest management to take account of this greater knowledge and awareness.

The case study approach envisaged in ECHOES, as well as in other relevant EU and national projects (see section 2.4 above), seems to us to provide a valuable means for making the transition from research findings and policy guidance to operational management planning. We believe that such ‘demonstration projects’ provide the essential link between theory and practice to increase the understanding of foresters and all those operational staff who are ultimately responsible for increasing the resilience of British forests to climate change. The case study mechanism can be seen as an ‘adaptive management’ approach whereby actions are proposed in the light of best available knowledge, the results monitored, and management strategy adjusted in the light of the observed responses. Deciding upon the most appropriate scale and scope of a case study seems to be one of the important methodological issues to be confronted within ECHOES over the next period of time.

We anticipate revising our country report before the end of the ECHOES action to reflect new policy initiatives as well as knowledge gained from the results of ongoing research.

References:

Adams, D., Alig, R., McCarl, B., Callaway, J. and Winnett, S. (1999) Minimum Cost Strategies for Sequestering Carbon in Forests. *Land Economics*, **75**(3), pp 360-374.

AEA Technology. (2005) Renewable heat and heat from combined heat and power plants – study analysis. A Report to DTI and DEFRA.

Albon, S.D., Clutton-Brock, T.H. and Guinness, F. (1987) Early development and population dynamics in red deer 2: Density-independent effects and cohort variation. *Journal of Animal Ecology*, **56**, 69-81.

Andersen, R.S., Towers, W. and Smith, P. (2005) Assessing the potential for biomass energy to contribute to Scotland's renewable energy needs. *Biomass and Bioenergy*, **29**, 73-82.

Anon. (1995) *Biodiversity: the UK Steering Group Report* – Volume 2: Action Plans. HMSO, London.

Anon. (2000a) *Climate change: the UK programme*. The Stationery Office, London.

Anon. (2000b) *Forestry Compendium Global Module*. CAB International, Wallingford, UK.

Anon. (2004) *The UK Forestry Standard: the Government's Approach to Sustainable Forestry*. Forestry Commission. Edinburgh.

Anon. (2006a) *The Scottish Forestry Strategy*. Forestry Commission Scotland, Edinburgh.

Anon. (2006b) *Northern Ireland Forestry: a Strategy for Sustainability and Growth*. Department of Agriculture and Rural Development Northern Ireland, Belfast.

Anon. (2007) *A Strategy for England's Trees, Woods and Forests*. Department for Environment, Food, and Rural Affairs, London.

Anon. (2008a) *Delivery plan 2008-2012 – England's Trees, Woods and Forests*. Forestry Commission, Edinburgh.

Anon. (2008b) *Delivery plan 2008-2012 – England's Trees, Woods and Forests* (Actions). Forestry Commission England, Cambridge.

Anon. (2009a) *Woodlands for Wales – the Welsh Assembly Government's Strategy for Woodlands and Trees*. Forestry Commission Wales, Aberystwyth.

Anon. (2009b) *Climate change action plan*. Forestry Commission Scotland, Edinburgh.

Anon. (2009c) *Preparing for a Changing climate: Second consultation to inform Scotland's climate change Adaptation framework*. Scottish Government, Edinburgh.

Anon. (2009d) *Adapting to climate change – UK Climate projections*, June 2009. Department for Food, Environment and Rural Affairs, London.

Anon. (2009e) *Forests and Climate Change Guidelines* – Consultation draft. Forestry Commission, Edinburgh.

Anon. (2009f) *Code of Good Practice for Forest Carbon Projects* – Consultation document. Forestry Commission, Edinburgh.

Arkell, B, Darch, G., and McEntee, P. (2007) *Preparing for a changing climate in Northern Ireland*. Sniffer UKCC13. Sniffer, Edinburgh.

Avery, B.W. (1990) *Soils of the British Isles*. C.A.B. International, Wallingford.

