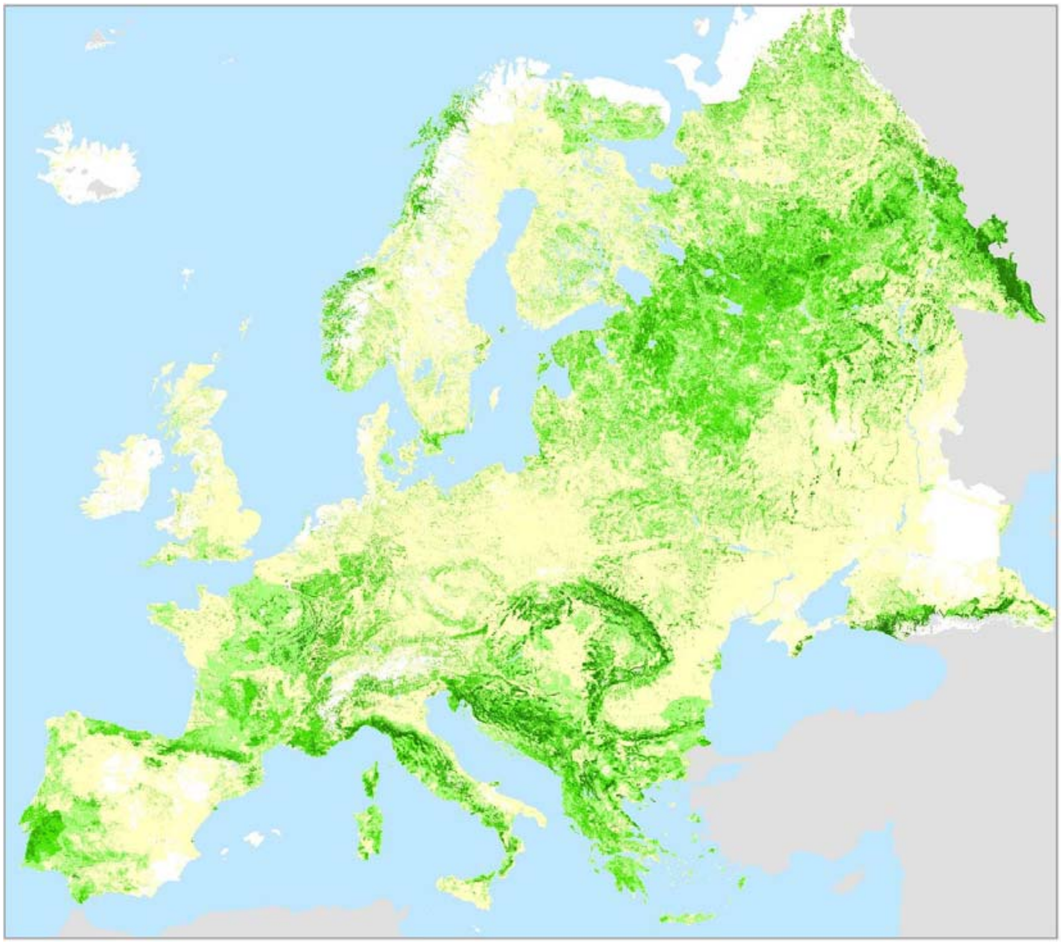
FORESTRY HORIZONS

Forest management and silvicultural responses to predicted climate change impacts on valuable broadleaved species



Short-Term Scientific Mission report for Working Group 1, COST Action E42

May 2007

Gabriel E. Hemery

ValBro

cost

Forest Research
An agency of the Forestry Commission

Acknowledgements

The Management Committee of Working Group 1 for financial support and assistance. Gary Kerr of Forest Research for supervision and personal support.

The following contributed ideas, data and evidence in support of this work:

Pam Berry and James Paterson (ECI, Oxford, UK), Gary Kerr, Mark Broadmeadow and Duncan Ray (Forest Research, UK), Jo Clark (Northmoor Trust, UK), Anantha Prasad (USDA Forest Service, USA), Jo Van Brusselen (European Forest Institute), Renate Köble (University of Stuttgart, Germany).

For supporting the author's study visit to France:

Richard Michalet, Yann Vitasse, Elsa Alfonsi and other staff and students at the University of Bordeaux for hosting the visit and personal support. Also in France: Antoine Kremer, Jean-Michel Carnus, Celine Meredieu of INRA Pierroton, for sharing their expertise and for providing literature and scientific contacts.

Citation

Hemery, G. E. (2007). Forest management and silvicultural responses to predicted climate change impacts on valuable broadleaved species. Short-Term Scientific Mission report for Working Group 1, COST Action E42. 73 pp. 196 refs. www.ForestryHorizons.eu.

Author contact address

Dr Gabriel E. Hemery CEnv MIEEM MICFor

Director

Forestry Horizons

Manor House

Little Wittenham

Oxfordshire

OX14 4RA

United Kingdom

tel: +44 (0)1865 408016

email: g.hemery@forestryhorizons.eu

web: www.ForestryHorizons.eu

Cover image

Calibrated broadleaved forest map of Europe (Schuck *et al.*, 2002)

Contents

1. EXECUTIVE SUMMARY

This report is the product of a Short-Term Scientific Mission conducted for COST Action E42, concerning the predicted impacts of global climate change in Europe, with the aims of: (1) appraising the scientific methods being used to predict the changes that will occur in distributions of valuable broadleaved species, and; (2) outlining forest management and silvicultural responses.

The current distribution and composition of European forests are relics of glacial history, although subsequently influenced by human activity. These forests are relatively species-poor compared to American and Asian forests, due to barriers in European topography limiting the ability of species to migrate and adapt to previous change (advance of ice). Predicted future impacts of climate change are wide ranging, from rising temperature and CO_2 (positive for tree growth in short to medium term), to large scale stochastic events such as increased incidences of fire, drought (frequency and severity), and increase (distribution and impact) of pests and pathogens. There is growing scientific evidence that climate change is impacting plant range and abundance, and examples are provided for impacts on forests and tree species in boreal, continental and Mediterranean biogeographic regions.

Understanding and modelling the impacts of climate change on European forests is crucial to plan for the future, both to minimise impacts through mitigation, and to develop adaptation strategies. It is important that policy interest and scientific activity is now focussed on adaptation as a priority. The shortcomings of climate envelope models were highlighted, in relation to the need to account for biological processes (*e.g.* evolution, interaction, dispersal) and anthropogenic factors. Specifically, the theoretical climate space predicted for many tree species, generally a 100 – 500 km shift north east, is unlikely to be realised due to physical topographic barriers and anthropogenic factors (agricultural, conservation, forestry and urban policies and development). More understanding of evolutionary mechanisms is needed, and wider international collaboration required.

Case studies focussing on modelling in France, the UK and the USA revealed widespread excellence but further scope for collaboration at European and wider scales. In particular, the Climate Change Tree Atlas developed for the north eastern USA, was highlighted as an exemplar. Such a tool, and the underlying pan-European collaboration of scientists (*e.g.* sharing of data and modelling approaches) that would be necessary if such an approach were taken, would be highly valuable as an outcome for scientists, and as a practical tool for forest owners and managers, and policy decision makers. The current lack of detailed distribution and abundance data for the valuable broadleaved tree species of Europe was revealed, where these are often ignored altogether or their identity lost in being grouped together as 'minor species'.

European forests will play a crucial role in the 21st Century. World timber trade trends are difficult to predict but it seems likely that the demand for timber products will rise in the future, and climate change may have a positive impact. A key function of forests will be in supporting a carbon-lean society: where material substitution (timber replacing brick, concrete or steel), bioenergy and management of forests as carbon sinks will be high priority. A stronger regional and domestic market may bring additionality to these functions. The provision of ecosystem services will become higher priority, such as adaptation provision for biodiversity, landscape connectivity, and soil and water protection and management.

Forest management and silvicultural practice must rise to meet these challenges, whilst forest owners should be able to capitalise on the multi-benefit provision from their resource. Assisting forests, tree species and associated biodiversity to adapt to change will be challenging. There may be a greater role for mixed-forests and close to nature forestry practice, and these may provide a more flexible and robust forest resource. The role of genetics and silvicultural best practice must be promoted in the sector. Decision makers will need to address some challenging questions in the light of predicted impacts, particularly in relation to provenance/seed transfer policies and even, with a view to the future, definitions of nativeness. Forestry adaptation strategies should be developed and adopted at regional and local scales, and adopted by certification schemes, to address gene management, forest protection and regeneration, silvicultural management and operations, and delivery of ecosystem services.

Broadleaved forests across Europe will therefore function as an invaluable resource to meet social, environment and economic priorities in the face of climate change. The role of valuable 'minor' species cannot be over stated.

2. INTRODUCTION

2.1. Rationale and objectives.

Valuable broadleaved tree species are an important element of forest production in Europe. Management of forests can contribute to society by providing ecosystem services and social inclusion, as well as income to landowners. However, the current delivery of social benefits using blunt policy instruments is not a sustainable model. Instead, forest owners can seek to maximise income by growing and managing quality timber as a prime objective, while delivering public good. State-of-art knowledge and strategic vision must combine to deliver sustainable forest management across Europe, addressing the mega-trends of climate change and the energy revolution, which are likely to play an increasingly important role in determining the future of Europe's forests. This Short-Term Scientific Mission (STSM) set out to map the likely responses of Europe's trees and woodlands to predicted climate change, and to explore future options for forest management and silvicultural responses to meet this challenge.

The goals of this STSM were to:

1. appraise the scientific methods being used to predict the changes that will occur in species distributions of E42 species;
2. outline some of the forest management and silvicultural responses to predicted global climate change on valuable broadleaved species.

The main body of the report within chapters 3 to 5 is arranged in the following logical sequence:

Chapter 3 - Predicting environmental change and impacts:
What change is detectable now and predicted for the future?

Chapter 4 - The context for European forests, woodlands and trees in the 21st Century
Why are forests important and what services will they be required to provide in the future?

Chapter 5 - Forest management and silvicultural options for the future:
Taking the above into account, how should we manage our forests?

The aims and further background to the COST (Cooperation in the field of Science and Technical research) Action E42[1] are detailed in Appendix III COST E42 and the work of WG1. Valuable broadleaved tree species (Table 1), such as European ash (*Fraxinus excelsior*), sycamore maple (*Acer pseudoplatanus*), wild cherry (*Prunus avium*), walnut (*Juglans regia*, *J. nigra* and hybrids), wild service tree (*Sorbus torminalis*), black alder (*Alnus glutinosa*), lime (*Tilia cordata*) and birch (*Betula pendula, B. pubescens*) are an increasingly important element of forest production in Europe. The natural range of these valuable broadleaved species expands from Finland in the north, to Italy in the south, from Poland in the east to France in the west. Regionally, they often occur in a mixture with other broadleaved trees and conifers.

The role of forests containing these valuable broadleaved tree species is becoming increasingly important; ecologically, socially and economically. High-quality timber from these species consistently realises high prices on the market and demand exceeds supply. Wood of lower quality, of which there is more supply than demand on the market, is of far less value. Even so the demand for valuable timber has increased recently, and there is a notable interest among forest owners and farmers to grow valuable broadleaved species. However, the current level of knowledge of these species is insufficient.

[1] http://www.valbro.uni-freiburg.de/index.php

Table 1 Valuable broadleaved species under consideration by Working Group 1, COST Action E42.

Common name(s)		Scientific name
Maples	Norway maple	*Acer platanoides* L.
	sycamore	*A. pseudoplatanus* L.
Alder	common or black alder	*Alnus* glutinosa (L.) Gaertner
Birches	silver birch	*Betula pendula* Roth
	downy birch	*B. pubescens* Ehrh.
Ashes	common ash	*Fraxinus excelsior* L.
	manna or flowering ash	*F. ornus* L.
Walnuts	common walnut	*Juglans regia* L.
	black walnut	*J. nigra* L.
	walnut hybrids	*J.* hybrids
Cherry	wild cherry	*Prunus avium* L.
Services	wild service tree	*Sorbus torminalis* (L.) Crantz
	service tree	*S. domestica* L.
Limes	small-leaved lime	*Tilia cordata* Mill.
	large-leaved lime	*T. platyphyllos* Scop.
Elm	common or English elm	*Ulmus procera* Salisb.

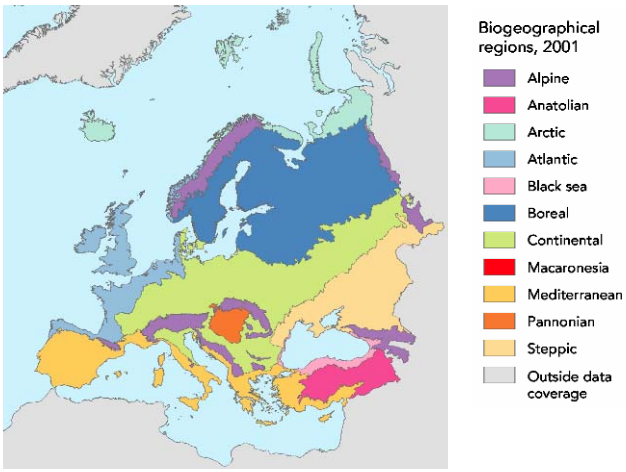


Figure 1 Current biogeographical regions of Europe (Source: http://www.eea.europa.eu © EEA, Copenhagen, 2001).

2.2. European forests – an overview

An understanding of the current composition and distribution of Europe's forests, and how they have changed through time, is important in predicting any impacts from climate change.

The current composition and distribution European forests are a product of long term environmental change affecting the continent. Europe was significantly influenced by glaciation during the Quaternary Period, causing massive regional extinctions of forest communities, particularly thermophilous and temperate species, which only survived in locally favourable refuge areas, primarily located in southern and south-eastern Europe (Petit *et al.*, 2002). The Mediterranean Sea and mountain ranges of Europe (Alps and Pyrenees) acted as barriers limiting the latitudinal migration of species during glaciations, resulting in fewer species recolonising north-west and central Europe during inter-glacial periods. For these reasons the European continent is relatively species-poor when compared with equivalent regions of North America and Asia. With the retreat of the icecap at the end of the Holocene, surviving thermophilous species (*Betula, Alnus, Pinus, Picea, Ulmus, Quercus, Tilia, Corylus*) took part in the post-glacial recovery of forest species in northern and central Europe.

Forest cover and silvicultural practice (*i.e.* plantation forestry) in Europe in the present day is largely influenced and dictated by broad climatic zones (Savill *et al.*, 1997) and biogeographic zones (Figure 1) (European Environment Agency, 2006). Accurate[2] baseline landcover information for Europe is available from The Global Land Cover 2000 (GLC2000)[3] project (Figure 2), overseen by the Joint Research Centre. GLC2000 was carried out to provide accurate baseline landcover information for the International Conventions on Climate Change, the Convention to Combat Desertification, the Ramsar Convention and the Kyoto Protocol.

[2] 1 km resolution

[3] http://www-gem.jrc.it/glc2000/

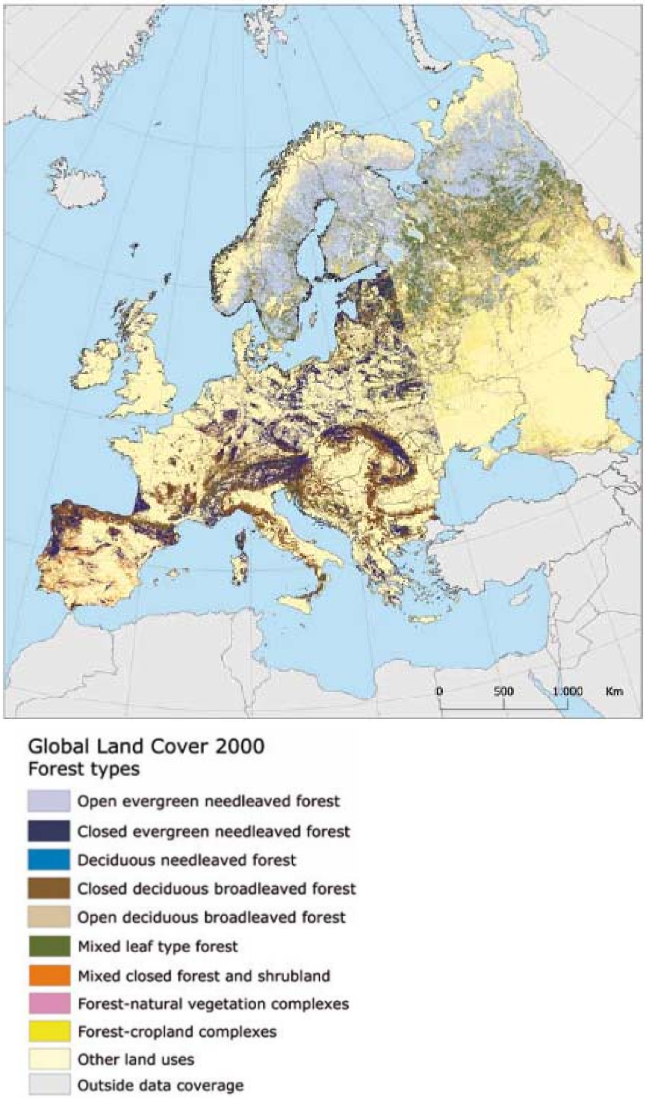


Figure 2 Global land cover 2000 forest types. Source: European Commission, Joint Research Centre.

Information on Europe's main forest types are available (European Environment Agency, 2006). At a detailed level, Pan-European tree species maps[4] (Päivinen *et al.*, 2001; Schuck *et al.*, 2002) provide information of the current composition of European forests by main tree species. The maps correspond both to the Forest Map of Europe (Schuck *et al.*, 2002) and National Forest Inventory statistics. The European Environment Agency (European Environment Agency, 2006) have catalogued and mapped European forests into 14 Categories and 75 types:

1. Boreal forest
2. Hemiboreal forest and nemoral coniferous and mixed broadleaved/coniferous forest
3. Alpine coniferous
4. Acidophilous oak and Oak/birch forest
5. Mesophytic deciduous forest
6. Beech forest
7. Mountainous beech forest
8. Thermophilous deciduous forest
9. Broadleaved evergreen forest
10. Coniferous forests of the Mediterranean Anatolian and Macaronesian regions
11. Mire and swamp forest
12. Floodplain forest
13. Non riverine alder, birch, or aspen forest
14. Plantations and self sown exotic forest.

More detailed species-level forestry information is publicly available from the EFISCEN inventory database[5] providing data (age class distribution, volume and increment per tree species at the sub-national or national level) for 31 European countries. The database is intended for use by a broad range of people who seek information about Europe's forests and its resources (*e.g.* modellers, policy and decision makers, researchers and the general public). For most countries, the input data have been derived from the most recent national forest inventories. Growing stock statistics can be found from national reports to the FAO/ECE Global Forest Resources Assessment 2005 (FRA 2005)[6] (Table 2). Broad scale vascular plant distribution data is available (e.g. Jalas and Suominen, 1976). It is interesting to note that there is no overall European database detailing species-level information such as distribution and abundance. However some preliminary European species maps were modelled by combining three pan-European data sets by Köble and Seufert (2001) (Figure 3).

---

4 Required text: This information is based on outputs from the project "Forest tree groupings database of the EU-15 and pan-European area derived from NOAA-AVHRR data", which was awarded by the European Commission, Joint Research Centre (Institute for Environment and Sustainability), to a consortium consisting of EFI, VTT Information Technology and the University of Joensuu under the contract number: 17223-2000-12 F1SCISPFI. The information contained herein has been obtained from or is based upon sources believed by the authors to be reliable but is not guaranteed as to accuracy or completeness. The information is supplied without obligation and on the understanding that any person who acts upon it or otherwise changes his/her position in reliance thereon does so entirely at his/her own risk. The European Commission nor the project consortium are responsible for its use in this publication and the content is at the sole responsibility of the end-user. http://www.efi.fi/information-services/pan-european-treesp-maps.html

5 www.efi.int/databases/efiscen/intro.php

6 http://www.fao.org/forestry/site/32179/en/

Table 2 National forest inventories available online. Some provide more detailed information at species level.