Bateman I. and Lovett A. (2001) *Estimated Value of Carbon Sequestered in Softwood and Hardwood Trees, Timber Products and Forest Soils in Wales*. Available at: http:// www.uea.ac.uk/ ~e089/ carbfinl.pdf, accessed 24/03/2009.

Bateman, I., Lovett, A.A. and Brainard, J.S. (2003) *Applied Environmental Economics: A GIS Approach to Cost–Benefit Analysis*, Cambridge University Press, Cambridge.

Bauen, A., Woods, J. and Hailes, R. (2004) *Bioelectricity vision: Achieving 15% of electricity from biomass in OECD countries by 2020*. A report to WWF.

Berry, P.M., Dawson, T.P., Harrison, P.A. and Pearson, R.G. (2002) Modelling potential impacts of climate change on the bioclimatic envelope of species in Britain and Ireland. *Global Ecology & Biogeography*, **11**, 453-462.

Biomass Task Force. (2005) *Biomass Task Force Report*. Available at: http://www.defra.gov.uk/farm /crops/industrial/energy/biomass-taskforce/index.htm, accessed 21/10/2006.

Brainard, J., Lovett, A.A. and Bateman, I. (2006) Sensitivity analysis in calculating the social value of carbon sequestered in British grown Sitka spruce. *Journal of Forest Economics*, **12**, pp. 201–228.

Brainard, J., Bateman, .I.J., Lovett, A.A. (2009) The social value of carbon sequestered in Great Britain's woodlands. *Ecological Economics*, **68**(4), pp. 1257-1267.

Broadmeadow, M. (2002) *Climate change: Impacts on UK forests*. Forestry Commission Bulletin 125, Forestry Commission, Edinburgh.

Broadmeadow, M. and Matthews, R. (2003) *Forests, carbon, and climate change*. Forestry Commission Information Note 48, Forestry Commission, Edinburgh.

Broadmeadow, M. and Ray, D. (2005) *Climate change and British woodland*. Forestry Commission Information Note 69, Forestry Commission, Edinburgh.

Broadmeadow, M.S.J., Ray, D., and Samuel, C.J.A. (2005) Climate change and the future for broadleaved tree species in Britain. *Forestry*, **78**, 145-161.

Brown, A. and Webber, J. (2008) *Red band needle blight of conifers in Britain*. Forestry Commission Research Note 2. Forestry Commission, Edinburgh.

Buse, A. and Good, J.E.G. (1996) Synchronisation of larval emergence in winter moth (Operophtera brumata L.) and budburst in pedunculate oak (Quercus robur L.) under simulated climate change. *Ecological Entomology*, **21**, 335-343.

Cannell, M.G.R. (2002) Impacts of climate change on forest growth. In: *Climate change: Impacts on UK forests*. (M. Broadmeadow (ed.). Forestry Commission Bulletin 125, Forestry Commission, Edinburgh. pp 141-148.

Cannell, M.G.R. (2003). Carbon sequestration and biomass energy offset: Theoretical, potential and achievable capacities globally, in Europe and the UK. *Biomass and Bioenergy*, **24**, pp. 97–116.

Cannell, M.G.R. and Dewar R.C. (1995). The carbon sink provided by plantation forests and their products in the Britain, 1995. *Forestry*, **68**, pp 35 – 48.

Cannell, M.G.R. and McNally, S. (1997) Forestry. In: J. Palutikof, S. Subak and M. Agnew (Editors), *Economic impacts of the hot summer and unusually warm year of 1995*. University of East Anglia, Norwich. pp 33-43.

Cannell, M.G.R. and Smith, R.I. (1986) Climatic warming, spring budburst and frost damage on trees. *J. Appl. Ecol*, **23**, 177-191.

Cannell, M.G.R., Dewar, R.C. and Pyatt, D.G. (1993) Conifer plantation on drained peatlands in Britain: a net gain or loss of carbon? *Forestry*, **66**, 353-369.