Country	Web link
Austria	http://web.bfw.ac.at/i7/oewi.oewi0002
Belgium (Wallony)	http://mrw.wallonie.be/dgrne/dnf/inventaire/chifp2.htm
Czech Republic	http://www.uhul.cz/il/vysledky/index.php
Estonia	http://www.metsad.ee/trykised_eesti_metsad.html and http://www.metsad.ee/avalik_m_statistika.html
Finland	http://www.metla.fi/julkaisut/metsatilastollinenvsk/
France	http://www.ifn.fr/spip/
Germany	http://www.bundeswaldinventur.de
Italy	http://www.ifni.it/
Luxembourg	http://www.environnement.public.lu/forets/dossiers/foret_lux/index.html
Macedonia	http://www.soer.moe.gov.mk/forest/index.htm
Netherlands	some tabular data available from: http://www.probos.net/bosdigitaal/
Norway	http://www.nijos.no/index.asp?startID=&topExpand=&subExpand=&menuid=1000415&strUrl=1002200i&context=2
Slovak Republic	http://www.fris.sk/en/index2.htm
Spain	http://www.mma.es/conserv_nat/inventarios/ifn/html/ifn2/existen_ccaa_201.htm
Sweden	http://www.svo.se/minskog/Templates/EPFileListing.asp?id=16863
Switzerland	http://www.lfi.ch/resultate/tabellen.php
United Kingdom	http://www.forestry.gov.uk/forestry/hcou-54pg4d

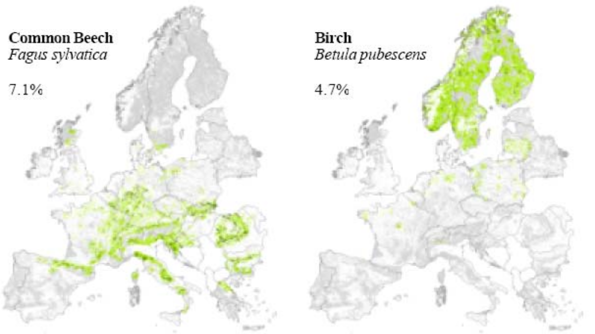


Figure 3 Species-level maps for two common broadleaved species in Europe. Bright green tones indicate a coverage < 50 % within the km² forest grid, dark tones > 50 %, grey = 0. Values below the species names refer to the percentage of the respective species in the total EU30 forest area (Köble and Seufert, 2001).

Unpublished data behind this work (Köble and Seufert, 2001) provides more information on some of the COST E42 species, provided by Renate Köble[7] (*pers. comm.*) (Table 3). However, the uncertainties in the data, especially for 'minor' tree species, might be quite high (Renate Köble, *pers. comm.*). Unfortunately the national forest statistics very often do not provide data for minor species or only in an aggregated way (*e.g.* as 'other broadleaves').

Some distributional maps, but not distributional data, are available for some species from the EUFORGEN website[8].

Modern long-term trends in forest resources in Europe have been towards stability and growth, with the forest area, growing stock and increment consistently increasing in Europe over recent decades (UNECE-FAO, 2006). The total area of forest and other wooded land has increased by 3 % (36 Mha) since 1980. For the European countries where long-term historical trends are available, growing stock has increased by 17 % and annual increment has risen by 33 % in total since 1950 (UNECE-FAO, 2006).

Europe's forests are growing faster than the annual level of fellings and this gap between fellings and increment has increased since 1960, with an European average felling-to-increment ratio of about 45 % (UNECE-FAO, 2006).

It is difficult to measure qualitative aspects of Europe's forests, but the little information that exists suggests that the quality of forest resources and forest management in Europe has probably been quite stable and may have increased in some respects (UNECE-FAO, 2006). The management of forests in Europe has followed a gradual and long term trend towards management for objectives other than wood production.

[7] Institute of Energy Economics and the Rational Use of Energy (IER), Department of Technology Assessment and Environment (TFU), University of Stuttgart.

[8] European Forest Genetics Programme: http://www.bioversityinternational.org/Networks/Euforgen/Euf_Distribution_Maps.asp

Table 3 Estimated proportional cover across the EU34 forest area for some broadleaved species. Based on unpublished data (Renate Köble, *pers. comm.*).

Tree species	Area cover in EU34(km^2)	% cover in EU34
Betula pubescens	77863	54.287
Betula pendula	38594	26.908
Fraxinus excelsior	9959	6.943
Acer platanoides	5623	3.920
Tilia cordata	3521	2.455
Prunus avium	2514	1.753
Acer sp.	2021	1.409
Fraxinus ornus	1509	1.052
Tilia platyphyllos	722	0.503
Sorbus aria	611	0.426
Sorbus torminalis	268	0.187
Sorbus domestica	165	0.115
Juglans regia	47	0.032
Juglans nigra	13	0.009

2.3. Climate change science and scenarios

Global circulation models (GCMs), the most complex of climate models, attempt to represent the main components of the climate system in three dimensions. GCMs are the tools used to perform climate change experiments from which climate change scenarios (possible representations of how the climate will evolve) can be constructed. They address radiative, dynamic, surface processes and provide the foundation to all aspects of climate change science and policy. The latest GCMs (*e.g.* HadleyCM3, GFDL CM2.1, PCM) combine atmospheric, ocean, sea-ice and land-surface data to represent historical climate variability and to estimate long-term increases in global temperature.

The Intergovernmental Panel on Climate Change (IPCC) released the Fourth Assessment Report (‘AR4’) in 2007. The reports by the three Working Groups provide a comprehensive and up-to-date assessment by many hundreds of climate scientists worldwide of the current state of knowledge on climate change. Working Group I address the *Physical science basis* (IPCC, 2007c), Working Group II *Impacts, adaptation and vulnerability* (IPCC, 2007a), and Working Group III *Mitigation* (IPCC, 2007b).

Key relevant findings from the Fourth Assessment Report are:

1. Global greenhouse gas (GHG) emissions have grown since pre-industrial times, with an increase of 70 % between 1970 and 2004 (IPCC, 2007b).
2. The understanding of anthropogenic warming and cooling influences on climate has improved since the Third Assessment Report (TAR), leading to “*very high confidence*” that the globally averaged net effect of human activities since 1750 has been one of warming (IPCC, 2007c).
3. Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level (IPCC, 2007c).
4. At continental, regional, and ocean basin scales, numerous long-term changes in

climate have been observed. These include changes in Arctic temperatures and ice, widespread changes in precipitation amounts, ocean salinity, wind patterns and aspects of extreme weather including droughts, heavy precipitation, heat waves and the intensity of tropical cyclones (IPCC, 2007c).

5. Observational evidence from all continents and most oceans shows that many natural systems are being affected by regional climate changes, particularly temperature increases (IPCC, 2007a).
6. With current climate change mitigation policies and related sustainable development practices, global GHG emissions will continue to grow over the next few decades (IPCC, 2007b).
7. Agricultural practices collectively can make a significant contribution at low cost to increasing soil carbon sinks, to GHG emission reductions, and by contributing biomass feedstocks for energy use (medium agreement, medium evidence: IPCC, 2007b).
8. Anthropogenic warming and sea level rise would continue for centuries due to the timescales associated with climate processes and feedbacks, even if greenhouse gas concentrations were to be stabilized (IPCC, 2007c).

Globally, commercial timber productivity is forecast to rise modestly with climate change in the short to medium term, with large regional variability around the global trend (IPCC, 2007a).

It is also worth noting that agricultural and forestry activities during the period of civil society may have been exerting an influence on climate for at least the last 8000 years (Salinger, 2007).

2.3.1. Evidence for recent climate-induced change in European forests

Effects of temperature increases have been documented (with 'medium confidence') on agricultural and forestry management at Northern Hemisphere higher latitudes, such as earlier spring planting of crops, and alterations in disturbance regimes of forests due to fires and pests (IPCC, 2007a).

A suite of large scale analyses generates 'very high confidence' (as laid down by the IPCC) that climate change is already affecting living systems (Parmesan and Yohe, 2003). A comprehensive review by Parmesan (2006) summarised widespread evidence for range shifts and changes in abundance for many animals and plants, in response to global climate change.

In relation to change affecting biomes, forests and tree species, evidence is growing. For example, long term data of floral distribution and abundance are revealing change (*e.g.* Lavergne *et al.*, 2006), whilst Penuelas and Marti (2003) provide specific evidence for a whole-scale biome shift in the mountains of north east Spain. Soja *et al.*, (2006) state that there is substantial evidence throughout the circumboreal region to conclude that the biosphere within the boreal terrestrial environment has already responded to the transient effects of climate change. An analysis of data from 1953-2002 by Lapenis *et al.*, (2005) demonstrated acclimation of trees to warming and precipitation. They detected a pronounced increase in the proportion of tree greenery (leaves and needles) across Russia although there was large geographical variation. Increases were greatest within European Russia, where summer temperatures and precipitation have increased. In the Northern Taiga of Siberia, where the climate has become warmer but drier, greenery decreased, whilst the proportion of aboveground wood and roots increased. These changes are consistent with experiments and mathematical models that predict a shift of carbon allocation to transpiring foliage with increasing temperature and lower allocation with increasing soil drought. Truong *et al.*, (2007) reported change in Boreal forests in northern Sweden, where an altitudinal shift in the tree line species mountain birch, *Betula pubescens* ssp. *tortuosa* is attributed to climate warming. Genetic data confirmed the high migration potential of the species in response to fluctuating environmental conditions and indicated that it is now invading higher altitudes due to the recent warming of the climate.

A temperate forest example is provided by Loacker *et al.*, (2007) where the spread of walnut (*Juglans regia*) in Alpine valleys in Austria, was attributed to milder winters having favoured seed germination and seedling survival.

2.4. Summary

The current distribution and constitution (paucity) of Europe's forests are features of previous environmental change (glacial activity).

Some good data are available providing estimates of current forest type distribution across Europe. However, detailed information for individual species, especially the so-called 'minor species' of interest here, is scarce. Estimating impacts of climate change, particularly on valuable broadleaved species, is very difficult without adequate data on current distributions. Improved data provision at a European scale would support scientific programmes and guide policy making.

The most recent IPCC reports indicate more strongly than ever before that climate change is detectable in natural systems and attributable to anthropogenic factors.

A substantial and growing evidence base is indicating that climate change is already impacting biomes, communities and individual tree species across Europe.

3. Predicting Environmental Change and Impacts

3.1. Introduction

The previous section summarised compelling evidence for recent changes in plant distribution, phenology and even extinction. Projections of future responses of forest ecosystems and individual tree species are complex to model. For forecasts to be accurate they need to be interdisciplinary, combining different modelling tools to address environmental change impacts, site effects (soil, altitude, aspect *etc.*), climate envelope, forest ecosystem dynamics (species and their interaction), and evolutionary mechanisms (genetics). This chapter reviews each of these in relation to European forests.

Growth in European forests is greater now, in the early 21st Century, than a hundred years ago. In part this may be due to improvements in silviculture, forest management or genetic quality. It is likely that increasing CO_2, nitrogen deposition and temperature are positively affecting biomass growth but their relative contributions are difficult to quantify at present (Broadmeadow and Randle, 2002).

Experts agree that natural disturbances will increase in frequency and intensity in response to global warming during this century (IPCC, 2007a). Extreme climate events such as spring temperature fluctuations and summer drought will increase in frequency and duration. In combination with a raised mean temperature, climate extremes will negatively affect trees and increase their susceptibility to secondary damage through pests and pathogens. Extreme events are likely to have a profound affect on Europe's forests and natural resources, for example on boreal (Schlyter *et al.*, 2006), alpine (Fuhrer *et al.*, 2006) and lowland forests (Dorland *et al.*, 1999).