Cannell, M.G.R., Grace, J., and Booth, A. (1989) Possible impacts of climatic warming on trees and forests in the United Kingdom: a review. *Forestry*, **62**, 337-364.

Carbon Trust. (2005) Biomass sector review. Available at: http://www.thecarbontrust.co.uk/Carbontrust/about/publication, accessed 02/12/2007.

Chapman S., Towers W., Williams B., Coull M. and Paterson E. (2001) Review of the contribution to climate change of organic soils under different land uses. Scottish Executive Central Research Unit, 62 pp.

Cosgrove, D., Roscoe, B., Rycroft, S. (1996) Landscape and identity at Ladybower Reservoir and Rutland Water. *Transactions of the Institute of British Geographers*, Vol **21**, pp 534-551.

DEFRA. (2001) The UK's third national communication under the UN Framework on Climate Change, London.

DEFRA. (2002) Climate Change: Draft UK Programme, Sections 1 - 4, Annex G – Carbon Sequestration. London.

DEFRA. (2005) Andrew Darnton Research: Public Understanding of Climate Change, Final Report for COI/DEFRA Communications Directorate/FUTERRA

DEFRA. (2006) Climate Change Programme. Available at: http://www.defra.gov.uk/, accessed 13/04/2008.

DEFRA. (2007a) Progress towards national and international targets. Statistical release: 2005 UK climate change SD indicator and GHG emissions final figures. London. Available at: http://www.defra.gov.uk/environment/climatechange/uk/progress/ index.htm, accessed 9/11/2009.

DEFRA. (2007b) Demonstrable Progress. The United Kingdom Report on Demonstrable Progress under the Kyoto Protocol. Tomorrow's Climate Today's Challenge. Available at http://www.defra.gov.uk/environment, accessed 9/11/2009.

DEFRA. (2007c) New Bill and strategy lay foundations for tackling climate change. News release. Available at http://www.defra.gov.uk/news/2007/070313a.htm, accessed 9/11/2009.

DEFRA. (2007d) UK Biomass Strategy. Available at: http://www.defra.gov.uk/ environment/climatechange/uk/energy/renewablefuel/pdf/ukbiomassstrategy-0507. pdf

DEFRA. (2008) Climate Change Act. Available at: http://www.defra.gov.uk/ environment/climate change/uk/legislation/provisions.htm, accessed 16/110/2009.

EC. (1992) The European Community aid scheme for forestry measures in agriculture Regulation (EEC) No 2080/92, Brussels.

EC. (1997) Energy for the Future: Renewable Sources of Energy. White Paper for Community Strategy and Action Plan, COM(97)599 FINAL (26/11/1997), Brussels.

EC. (1998) Communication from the commission to the council and European parliament on a forestry strategy for European Union. COM(1998)649, 03/11/1998, Brussels.

EC. (2002a) EU burden sharing. Council decision 2002/358/EC, Brussels.

EC. (2002b) "Mid – term review of common agricultural policy". COM(2002)349FINAL, 10/01/2002, Brussels.

ECCP. (2004) Conclusions and recommendations regarding forests related sinks & climate change mitigation. Available at: www.europe.eu.int/comm/environment/ climate/, accessed 16/03/2006.

Elsayed, M.A., Matthews, R.W. and Mortimer, N.D. (2003) *Carbon and energy balances for a range of biofuel options*. Report URN 03/086, Project No B/B6/00748/REP for DTI.

ENDS (Environmental Data Services). (2007) Climate Review 2006/07, London.

EU Biomass Action Plan. (2005) Communication from the EU Commission: Biomass action plan 2005. Commission of the European Communities. Brussels, 7.12.2005 COM(2005) 628 final. Available at: http://eur-lex.europa.eu/LexUriServ/ LexUriServ.do?uri= COM: 2005:0628:FIN:EN:PDF, accessed 10.06.2006.

Evans, H., Straw, N. and Watt, A. (2002) Climate Change: Implications for insect pests. In: M. Broadmeadow (Editor). *Climate Change: Impacts on UK Forests*. Bulletin 125, Forestry Commission, Edinburgh.

FAO. (2005) Global Forest Resources Assessment 2005: 15 Key Findings. Available at: www.fao.org/forestry, accessed 23/09/2008.

Forestry Commission. (2007a) *Forests and climate change: a convenient truth*. Forestry Commission Edinburgh.

Forestry Commission. (2007b) *Forestry facts and figures*. Forestry Commission, Edinburgh.

Forestry Commission. (2008a) *Forestry economics and statistics*. Annual reports and accounts. Available at: http://www.forestry.gov.uk/statistics and http://www.forestry.gov.uk/pdf/gb&eara2008pdf/$FILE/gb&eara2008.pdf, including Climate Change Action Plan 2009-2011 http://www.forestry.gov.uk/forestry/infd-7bglg8 Edinburgh.

Forestry Commission. (2008b) *Climate change and the National Forest Estate*. Consultation on forestry provisions in the Scottish Climate Change Bill, FC, Edinburgh, Available at: http://www.forestry.gov.uk/sfs, accessed 12/01/2009.

Forestry Commission. (2009) *The National Assessment of UK Forestry and Climate Change*. Available at: http://www.forestry.gov.uk/website/forestry.nsf/byunique/infd-7m8ghy, accessed 13/07/2009.

Fraser of Allander Institute. (2006) *The economic impact of wood heat in Scotland.* A report to Scottish Enterprise Forest Industries Cluster. Available at: www.forestryscotland.com/download.asp?file=Fraser%20of%20Allander%20Woodheat, accessed 29/07/2008.

Freer-Smith, P.H., Broadmeadow, M.S.J., and Lynch, J.M. (2007) *Forestry and climate change*. CAB International, Wallingford, Oxford.253 p.

Galbraith, D., Smith, P., Mortimer, N., Stewart, R., Hobson, M., McPherson, G., Matthews, G.R., Mitchell, P., Nijnik, M., Norris, J., Skiba, U., Smith, J. and Towers, W. (2006) Review of Greenhouse Gas Life Cycle Emissions, Air Pollution Impacts and Economics of Biomass Production and Consumption in Scotland, SEERAD final report, 265 pp.

Gardiner, B.A., Suarez, J., Achim, A., Hale, S. and Nicoll, B. (2004) *ForestGALES: a PC-based wind risk model for British forests*. User's Guide Version 2.0. Forestry Commission, Edinburgh.

Grace, J., Berninger, F. and Nagy, L. (2002) Impacts of climate change on the tree line. *Annals of Botany*, **90**, 537-544.

Grant, N. and Smillie, A. (2007) *UK Public Opinion of Forestry 2007*. Forestry Commission, Edinburgh.

Guyomard, H., Lankoski, J.E. and Ollikainen, M. (2006) *Impacts of agri-environmental policies on land allocation and land prices*. Discussion paper Number 14, Environmental Economics, University of Helsinki, Available at: http://www.mm.helsinki.fi/mmtal/abs/DP14.pdf

Harrison, P., Berry, P., Butt, N. and New, M. (2006) Modelling climate change impacts on species' distributions at the European scale: implications for conservation policy. *Environmental Science and Policy*, **9,** 116-128.

Hubert, J. and Cottrell, J. (2007) *The role of genetic resources in helping British forests respond to climate change*. Forestry Commission Information Note 86. Forestry Commission, Edinburgh.

Hulme, M. and Jenkins, G.J. (1998) *Climate change scenarios for the United Kindgdom*. UKCIP Technical Report 1, Climatic Research Unit, University of East Anglia, Norwich.

Hulme,M., Jenkins,G.J., Lu,X., Turnpenny,J.R., Mitchell,T.D., Jones,R.G., Lowe,J., Murphy,J.M., Hassell,D., Boorman,P., McDonald,R. and Hill,S. (2002) *Climate change* *scenarios for the UK: the UKCIP02 scientific report* . Tyndall Centre, UEA, Norwich, UK, 112pp.