This chapter discusses climate envelope mapping and considers the likely impacts of environmental change on forest ecosystem dynamics and evolutionary mechanisms. The final section, entitled Modelling change, presents three case studies where different elements of these processes have been applied to model, or as a knowledge-based tool to predict, species' responses to climate change.

3.2. Climate envelope mapping

Climate envelope models are commonly used to predict the responses of species to climate change scenarios. As Booker (2006) explains, a range of climate parameters are fitted to existing species distributions and, using future climate scenarios produced by global circulation models (GCMs), the possible future distribution of the species is then calculated. However, climate envelope models have been criticised for ignoring biological processes such as evolution, dispersal and interaction (Hampe, 2004), although the debate continues (Pearson and Dawson, 2004). A key challenge for future research is integrating factors such as land cover, direct CO_2 effects, biotic interactions and dispersal mechanisms into species-climate models (Heikkinen *et al.*, 2006).

Projects such as MONARCH (Berry *et al.*, 2005) provide individual species level information for some woodland species in the UK using an envelope modelling approach. MONARCH[9] was a seven year study on the impacts of climate change on nature conservation in the UK and Ireland. The model was developed and improved by considering changes in species' distribution and dispersal and broad-scale changes in land use. Future climate envelopes for 120 biodiversity action priority (BAP) species have been mapped (Walmsley *et al.*, 2007).

[9] http://www.eci.ox.ac.uk/research/biodiversity/monarch.php

3.3. The geography of change

The sensitivity of forest growth to climate change and management will vary across Europe. In the main bioclimatic zones of Europe (Figure 1), the limitations and potential for forest production in current and future climate (Kellomäki and Leinonen, 2005b) will be:

- **northern boreal** - production is mainly limited by low temperature, and often by nutrient availability. Precipitation is normally not limiting. Higher air temperature predicted by scenarios for the future climate will prolong the growing season and thereby increase production.
- **southern boreal** - production is more limited by water, and less by temperature and nutrients, resulting in a higher production than in the North.
- **temperate maritime** - production is higher than in the boreal zone; this is the result of higher air temperature and less water limitation.
- **temperate continental** - production is generally more constrained by water than in the temperate maritime zone.
- **Alpine** - production is water limited at low altitudes, but not at higher altitudes where precipitation was significantly higher. In future climate at low altitudes a loss in production is likely if not counteracted by an increase in production as a result of elevated CO_2. Production at higher altitudes will increase in the future climate, mainly because of a prolonged growing season.
- **Mediterranean** - production is limited by low air humidity and soilwater because of high evaporative demand. Production in future climate will likely be less compared to that today.

Climate changes will impact first and most notably at the extreme limits of a tree species' range in boreal, Alpine and Mediterranean regions, and less severely in continental regions.

Mediterranean forests are susceptible in many ways and impacts are already evident (Lavergne *et al.*, 2006; Resco de Dios *et al.*, 2007), whilst specific studies illustrate, for example, impacts from insects (Battisti, 2004), fire (Carvalho *et al.*, 2006), and on phenology (Orshan, 1989) and seedling diversity (Lloret *et al.*, 2004).

Many studies have been conducted on impacts of climate change on Boreal forests (*e.g.* Bergh *et al.*, 2003; Lapenis *et al.*, 2005; Schlyter *et al.*, 2006), and recent distributional change (Truong *et al.*, 2007) and growth (Briceño-Elizondo *et al.*, 2006) whilst specific studies illustrate the importance of phenology (Heide, 2003; Kramer, 1999; Kramer *et al.*, 2000; Partanen, 2004).

3.4. Environmental change impacts on forests and trees

3.4.1. *Temperature*

Temperature changes are widely predicted to profoundly affect trees and forests by altering photosynthesis and respiration, soil organic matter decomposition and mineralisation, phenology and frost hardiness, species distributional changes, and adaptation and evolution.

In a review of extreme scenario planning for the UK, Semenov (2007) developed a methodology to construct daily site-specific climate scenarios, based on a stochastic weather generator. Under a warmer climate, extreme statistics related to temperature, such as heat-waves, are predicted to increase substantially in magnitude and frequency.

Saxe *et al.,* (2001) summarise the responses of temperate and boreal trees and forests to change in temperature:

- photosynthesis and respiration;
  warmer temperatures may enhance photosynthesis and overall, a warming of up to 2°C may be beneficial but response is species dependent.

- soil organic matter decomposition and mineralisation;
  soil decomposition is affected by warming and elevated CO_2, vegetation cover, and human disturbance, but currently modelling is not predicting clear trends.

- phenology and frost hardiness;
  tree growth (cessation and onset) at high and temperate latitudes are regulated by temperature and night length. For broadleaves bud burst timing is of paramount significance. This is covered in more detail below.

- species distributional changes;
  change in growing season length and rising soil temperatures may permit tree species to migrate or be transplanted northwards in Europe but precipitation and other factors may in reality limit the success of any movement.

- adaptation and evolution.
  essentially a tree's ability to resolve the utilisation of the growing season (for growth and breeding) whilst minimising frost damage.

3.4.2. *Co₂*

Increases in this greenhouse gas (GHG) not only affect the global climate but directly impact plant photosynthesis and respiration. Difficulties in implementing experimental studies of increased CO_2 on trees, particularly mature trees, have limited scientists' ability to fully understand any effect, particularly in the longer term. However, in general research has indicated increased growth rates but with impacts on water use, carbon, nutrient allocation and timber quality (Broadmeadow and Randle, 2002).

3.4.3. *Fire*

For many decades the policy of the United States Forest Service was to suppress all fires. This policy was epitomized by the mascot Smokey Bear. The policy began to be questioned in the 1960s, when it was realized that Giant Sequoia trees (*Sequoia sempervirens* Lamb. ex D. Don) were not regenerating in the forests of California, as fire is an essential part of their life cycle.

Today it is accepted that wildfires are a natural part of some forest ecosystems, where plants have evolved to survive fires by a variety of strategies (from possessing reserve shoots that sprout after a fire, to fire-resistant seeds), or even encourage fire (for example eucalypts contain flammable oils in their leaves) as a way to eliminate competition from less fire-tolerant species. Fire is one of nature's primary carbon-cycling mechanisms but human activity interferes with, and confounds, this mechanism (Saxe *et al.*, 2001). When the weather conditions are conducive to the expansion of forest fires, this anthropogenic effect becomes especially pronounced. Backward modelling of forest fire incidences with climate records in Siberia and the Russian Far East indicate increased likelihood of forest fires for these areas in the future (Groisman *et al.*, 2007). Another study, this time for southern Europe, estimated 100 % increases in fire incidences in most districts of Portugal (Carvalho *et al.*, 2006).

The main concern for most of Europe is the impact on the forest environment which, in the most part, is neither adapted (*e.g.* serotinous) nor dependent on wildfires. Native species will be poorly adapted and changes to forest ecology difficult to predict although it is likely that fast colonizers and non-native invasive species may alter existing communities. The other issue for Europe, and where it differs from North America, is the lack of large tracts of wilderness, therefore the conflict of human interest and natural forest management may be difficult to resolve in countries with high population densities.

3.4.4. Drought

Few studies have assessed the impact of summer droughts on forest biodiversity and ecosystem functioning (Archaux and Wolters, 2006). Generally drought will impact by negatively affecting ecosystem productivity and increasing mortality. Competitive species, those adapted to cold and wet conditions, as well as species with low reproduction rates and/or limited mobility, seem to be the most affected. However, species-specific effects are regulated by mechanisms allowing for resistance to drought. The short-term consequences of drought on biodiversity depend on a species' ability to resist and to recover after drought, and on competitive interactions between species. Although the abundance of many species generally decreases during drought, some taxa may increase in number during drought or shortly after (Archaux and Wolters, 2006). Fuhrer *et al.,* (2006) cite evidence for intraspecific variation in response to drought conditions and consequently, more frequent exceptionally dry summers could have a more serious impact than a single event and would give certain species a competitive advantage. Indeed, relictual taxa are more drought tolerant than extinct taxa (Svenning, 2003). Therefore in the long run, a change in the frequency of hot and dry years could affect tree species composition and diversity.

The severe (in duration and intensity) drought of 2003 serves as a recent and real example of drought impact in Europe. In some areas, especially in Germany and France, it was the strongest drought for the last 50 years, lasting for more than six months. Granier *et al.,* (2007) modelled the onset date, and duration and intensity of soil water shortage using measured climate and site properties: namely, leaf area index and phenology (that both determine tree transpiration and rainfall interception), and soil characteristics and root distribution (both influence water absorption and drainage). Their work indicated a wide spatial distribution of drought stress over Europe, with a maximum intensity within a large band extending from Portugal to NE Germany. A higher sensitivity to drought was found in beech, and surprisingly, in the broadleaved Mediterranean forests. The effect of drought on tree growth was also large at the three sites where annual tree growth was measured. A pronounced lag effect was detected, especially in beech, where growth reduction was more pronounced in the year following the drought (2004).

One forester's personal observations on the impacts on trees following the 1976 severe drought in the UK provides a detailed insight in respect to the E42 species (Coultherd, 1978) (

Table 4). A detailed study of *Fagus sylvatica* in one mixed woodland revealed effects over 16 years following the 1976 drought in England (Peterken and Mountford, 1996). Furthermore, these authors recorded marked changes in the structure and future successional patterns in the wood. This emphasises the impact that climate change may have on one sensitive species and how this may indirectly affect other species in mixed woodland communities.

Archaux and Wolters (2006) conclude that more information is required to understand the effects of droughts on plants and communities. They particularly recommend the development of a drought classification scheme for plants, linked to sensitivity to drought or to environmental features associated with drought, as these species will be the first to be seriously affected. Archaux and Wolters (2006) also call for research focussed on the simultaneous effects of drought and other factors, such as forest management, pollution and global warming. The impact of strategies that are being proposed to mitigate the effects of drought on trees on forest biodiversity should be rapidly evaluated, especially the impact of the plantation of drought-tolerant tree species and of the reduction of the rotation length. They highlight the effects of drought events on forest biodiversity and suggest they should be considered in both planning (*e.g.* tree species selection) and forest management (*e.g.* retention of deadwood). In light of this lag effect the effects of recurrent droughts on species vulnerability and habitat change need to be further studied.

Table 4 The effect of the 1976 drought on established and recently-planted trees in the UK (Coultherd, 1978).