IBN-DLO. (1999) *Resolving Issues on Terrestrial Biospheric Sinks in the Kyoto Protocol*. Dutch National Research Programme on Global Air Pollution and Climate Change, Wageningen.

ICF International. (2008) *Finance and Investment to Address Climate Change*. London: IETA Special Report.

IPCC. Climate Change. (2007a) Synthesis Report, *An Assessment of the Intergovernmental Panel on Climate Change*, adopted section by section at IPCC Plenary XXVII, Valencia, Spain, 12-17 November 2007. Available at: http://www.i pcc.ch/pdf/assessment-report/ ar4/syr/ar4_syr.pdf, 2007, accessed 22/03/2009.

IPCC. (2007b) Climate Change: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, in: Metz B, Davidson OR, Bosch PR, Dave R, Meyer LA (eds), Cambridge Univ Press, Cambridge.

Irvine, R.J., Broadmeadow, M., Gill, R.M.A. and Albon, S.D. (2007) Deer and global warming. *Deer* magazine, Autumn.

Jarvis, P. and Linder, S. (2000) Constraints to growth of boreal forests. *Nature 2000*; **405**(6789), pp 904-905.

Jarvis, P.G. and Linder, S. (2007) *Forests remove carbon dioxide from the atmosphere: spruce forest tales!* In: Forestry and Climate Change (eds., Freer-Smith, P.H., Broadmeadow, M.S.J. and Lynch, J.M.) CABI, Wallingford, pp 60-72.

Jenkins, G.J., Perry, M.C. and Prior, M.J.O. (2007) *The climate of the United Kingdom and recent trends*. Met Office Hadley Centre, Exeter, UK.

Kirby, K.J., Smart, S.M., Black, H.I.J., Bunce, R.G.H., Corney,P.M. & Smithers, R.J. (2005) *Long Term Ecological Change in British Woodland* (1971–2001). English Nature Research Reports, number 653. Peterborough: English Nature.

Kirby, K., Quine, C.P. and Brown, N. (in press) Adapting woodland. In: *The Assessment of UK Forestry and Climate Change*. Forestry Commission, Edinburgh.

Krcmar, E., Vertinsky, I. and van Kooten, G.C. (2003) Modeling alternative zoning strategies in forest management. *International Transactions in Operational Research*, **10** (5), pp 483 - 498.

Lonsdale, D. and Gibbs, J. (2002) Effects of climate change on fungal diseases of trees. In: M. Broadmeadow (Editor), *Climate Change: Impacts on UK Forests*. Bulletin 125, Forestry Commission, Edinburgh.

LUPG (Land Use Policy Group). (2004) CAP Reform (June 2003): *Implications for Woodlands*, Issues Paper From the Woodland Policy Group with Input from the Forestry Commission. Available at: http://www.lupg.org.uk/pdf/pubsWoodlandand CAPreform[1].pdf

Luyssaert, S., Schulze, E.D., Börner A., Knohl, A., Hessenmöller, D., Law, B.E., Ciais, F. and Grace, J. (2008) Old-growth forests as global carbon sinks. *Nature*, **455**, pp 213-215, doi:10.1038/nature07276.

MacDonald, J., Wood, R.F., Edwards, M.V. and Aldhouse, J.R. (1957) *Exotic forest trees in Great Britain*. Forestry Commission Bulletin 30. HMSO, London.

Magnani, F. et al. (2007) The human footprint in the carbon cycle of temperate and boreal forests. *Nature*, **447**, 848-852.

Mason, W.L. and Kerr, G. (2004) *Transforming even-aged conifer stands to Continuous Cover Management*. Forestry Commission Information Note 40. Forestry Commission, Edinburgh.

Mason, W.L. (2007) Changes in the management of British forests between 1945 and 2000 and possible future trends. *Ibis*, **149**, (Suppl. 2), 41–52.

Mason, W.L., Nicoll, B.S. and Perks, M.P. (in press) Mitigation potential of sustainably managed forests. In: *The Assessment of UK Forestry and Climate Change*. Forestry Commission, Edinburgh.

Mather, A. and Thomson, K. (1995) The effects of afforestation on agriculture in Scotland. *Journal of Rural Studies*, Vol **11** (2), pp 187-202.

Mather, A., Hill, G. and Nijnik, M. (2006) Post-productivism and rural land use: cul de sac or challenge for theorization? *Journal of Rural Studies*, **22**, 441-455.

Matthews, R. and Robertson, K. (2003) Forest products and bioenergy. In: Karjalainen, T., Apps, M. J., (eds.): *Carbon sequestration in the global forest sector*. IUFRO Task Forces on Environmental Change state of the art report.

Mayle, B., Ferryman, M. and Pepper, H. (2007) *Controlling grey squirrel damage to woodland*. Forestry Commission Practice Note 4. Forestry Commission, Edinburgh.

McKay H., Bijlsma A., Bull G., Coppock R., Duckworth R., Halsall L., Hudson J.B., Hudson R.J., Johnson D., Jones B., Lightfoot M., Mackie E., Mason W., Matthews R., Purdy N., Sendros M., Smith S., Ward S. (2003) *Woodfuel resources in Britain*, Final Report URN03/1436.

MCPFE. (2007) *State of Europe's forests 2007* – the MCPFE report on sustainable forest management in Europe. MCPFE, Warsaw.

Miller, K.F. (1985) *Windthrow hazard classification*. Forestry Commission Leaflet 85. HMSO, London.

Milne R. (2002). *Counting Carbon for Offset Purposes and Estimation of Carbon Offset by Trees*. ECCM Technical Documents No 5-7, Edinburgh.

Moran, D.; MacLeod, M.; Wall, E.; Eory, V.; Pajot, G.; Matthews, R.; McVittie, A.; Barnes, A.; Rees, B.; Moxey, A.; Williams, A. (2008) *UK marginal abatement cost curves for the agriculture and land use, land use change and forestry sectors out to 2022, with qualitative analysis of options to 2050.* Final Report to the Committee on Climate Change, Report No. RMP4950, 152pp.

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.

Mountford, E.P. and Peterken, G.F. (2003) Long-term change and implications for the management of wood pastures: experience over 40 years from Denny Wood, New Forest. *Forestry*, **76**(1), 19-43.

Mountford, E.P. (2006) Long term patterns and impacts of grey squirrel debarking in Lady Park Wood young-growth stands (UK). *Forest Ecology and Management*, ***232***, 100-113.

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: *Climate Change 2007*: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Nijnik, M. (2008) *The Kyoto Protocol and carbon markets: a focus on forestry*. International scientific conference "The European Forest-Based Sector: Bio-Responses to Address New Climate and Energy Challenges? Nancy, Nov. 6-8.

Nijnik, M. (in press) Carbon capture and storage in forests, in: Hester R (ed,) *Carbon capture and storage*, The Royal Society London pubs.

Nijnik, M. and Bizikova, L. (2008) Responding to the Kyoto Protocol through forestry: a comparison of opportunities for several countries in Europe. *Forest Policy and Economics*, **10**, pp 257-269.

Nijnik M, Mather, A. (2008) Analysing public preferences for woodland development in rural landscapes in Scotland. *Landscape and Urban Planning*, №**86**, pp 267-275.

Nijnk, M, Zahvoyska L, Nijnik A, and Ode, A. (2008) Public evaluation of landscape content and change. *Land Use Policy*, №**26**, pp 77-86.

Nijnik, M., Pajot, G., Moffat, A., Slee, B. (2009). *Analysing socio-economic opportunities of British forests to mitigate climate change*. The European Association of Environmental and Resource Economics papers, Amsterdam.