Species	Symptoms and possible causal factors
Acer platanoides and *A. pseudoplatanus*	Maples suffered some premature leaf fall though generally did well. *A. monspessulanum, A. opalus* and *A, platanoides* were better than others. A. *campestre* being an exceptionally good transplant in severe conditions. As expected very large open grown maples suffered due to high transpiration rates. No deaths recorded except with sooty bark disease on sycamores.
Alnus glutinosa	The common alder had a very good crop of catkins but this tree, which likes waterside habitats, suffered as water tables lowered. Wilting and leaf fall ensued.
Betula pendula and *B. pubescens*	*B. pendula,* the silver birch, died throughout the country on all sites, complicated by honey fungus. *B, pubescens* and *B. papyrifera* also suffered and died. Problems of short root system. 'Difficult' transplant.
Fraxinus excelsior and *F. ornus*	*F. excelsior* surprisingly did not suffer too badly—some wilting, but generally no drought problems. The ash's vigorous root system was probably the answer.
Juglans regia, J. nigra and hybrids	Walnuts did very well in 1976, the common walnut, *J. regia* having an exceptional crop of nuts.
Prunus avium	Species in the *Prunus* genus had mixed fortunes in 1976. However, *P. avium,* the native wild cherry or gean was outstandingly resistant, and flourished.
Sorbus torminalis and *S. domestica*	*S. aucuparia,* the mountain ash did very well in the drought conditions. Fruiting was magnificent. *S. aria* (native to UK) survived the summer as well as any species. The white 'down' (hairs), on the underside of the leaves, playing an important part in restricting water loss.
Tilia cordata and *T. platyphyllos*	The common lime [hybrid?], like other members of the genus, suffered badly in 1976. *T. cordata,* the small-leaved lime, is a native species and fared better than the others. Premature leaf fall, and heavy wilting was common. Aphid problem.
Ulmus procera	Elms which were suffering from elm disease, were killed off. The 'early autumn' effect of the drought enabled diseased trees to be located. The warm summer encouraged the breeding of bark beetles. The 'aggressive' strain of the disease spread further north.

3.4.5. Wind

Extreme wind events are a major cause of natural disturbance in forests of eastern North America, accounting for thousands of hectares of disturbed area annually (Peterson, 2000). Although Tornados are the most extreme of these events, downbursts are important type of wind disturbance in the Great Lakes area. Downbursts vary widely in size, but large ones can damage thousands of hectares, while tornadoes are much smaller, seldom affecting more than several hundred hectares.

Windthrow damage in Europe increased in the 20th Century but loss of timber was typically smaller than annual timber harvests (Schelhaas *et al.*, 2003). Windthrow can also have positive ecological effects but where damage levels exceed harvesting or salvage harvesting costs are high, *e.g.* in mountainous terrain.

Dorland *et al.,* (1999) estimate annual mean insured damages could increase by 80 % in 25 years (the year 2015) due to a 2 % increase in highest wind speed in the Netherlands.

3.4.6. Extreme precipitation

Heavy precipitation can be associated with high costs, both financial and human life, and can impact the environment particularly through loss of fertile topsoils by soil erosion. Fuhrer *et al.,* (2006) for example, cite evidence for severe impacts of heavy precipitation in Switzerland, noting that these were attributable to relatively few but extreme events.

Simulations undertaken with GCMs suggest that a global-scale climate warming could be associated with a substantial increase atmospheric moisture content of about 7 % per degree of warming (Frei *et al.*, 2000). Frei *et al.,* (2000) argue that climate change should in fact refer more to "climate moistening" than to "climate warming".

Frei *et al.,* (2000) summarise that for future precipitation in the Alpine and pre-Alpine region, the temperature–moisture feedback is likely to play an important role during cold seasons. During the summer season, however, changes in heavy precipitation events are more difficult to assess, as these are affected by additional factors. This uncertainty comes from the fact that summer precipitation over the European continent is affected by the underlying land surface.

Changes to forest cover, tree health and the rainfall climate will also impact water flow. There is concern for any impact on soil carbon due to increased run off. However, trees and forests play an important role in regulating hydrological processes. Forest management will therefore become an increasingly important tool in the future in ameliorating the effects of extreme precipitation.

3.4.7. Frost

For species with a large chilling requirement, milder winters might result in inadequate chilling and hence delayed and erratic bud burst in spring (Cannell and Smith, 1986). Climatic warming may cause premature bud burst of trees in Finnish conditions during mild spells in mid-winter resulting in heavy frost damage during subsequent periods of frost. (Hänninen, 1996).

A practical example, both for the impact of frost and of the need for genetic diversity in forest stands, was in the forests surrounding INRA Pierroton (SW of Bordeaux, France) where 300 ha of land forested with maritime pine (*Pinus pinaster* Aiton.) was destroyed by fire in 1949 (Antoine Kremer[10], *pers. comm.*). The reforestation of this large area required seeds to be brought in from Portugal after local seed stocks were exhausted. Trees grew well until a severe frost several decades later killed virtually all trees of Portuguese provenance. This example starkly demonstrates the impact of extreme events. It also highlights that if these provenances had survived long enough to hybridise with local populations, then this may have been beneficial for fitness but this was prevented by a single extreme stochastic event.

3.4.8. Pests and pathogens

Predicting future pest and pathogen trends is difficult because of the fine balance between pest / pathogen, the health of the host tree species, and any natural defence mechanisms/pest predators. However, stressed trees are more susceptible to insect pests and diseases, and many insect pests are likely to benefit from climate change as a result of increased breeding activity and reduced winter mortality.

One example of a scientific project addressing this is within the CARBOFOR project[11]: *Evaluer et hiérarchiser les risques et impacts de stress abiotiques et de pathogens* [Evaluating and treating on a hierarchical basis the risks and abiotic impacts of stress and pathogens], coordinated by Jean-Luc Dupouey, INRA.

Insects

Climate change has been linked with range expansion northward and upward of several insect species of northern temperate forests. Several

[10] Research Director Biodiversity Research Unit, INRA Bordeaux, France

[11] http://www.pierroton.inra.fr/carbofor/index.htm

papers have dealt with the prediction of the most likely consequences of climate change on phytophagous insects, including some of the most important forest pests (*e.g.* Schlyter *et al.*, 2006). Increased levels of CO_2 in the atmosphere involve an increase of the C/N balance of the plant tissues, which in turn results in a lower food quality for many defoliating insects (Battisti, 2004). The response of some insect species is to consume more and consequently increasing damage to the tree, whereas others show higher mortality and lower performance. The level of plant chemical defences may also be affected by a change of CO_2. Temperature can affect either the survival of the insects which are active during the cold period, such as the pine processionary moth (*Thaumetopoea pityocampa*), or the synchronization mechanism between the host and the herbivores, as in the case of the larch bud moth (*Zeiraphera improbana*). An increase of temperature may alter the mechanism by which the insects adjust their cycles to the local climate (diapause), resulting in faster development and higher feeding rate. Outbreaks of spruce webspinning sawfly (*Cephalcia arvensis*) outbreaks in the Southern Alps are an example of favourable climatic conditions interfering with the mechanism of the induction of extended diapause, allowing an exponential growth of the population and consequent damage to trees (Battisti, 2004).

It is extremely difficult to predict with any certainty the impact of climate change on insect pests but it seems certain that their distributions will change. Impacts on our valuable broadleaved species are also uncertain as much of current scientific work in this area has focussed on coniferous species. The impact of facultative pathogens such as sooty bark disease of sycamore may worsen, while some insect pests that are present at low levels, or currently not considered important, may become more prevalent (Broadmeadow, 2000). Examples of the latter include defoliating moths and bark beetles. Further work in this area is important as impact from new or more abundant populations of existing pests should be carefully considered when selecting species for afforestation.

Other pests

The direct impact on forests from herbivorous mammals in light of a changing climate does not seem to have been considered in depth by the scientific community. Existing concerns in parts of Europe (*i.e.* Italy and the UK) of the spread of the grey squirrel (*Sciurus carolinensis*) are likely to worsen with the continued spread of this damaging species, predicted to reach both France and Switzerland in the 2020s[12]. Squirrel damage to the UK forest resource in 2000 was estimated to cost €17 million[13]. Climate change may enhance the species' ability to expand due to increasing food supplies (*i.e.* tree seed setting) and reduced winter temperatures leading to lower mortality (Broadmeadow, 2000).

Populations of deer are also likely to increase, again as a result of reduced winter mortality. Also, increased growth of ground vegetation is likely to increase forage availability during the critical spring period (Langvatn *et al.*, 1996).

Pathogens

Predicting the effects of climate change on tree pathogens is possible but again, the issue of interest is the interaction between pathogen and host and this is more difficult to predict. It seems certain than reduced health of tree species due to stress (*e.g.*. from drought) is likely to increase susceptibility. A large number of published studies suggest a positive association between drought, disease, and tree health status, with a predominance of canker/dieback diseases caused by pathogens such as *Biscognauxia, Botryosphaeria*, , *Cytospora, Phytopthera* (Figure 4) and *Sphaeropsis* (Desprez-Loustau *et al.*, 2006).

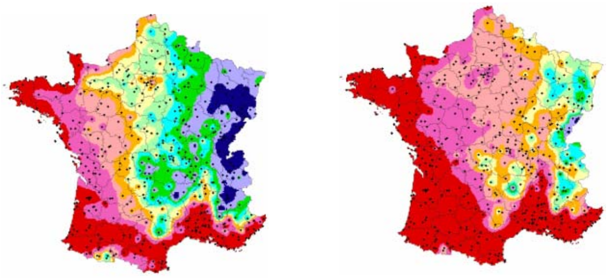


Figure 4 Projected spread of cold-limited thermophilic species *Phytopthora cinnamomi* on *Quercus robur* in France, 1960-1990 (left) and 2070-2100 (right) (Desprez-Loustau et al., 2006). Warm colours denote population increases, cool colours decreases.

Lonsdale and Gibbs (2002) summarise a wealth of evidence concerning direct impacts from climate change on pathogens, effects on their reproduction, dispersal and winter activity, together with direct effects on host tree species and the interaction between host and pathogen (Table 5).

12 http://www.europeansquirrelinitiative.org/italydownload.html

13 http://www.forestry.gov.uk/pdf/greysquirrel-annex.pdf/$FILE/greysquirrel-annex.pdf

Table 5 Some pathogens and their likely impact on broadleaved tree species in Europe (source: Lonsdale and Gibbs, 2002).

Pathogen(s)	Host	Notes
Armillaria sp.	Broadleaves	Host stress can increase susceptibility. Drought could be a major stress cause.
Botryospaeria canker	*Sorbus aucuparia*	Fungal canker development promoted by frost damage.
Cristulariella pyramidalis	*Juglans nigra*	Leaf spot fungi activity may decrease with reduction in summer rainfall.
Cryptostroma corticale	*Acer pseudoplatanus*	Often present in host but becomes prevalent during drought stress.
Diatrypaceae and *Xylariaceae* families	Broadleaves	Often found in healthy trees but becomes fatal when tree host stressed by drought. *e.g. Biscogniauxia mediteranea* damage to *Quercus cerris* and *Q. suber* in southern Europe.
Phytopthora cinnamomi	Broadleaves	A widespread fungi causing root and stem-based diseases, predicted to spread with increasing year-round temperatures.