Office of Public Sector Information. (2008) Climate Change Act 2008, London Available at: http://www.opsi.gov.uk/acts/acts2008/ukpga_20080027_en_1

Pajot, G.; Slee, B. and Craig, T. (2009) Community level response to climate change in rural Scotland IARU Conference Climate Change: Global Risks, Challenges Decisions, Copenhagen, 10-12 March 2009.

Peterken, G.F. (1996) *Natural woodland: Ecology and Conservation in northern temperate regions*. Cambridge University Press, Cambridge.

Prebble, C. (2008) *Climate change: opportunities and challenges for the forest and wood-using industry*. Confederation of Forest Industries (UK) Ltd., Edinburgh.

Pyatt, D.G., Ray, D. and Fletcher, J. (2001) *An Ecological Site Classification for Forestry in Great Britain*. Bulletin 124, Forestry Commission, Edinburgh.

Quine, C.P. (2000) Estimation of mean wind climate and probability of strong winds from assessments of relative windiness. *Forestry*, **73**, 237-258.

Ray, D. (2008a) *Impacts of climate change on forests in Scotland* – a preliminary synopsis of spatial modeling research. Forestry Commission Research Note 101. Forestry Commission, Edinburgh.

Ray, D. (2008b) *Impacts of climate change on forestry in Wales*. Forestry Commission Research Note 301. Forestry Commission, Edinburgh.

Ray, D., Pyatt, D.G., and Broadmeadow, M. (2002) Modelling the future climatic suitability of plantation forest tree species. In: *Climate change: Impacts on UK forests*. (M. Broadmeadow (ed.)). Forestry Commission Bulletin 125, Forestry Commission, Edinburgh. pp 151-167.

Ray, D., Wainhouse, D., Webber, J. and Gardiner, B.A. (2008) *Impacts of climate change on forests and forestry in Scotland*. Forest Research, Edinburgh.

Rayden, R.J. and Savill, P.S. (2004) Damage to beech woodlands in the Chilterns by the grey squirrel. *Forestry*, **77**, 249-253.

Redfern, D. and Hendry, S. (2002) Climate change and damage to trees caused by extreme temperatures. In: *Climate change: Impacts on UK forests*. (M. Broadmeadow (ed.)). Forestry Commission Bulletin 125, Forestry Commission, Edinburgh. pp 29-39.

Rollinson, T.J.D. (2007) *Forests and climate change: conclusions and the way forward*. In: Freer-Smith, P.H., Broadmeadow, M.S., Lynch, J.M. (eds,) Forestry and climate change. CABI, Wallingford, pp. 233-240.

Rippengal, R. (2005) *Scoping study: the commercial opportunities of wood fuel heating in Scotland*. A report for Scottish Enterprise, published 17/12/2005.

RCEP (Royal Commission for Environmental Pollution). (2004) *Biomass as a renewable energy source*. A special report by the RCEP. Available at: http://www.rcep.org.uk/bioreport.htm , accessed 30/01/2008.

RSE (Royal Society of Edinburgh). (2008) *Committee of Inquiry into the Future of Scotland's Hills and Islands*, Report. September 2008.

Samuel, C.J.A., Fletcher, A.M. and Lines, R. (2007) *Choice of Sitka spruce seed origins for use in British forests*. Forestry Commission Bulletin 127. Forestry Commission, Edinburgh.

Savill, P.S. (1983) Silviculture in windy climates. *Forestry Abstracts*, **44**, 473-488.

Scottish Executive. (2006) *Changing our Ways: Scotland's Climate Change Programme*. http://www.scotland.gov.uk/Publications/2006/03/30091039/0

Scottish Executive. (2007) *Biomass Action Plan for Scotland*. http://www.scotland.gov.uk/Publications/2007/03/12095912/0

SDC (Sustainable Development Commission for Scotland). (2005) *Wood fuel for warmth*. http://www. sd-commission.org.uk/publications/downloads/ 050626- SDC- Wood-Fuel-for-Warmth.pdf, 2005, accessed 19/03/2006.