3.5. Forest ecosystem dynamics

Climate change is already affecting species distributions and ecosystem functioning worldwide. Niche-based models can be used to analyse the potential impact of climate change on tree species' fundamental niche (climate space) and functional diversity. Ecologists are increasingly conscious of the need to encapsulate a wider complexity of information to provide better knowledge and predictability of natural systems.

3.5.1. Forest communities

European forests and their component tree species will play a vitally important role in supporting ecological communities under changing environmental conditions.

Interactions between plants, or 'plant-plant interactions' (Brooker, 2006), play an important role in understanding and modelling environmental change. As discussed above, simple climate envelope models have traditionally dismissed these interactions but there is evidence that plant-plant interactions can have a considerable modifying affect. One study demonstrated a strong effect of *Nothofagus* spp. in New Zealand's old growth forests, where the presence or absence of *Nothofagus* determined the ranges and the climate-distribution fit of other tree species (Leathwick and Austin, 2001).

There is substantial evidence that plant-plant interactions play an important role in determining how environmental change may affect plant species and communities (Brooker, 2006). These key roles are in competition, facilitation and evolutionary processes. The roles of competition and evolution are perhaps widely accepted but Brooker (2006) cites growing evidence for facilitative interactions between plants at all life-stages, and highlights how these can play an important role in regulating the composition of plant communities. Brooker *et al.,* (2005) argued that failure to distinguish between 'importance' and 'intensity' of competition has hindered our ability to resolve key questions about the role interactions may play in plant communities.

One study identified a key role for species-rich broadleaved deciduous forests in the future of different European regions (Thuiller *et al.*, 2006). Temperate areas were projected to lose both species richness and functional diversity due to the loss of broadleaved deciduous trees. These were projected to migrate to boreal forests, thereby increasing the species richness and functional diversity in these forests. Atlantic areas provided an intermediate case, with a predicted reduction in the numbers of species and occasional predicted gains in functional diversity.

Competition is a key process that structures plant communities (*e.g.* light, water, nutrients or space resources) and impacts the growth, reproduction or survival of plants. However, quantifying the impact of competition is problematic. Understanding the relative effects of ecological functions along gradients provides insight into generality, conditionality, and mechanism, and provides the baseline information for predicting the impacts of many key environmental drivers (Brooker *et al.*, 2005).

A greater understanding of these natural processes, and their inclusion in modelling and scenario planning, should assist the forest sector in setting research priorities and policy development.

3.5.2. Phenology

Shifts in the timing of plant activity (*i.e.* phenology) provide some of the most compelling evidence that species and ecosystems are being influenced by global environmental change. The effects of climate change on seasonal activity in terrestrial ecosystems are significant and well documented (Cleland *et al.*, in press). Temperature is a main driver of many plant developmental processes, and in many cases higher temperatures have been shown to accelerate plant development. In a comprehensive review Badeck *et al.,* (2004) summarise that analyses of spring phenology in middle and high latitudes indicate vegetation responses that are consistent with predictions based on climate change trends. Ground-based observations on phenology have shown advancement of spring bud burst and flowering dates in parallel with the global warming trend. The detected trends are of the order of magnitude of several days per decade. However, the authors also identify differences in trend estimates varying in the range of 2–5 days per decade that still need to be resolved. It also appears that spring phenology does not respond to global mean temperatures, but rather to regional changes in winter and spring temperatures, and to temperatures in the weeks immediately preceding the triggering of the phenological switches.

Models that accurately predict plant phenology are important tools for predicting the response of ecosystems to climate change. Numerous phenological models have been developed to predict the growth timing of temperate or boreal trees but they are in general empirical, nonlinear and non-nested and therefore difficult to independently test and compare (Chuine, 2000). Chiune (2000) proposes a unified model.

In relation to the role of genetics in phenology, the high gene flow expected in forest tree species, in combination with high between-year variance in temperature and high plasticity of phenological response, might suggest that genetic variation of phenology between populations is likely to be insignificant for many lowland tree species. Modelling the role of genetic variation in phenology has indicated that while clinal variations can be observed in the phenological response to temperature between populations, only one species (*Corylus avellana* L.) showed significantly different responses between populations and even then only one of three populations could be separated from the others (Chuine *et al.*, 2000). The authors conclude that local adaptation will probably not be a serious constraint in predicting the phenological responses of temperate lowland tree species to global warming.

Autumn temperatures also play an important role in tree phenology. Controlled experiments on boreal species (saplings of *Betula pendula*, *B. pubescens*. and *Alnus glutinosa*) revealed a highly significant correlation between autumn temperature and days to bud burst in the subsequent spring (Heide, 2003). Rising autumn temperatures may therefore counterbalance the advancing effect on spring bud burst that would otherwise occur in response to higher winter temperatures caused by climate warming. Heide (2003) concludes that this autumn temperature response may be important for reducing the potentially adverse effects of higher winter temperatures on dormancy stability of boreal trees during climate warming.

Phenology also impacts forest growth and yield and should be considered when predicting future stand management (Rötzer *et al.*, 2004). This is considered later in the Section 5.4 Yield.

For many tree species, phenology is also affected by light levels and altitude. For example, Vitasse *et al.,* (in prep) observed an advancement of leaf unfolding with decreasing elevation (increasing temperature). Phenology responses were highly species-dependent according to altitude and temperature. This study suggests that some of species which have strong amplitude along an altitudinal gradient could react quickly to an increase of temperature. See also Appendix I Field study visit to southern France.

3.5.3. Stand dynamics

Many studies investigate forest species composition, ecosystem stability or plant biomass. However, although important for conservation purposes, for forestry the stability of the standing biomass, or even more relevantly the stability of the economic yield, is a major concern (Bodin and Wiman, 2007). Planning to enable a forest to be robust and therefore capable of combating environmental change is problematic as it is highly unlikely that there exists one strategy option that can optimise for all types of disturbances, whilst also delivering the intended outputs of forest management. Therefore, management needs to be related to the most relevant or likely disturbances, or alternatively, a range of management options may be combined as an insurance strategy. Possibly, heterogeneous/mixed forest communities could insure against climate-change related pressures (Bodin and Wiman, 2007). These concepts are revisited in Chapter 5.

3.5.4. Functional traits

Functional traits are morpho-physio-phenological traits which impact fitness indirectly via their effects on growth, reproduction and survival; the three components of individual performance (Violle *et al.*, 2007). Functional traits are currently a major focus amongst ecologists (*e.g.* Lavorel *et al.*, 2007; Lavorel and Garnier, 2002). McGill *et al.,* (2006) argued that current approaches to understanding community ecology that ignore the environment or focus on a few species at a time, cannot address this question. Instead the authors advocated a functional trait-focused approach using four themes: traits, environmental gradients, the interaction milieu and performance currencies.

McGill *et al.,* (2006) proposed that scientists should go beyond 'How many species and why?' and ask 'How much variation in traits and why?'. They also argued that we should consider 'What traits and environmental variables are most important in determining fundamental niche?' rather than just 'In what environments does a species occur?'. They argue that current habitat modelling approaches seek only correlation between environment and species presence, which ignores the mapping from fundamental to realised niche and has serious limitations. Instead developing a mechanistic, predictive theory of the fundamental niche. Ackerly and Cornwell (2007), provide an insight into future application of this emerging scientific approach.

3.6. Evolutionary mechanisms

Evolution is a fundamental mechanism in understanding and predicting nature's response to environmental change. The maintenance of genetic diversity in the face of extensive habitat fragmentation is currently a concern. Hamrick (2004) however argues that many forest trees may be buffered from the adverse effects of habitat fragmentation. Firstly, as the longevity of individual trees may retard population extinction and allow individuals and populations to service until habitat recovery occurs. Secondly, that considerable evidence is available that both animal and wind-pollinated tree species in fragments experience levels of pollen flow that are sufficient to counteract the effects of genetic drift. The combination of individual longevity, high intra-population genetic diversity and the potential for high rates of pollen flow should make tree species especially resistant to extinction and the loss of genetic diversity during changing environmental conditions (Hamrick, 2004).

The views of the geneticist reflect those of the ecologist (see Section 3.2 Climate envelope mapping) in highlighting concerns regarding the accuracy and validity of climate envelope models (Antoine Kremer, *pers. comm.).*

Forecast distribution maps for forest tree species for the end of this century indicate major changes in distribution (Badeau *et al.*, 2005; Thuiller, 2003) or even extinctions for some plants (*e.g.* over half of 1350 European plant species might be vulnerable or threatened by 2080: Thuiller *et al.*, 2005). When physical barriers such as major mountain ranges are included, they further disrupt the relatively simple bioclimatic envelope model. More recent studies have highlighted the role of population genetics in the evolutionary process (Kremer, in preparation; Thuiller *et al.*, in preparation).

If it is the case that species are predicted to migrate, for example 100-500 km north east in France (Badeau *et al.*, 2005), it might be reasonable to expect that this trend is already apparent. The section above, entitled Evidence for recent climate-induced change in European forests, summarised growing evidence for such trends.

Hamrick (2004) postulated that the affects of pollen flow may have been underestimated, and therefore its role in enhancing tree survival. For example, gene flow of high adaptation value from southern latitudes would rapidly invade northern populations. So, if it is not possible for a tree species to physically invade or migrate northwards by seed, it certainly may be possible by pollen transfer. Most studies show that pollen distribution is possible at 1 km per year. But also, at lower levels, dispersal at much further distances is possible. For example, Schueler and Schlünzen (2006) simulated that, depending on the meteorological situation of the simulated days, a pollen cloud with about 10 pollen/m^3 may extend up to 30 km from the source and that downstream of an oak stand, approximately 1,000 pollen/m^2 may be deposited up to a distance of 25 km, with lower amounts of pollen deposited up to 100 km away. Such levels are certainly a low amount but would be compensated by higher fitness of genes introduced. Such affects may have some negative consequences, for example highly fragmented species may not be able to benefit from this process. Other studies suggest a less optimistic outlook. McLachlan *et al.,* (2005) studied two north American broadleaved species and estimated migration rates of less than 100 m/yr. The authors conclude that their chloroplast DNA results were consistent with predictions based on life history and dispersal data, and suggest that past migration rates were substantially slower than the rates that will be needed to track 21st Century warming. However, it seems evident that pollen flow will increase fitness of local populations.

The key question for evolutionary modellers and scientists is clearly 'Can species adapt quickly enough to cope with rapid environmental change?' The answer may be found in studying the autecology of introduced species. A good example can be found in northern red oak *Quercus rubra* L., introduced to Europe from the Appalachian mountains of the USA. Observations on the offspring from natural and introduced populations in a large scale provenance test demonstrated variation in bud burst and leaf colouration between introduced populations and those from the natural range (Daubree and Kremer, 1993), providing clear evidence for rapid evolution since their introduction only 200 years earlier.

Existing evidence from these three sources all indicate that trees are capable of adapting to climate change. Looking at evolutionary biology at a longer timescale than the Holocene, there were many more species (*e.g.* 4M years BP), and many extinctions (Svenning, 2003). However, during recent ice ages there were very few species extinctions.

Botkin *et al.,* (2007) refer to this as the 'Quaternary conundrum': namely, while current empirical and theoretical ecological results suggest that many species could be at risk from global warming, during the recent ice ages surprisingly few species became extinct. It may be a logical conclusion that species susceptible to climate change have already been eliminated. But perhaps, only those intolerant to cold, not species vulnerable to heat and drought. However, Svenning (2003) conclude that taxa widespread today are not only more tolerant of cold growing season and winter temperatures than extinct and relictual taxa, but that relictual taxa are more drought tolerant than extinct taxa. Botkin *et al.,* (2007) propose that the answer to the Quaternary conundrum lies in part with the ability of species to survive in a patchy, disturbed environment whose complexity allows faster migration than forecast for a continuous landscape, within which species move only at a single rate. The answer may also lie in part with greater genetic heterogeneity within species, including local adaptations, allowing rapid evolution.

Another important evolutionary mechanism is plasticity. Recent studies have shown that plants are plastic for a remarkable array of ecologically important traits, ranging from diverse aspects of morphology and physiology, to anatomy, developmental and reproductive timing, breeding system, and offspring developmental patterns (Sultan, 2000). Indeed, Sultan and Spencer (2002) demonstrated that with migration between sites the plastic type is favoured over local specialists across a broad range of parameter space. Furthermore the plastic type may dominate or be fixed even in a environmentally uniform site, and even if the plasticity has imperfect accuracy or bears some cost such that a local specialist has higher fitness in that site, as long as there is some migration between sites with different distributions of environmentally states.

(Kremer, in preparation) conclude that there is a growing body of evidence stemming from different sources of information (Quaternary evolutionary history; lessons from population and species transfers; provenance experiments) and that trees may have the resources and mechanisms to respond to climate change. It is clear that this evidence is fragmentary however, in terms of being conducted on different species, under different conditions and timeframes. Ideally long-term experiments are required to provide sufficient information although Kremer (in preparation) provides some recommendations for short-term practical research:

- construction of response functions in provenance tests;

  analysis of existing provenance and progeny tests in the European community through wider collaboration would provide information regarding the transferability of forest reproductive material, and fitness.

- Monitoring of evolutionary change in transferred tree populations;

  further analysis of historical examples of artificial transfers of tree populations or species may provide practical real-life information on possible impacts of climate change This would be especially valuable as the data would reveal actual evolutionary behaviour, and at scales (both time and geographic) beyond that often possible in provenance experiments.

In summary, further information is required from three sources, to provide better predictions of the impact of climate change on species' migratory ability and future distributions:

- evolutionary biology;
- provenance tests;
- observations on behaviour of exotic species.

3.7. Modelling change

A large number of scientific studies have been published providing an estimate of ecological impacts from climate change on natural forests. Typically these report their results in terms of changes to the ecosystem, net primary productivity and carbon storage. Most studies of impacts of climate change on economic land use, such as agriculture, provide integrated assessments of biological and economic impacts. In these, different scientific disciplines provide estimated outputs for variables such as crop yields, livestock productivity, soils and nutrients, and water demand and supply. These are directly used to construct economic models. Shugart *et al.*, (2003) suggest that in contrast, studies of forestry have not fully integrated analysis of biological and economic impacts. Ecological impact studies do not directly translate into harvestable yield forecasts although perhaps economists have assumed they do. Accordingly, modelling and analyses of forest impacts under a changing climate cannot be considered to be fully integrated.

Different approaches to modelling impacts on forests due to climate change have been adopted by countries within Europe and beyond. It is hoped an independent review of a limited range of these will provide an opportunity for scientists and policy makers to learn from experience elsewhere, and to identify prospects for greater collaboration. This section reviews three current approaches to modelling change on forest and tree species distributions; in France, the UK and the USA. These combine different data types and produce different output tools.

3.7.1. France – a case study

During the 1990s, a country-wide site classification programme was undertaken using a regional approach. These are commonly referred to as "Catalogue des Stations" or 'Typologie Forestiere' (*e.g.* Michalet *et al.*, 1995). These regional catalogues provide physical and biotic descriptions (climate, geology, soils, vegetation, forest management), with an inventory of forest types. Rameau *et al.*,(2000) extended this work by considering site condition, habitat and forest communities.

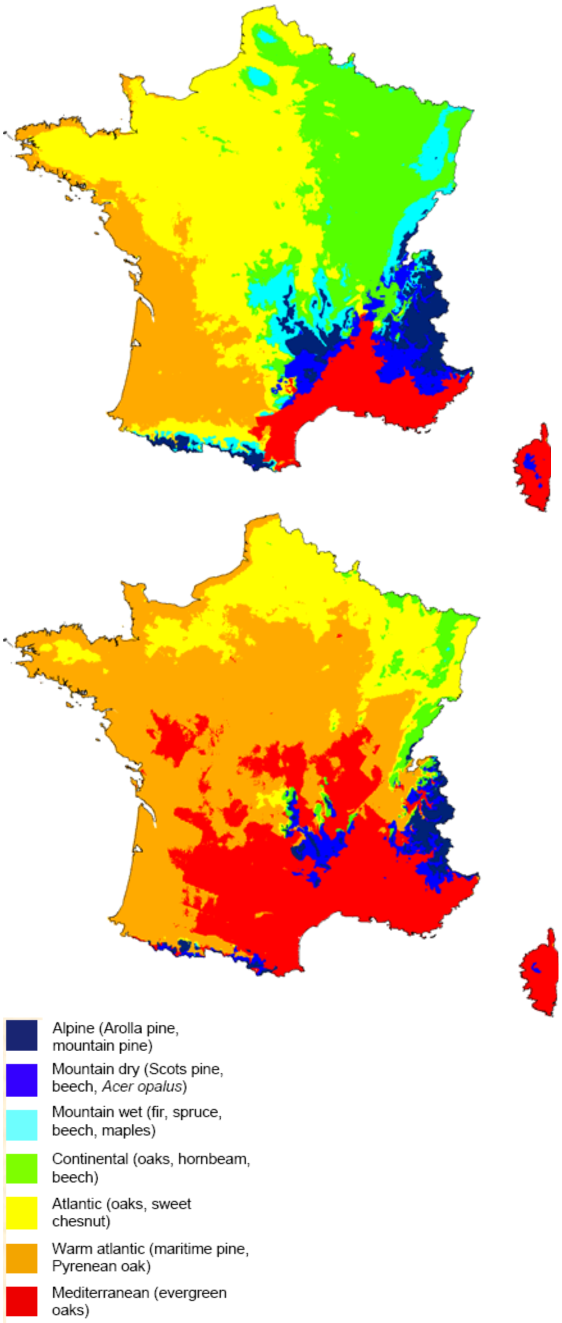


Figure 5 Seven bioclimatic areas in France, with contrasted tree species compositions, were created for modelling the effect of climatic change between 1980 (top) and 2100 (bottom) (Badeau et al., 2005).

Currently the CARBOFOR project[14] in France is studying climatic impacts on the overall potential surface of the principal forest types, and to model their displacement under the effect of climate change. The main three programmes of CARBOFOR are addressing: (1) an inventory of the resource, (2) impacts of climate change, and (3) their vulnerability. Many factors other than climate control the surface distribution of species, particularly for example, anthropogenic factors and topography. The project is characterising the principal climatic parameters affecting the ecological niche of the principal French forest types, and modelling change between 1960 and 2100 using the ARPEGE-Climat model of Météo France. It is simulating changes in potential distribution of the species under various scenarios of climatic change (Figure 5). Of key interest will be those species whose current distribution presents a northern and/or altitudinal limit within France, *e.g. Fagus sylvatica* (Figure 6). A final project report will be produced later in 2007[15], which will include results from external partners on tree phenology and distributional changes in damaging pests.

Within CARBOFOR, the experimental sites and predictive models do not directly address the species of interest to this COST Action, instead focussing mainly on *Fagus* and *Quercus* species. Predictions using climate envelope modelling indicate a neutral or positive effect on *Fagus sylvatica* productivity in the north east of France with no significant effect for other deciduous species in the north west (Loustau *et al.*, 2005).

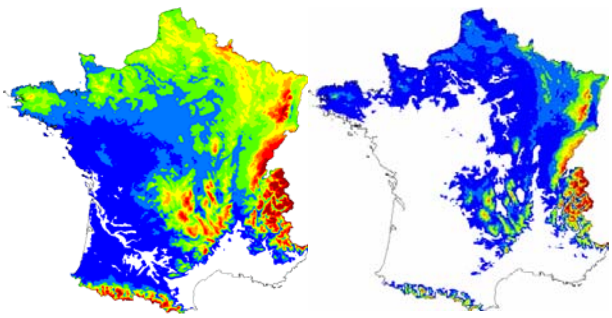


Figure 6 Change in distribution of *Fagus sylvatica* due to climate change from present day (left) to 2100 (right) (Badeau *et al.*, 2005). Warm colours denote high distribution, cool colours low distribution (*i.e.* white denotes absent altogether).

3.7.2. UK – a case study

A knowledge-based model was developed in the UK, termed *Ecological Site Classification* (ESC) (Pyatt *et al.*, 2001). It incorporated four climate and two soil factors, and was closely linked with the UK's National Vegetation Classification (NVC). Surprisingly for a publication in the 21st Century, climate change was not included in the

[14] http://www.pierroton.inra.fr/carbofor/index.htm

[15] Loustau *et al.*, (in preparation) eds. Response of temperate and Mediterranean forests to climate changes: effects on carbon cycle, productivity and vulnerability.

model. As a result, no provision was made for a change to drier and warmer climates in the south and east of England, or to wetter and warmer climates in the north-west of Scotland. Another issue with a knowledge-based model such as ESC is that it cannot account for predicted rise of CO_2 and therefore presents a worse case scenario, by not accounting for increased water use and yield increases (Ray *et al.*, 2002).