Shucksmith, M., Watkins, L. and Henderson, M. (1993) Attitudes and policies towards residential developments in the Scottish Countryside. *Journal of Rural Studies*, Vol **9**(3) pp 243-255.

Sing, L., Peace, A., Ray, D. and Brown, T. (2006) Modelling Sitka spruce yield in southern Scotland. In: K. Reynolds (Editor), *Sustainable Forestry in Theory and Practice*, April 4-8, 2005. USDA Forest Service, Corvallis, Oregon. Edinburgh University.

Smith, P., Smith, J., Wattenbach, M., Meyer, J., Lindner, M., Zaehle, S., Hiederer, R., Jones R., Montanarella, L., Rounsevell, M., Reginster, I., Kankaanpää, S. (2006) Projected changes in mineral soil carbon of European forests, 1990-2100. *Canadian Journal of Soil Science*, **86**, pp 159-169.

SNIFFER (Scotland and Northern Ireland Forum for Environmental Research). (2008) *Differential Social Impacts of Climate Change in the UK*, London. http://www.sniffer.org.uk/resources/UKCC22/LayoutDefault/0.aspx?backur, accessed 12/02/2009.

Sparks, T., and Gill, R. (2002) Climate change and the seasonality of woodland flora and fauna. In: *Climate change: Impacts on UK forests*. (M. Broadmeadow (ed.)). Forestry Commission Bulletin 125. Forestry Commission, Edinburgh. pp 69-82.

Stern Review Report: *The Economics of Climate Change*. (2006) London, UK: Her Majesty's Treasury.

Tipper, R., Carr, R., Rhodes, A., Inkinen, A., Mee, S., Davis, G. (2004) The UK's Forest: a neglected resource for the low carbon economy. *Scottish Forestry*, **58**(3), pp. 8-19.

The Royal Society. (2002) *Economic instruments for the reduction of carbon dioxide emissions*. http://royalsociety.org/displaypagedoc.asp?id=12, accessed 4/07/2006.

Towers, W., Birnie, R., Booth, E., Walker, K., Howes, P. (2004) *Energy from crops, timber and agriculture residue*. SEERAD Report MLU/926/03.

Towers, W., Scharwz, G., Burton, R., Ray, D., Sing, L. and Birnie, R. (2006) *Possible Opportunities for Future Forest Development in Scotland*. A Scoping Study report to Forestry Commission.

Turley, D.B., Boatman, N.D., Ceddia, G., Barker, D., Watola, G. (2004) *Liquid biofuels – prospects and potential impact on UK agriculture, the farmed environment, landscape and rural economy*. Report prepared for DEFRA.

UK Biomass Study. (2007) *Economic analysis of biomass energy*. Energy Technologies Unit Department of Trade and Industry May 2007 URN 07/950. http://www.berr.gov.uk/files/file39040.pdf, accessed 1.07.2009

UKRC. (2007) Climate Change Survey, UKRC/EPC global http://www.setwomenresource.org.uk

UNFCCC. (2004) *Japan marks the Protocol's entry into force on 16 February*. UNFCCC, Bonn. http://unfccc.int/2860.php, accessed 12.01.2008.

Van Kooten, G.C. (2004) *Climate Change Economics*, Edward Elgar, Cheltenham.

Warren, C. (2002) *Managing Scotland's environment*. Univ. Press, Edinburgh.

Watt, A.D. and MacFarlane, A.M. (1991) Winter moth on Sitka spruce: synchrony of egg hatch and budburst, and its effect on larval survival. *Ecological Entomology*¸ **16**, 387-390.

Wesche, S., Kirby, K. and Ghazoul, J. (2006) Plant assemblages in British beech woodlands within and beyond native range: Implications of future climate change for their conservation. *Forest Ecology and Management*, **236**, 385-392.

Worrell, R. and Malcolm, D.C. (1990) Productivity of Sitka spruce in northern Britain, II. Prediction from site factors. *Forestry*, **63**, 119-128.