Currently a new project is being developed to research the spatial distribution of key biophysical factors limiting tree growth and suitability in France, (Duncan Ray[16], *pers. comm.*). With the projected northerly migration of the bioclimatic envelope, UK researchers are looking to southerly regions (*i.e.* France) both to test models and to learn from current ecosystem functioning.

Climate change tree species suitability scenarios for the UK have been published using the original ESC system (Broadmeadow *et al.*, 2005). Researchers in the UK Forestry Commission have tried to extend the range of the ESC suitability models, but with only limited success for a few species, although it is only in south east England where species response curves are 'off scale' for moisture deficit and accumulated temperature (Duncan Ray, *pers. comm.*). Hence the need for the new project, to try and provide experience and knowledge to underpin the suitability models in ESC for a greater number of species in south east England over the next 100 years, as a knowledge-based validation exercise.

Another criticism aimed at ESC is the lack of validation for many of the models. According to Duncan Ray (*pers. comm.*), only the Sitka spruce yield models were validated with empirical data from an unpublished report. Subsequent research has indicated that the yield model for Sitka spruce is reasonably accurate and indicates that ESC site factors are useful site-based factors for estimating yield and suitability, and this may indeed be the case for most species. If there were sufficient mensuration data for broadleaved species such as *Fraxinus excelsior* the knowledge-based models could be properly tested with empirical data. However such data are currently unavailable for broadleaved species in the UK.

An interesting research programme is underway that will feed valuable data into future modelling scenarios, and guide policy in UK forestry (Box 1). The PhD programme has already revealed some startling phenology results in relation to chilling temperature and growing degree day accumulation, and their impact on provenance material from different latitudes (Jo Clark[17], *pers. comm.*). The programme as a whole should provide both an indication of the suitability of provenance material from further south for current growing conditions, and the impact of predicted climate change on material currently growing in the UK.

[16] Project Leader, Ecology Division, Forest Research, UK

[17] Jo Clark, Forestry Research Manager, Northmoor Trust.

Box 1: Adaptation of British ash *Fraxinus excelsior* populations to climate change

PhD project by Jo Clark, Northmoor Trust, England, and University of Wales, Bangor.

2005-09

Introduction

Ash (*Fraxinus excelsior* L.) is one the most common and important hardwoods in Britain. It is the foundation of many valued ecosystems, is an important species in the British landscape and produces valuable timber. Recent research suggests that under low increases of carbon dioxide emissions, climate change may increase yields in ash by the year 2050, but yields will decrease compared to productivity levels today with higher emissions.

Aims

The aim of this work is to study the implications of climate change on ash. The null hypothesis put forward is that 'Predicted climate change will have no adverse affect on the survival and growth of ash (*Fraxinus excelsior*).'

Objectives

1. To test the adaptability of native ash across a range of UK locations by matching it to the predicted climate in 2050 and 2080.
- *Hypothesis: The fitness of ash of native British origin will be reduced with predicted changes in climate.*
2. To identify provenances of ash that may be closely matched to the future climate and to test them in the current climate through a series of reciprocal transplant experiments.
- *Hypothesis: Species from locations with a climate matched to that of the British predicted climate will survive and grow productively in the UK.*
3. To investigate the phenology of ash provenances for their suitability for growing in the predicted climate of 2080.
- *Hypothesis: Individuals that flush early will be susceptible to late spring frosts and thus unsuitable for economic timber production.*
4. To investigate outbreeding depression and its effects on the F1 generation.
- *Hypothesis: Crosses between British provenances and those from mainland Europe will produce less fit progeny.*

Method *Reciprocal Transplant Experiments*

Reciprocal transplant experiments (RTEs) will be used to directly estimate localised adaptation to environmental heterogeneity. The experimental design will test 'home' and 'away' populations for germination, survival and growth. Two populations have been selected from each of five climatic regions along a north south transect at approximately three degree intervals. Five RTEs will be established, one in each of the climatic regions, these being:

- Cawdor Estate (Inverness, Scotland: 57°N)
- Parlington Estate (Yorkshire, England: 54°N)
- Little Wittenham (Oxfordshire, England: 51°N)
- Dourdan (south of Paris, France: 47°N)
- Monein (near Pau, France: 44°N).

Other work

- Analyse existing provenance or progeny trials across Europe (*e.g.* the RAP and Fraxigen *Fraxinus* trials planted in 2004) to assess their suitability under future climate conditions.
- Carry out cpDNA analysis on the populations to ensure nativeness
- Phenology studies on provenance trials and in controlled environment rooms
- Assess seedlots commonly available from forest nurseries of imported continental material (*e.g.* Romania, Poland, Hungary, Holland)
- Record phenology data, such as time of flushing, to identify those individuals most suited to the British climate and correlate this with local temperature data.

Contact

Jo Clark, Forestry Research Manager, Northmoor Trust: Jo.Clark@northmoortrust.co.uk

3.7.3. USA – case study: a Climate Change Tree Atlas

The United States Department of Agriculture (USDA) Forest Service developed, and made available online[18], a spatial database and climate change atlas for 80 forest tree species of the Eastern United States (Prasad and Iverson, 1999-ongoing).

In April 2007 a new version of the atlas was released[19] incorporating finer resolution (20 × 20 km) and more species (total 134), and new Forest Inventory Analysis (FIA) data (Iverson *et al.*, in preparation). It is based on 'Random Forests' and includes 'regression trees' and bagging trees' (Prasad *et al.*, 2006) for added interpretability. It also includes new GCMs for the climate scenarios.

The 2007 Atlas uses different GCMs to produce two average scenarios, plus a cool scenario (PCM B1) and the warmest scenario (HadCM3 A1F1) (Iverson *et al.*, in preparation). Tree data were obtained from 100,000 Forest Inventory and Analysis (FIA) plots for the eastern United States, representing almost 3 million trees (Miles *et al.*, 2001).

The modelled results of the 2007 Atlas indicate that overall scenarios, 55 % of the 134 species show increases in suitable habitat by at least 2 % of the total area (Iverson *et al.*, in preparation). Only 14 % of species studied showed decreases of at least 2 %, several species showed severely diminished habitat especially under extreme scenarios (including *Acer spicatum* Lam. and *Juglans cinerea* L.), whilst two rare species, (*Quercus durandii* Buckl. and *Sorbus americana* Marsh.), might lose all suitable habitat. As in Europe, a general northward shifting of habitat is responsible for these patterns. Importantly however, a separate project by some of the same authors attempted to model estimated range changes in several species using the SHIFT model. Iverson *et al.,* (2004) estimated that for four species, less than 15 % of suitable habitat would have a 1:50 chance of being colonised naturally within 100 years. It seems clear therefore that the projected migration by the Atlas of the 134 species by 2100 is theoretical only, as the organisms are long-lived and immobile. Human influence will play a key role in either deliberately or accidentally assisting species to utilise new habitat.

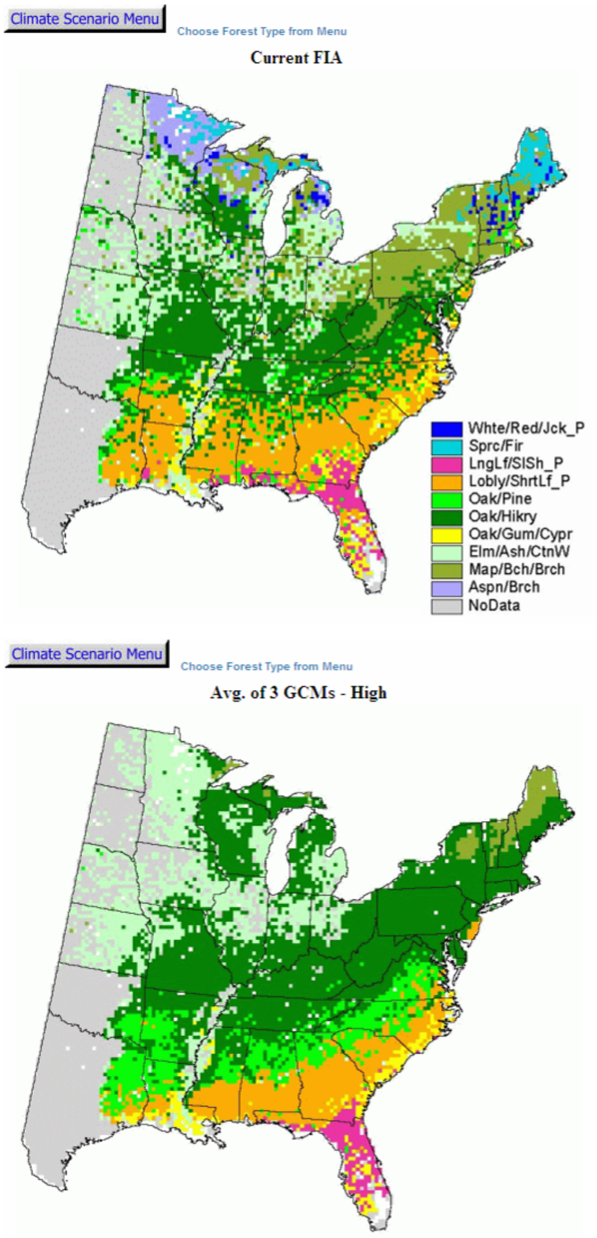


Figure 7 **Screen shots from the online Climate Change Tree Atlas showing forest type across the eastern USA using current Forest Inventory Analysis (FIA) data (top), and predicted forest type for 2100 under a high scenario using three combined Global Climate Models (GCMs) (bottom) (Iverson *et al.*, in preparation) and (http://www.nrs.fs.fed.us/atlas/tree/tree_atlas.html).**

[18] http://www.fs.fed.us/ne/delaware/atlas/#

[19] http://www.nrs.fs.fed.us/atlas/tree/tree_atlas.html

3.8. Summary

This chapter has revealed a lack of data for predicting the impact of climate change on the valuable broadleaved species of interest to this COST Action. Most studies that concern broadleaves address *Fagus* or *Quercus* species, as forests comprising these species cover more extensive areas across Europe. Some evidence was reviewed here for *Betula* spp. as these species are an important component of boreal forests, which in turn have been of interest to the scientific community due to their vulnerability to environmental change.

The affects of climate change on European forests and their constituent tree species are already becoming evident. They are most apparent in more northerly and southerly latitudinal extremes, *i.e.* boreal and Mediterranean ecosystems respectively. The ATEAM project[20] indicated that the Mediterranean and Pannonian regions of Europe are the most sensitive, a finding repeated (unpublished) in the BRANCH project (Pam Berry, *pers. comm.*).

Although some national growing stock statistics are available, there is no pan-European information base detailing species by species details such distribution and abundance (Chapter 2). This makes the modelling and prediction of changes to the forest resource, and in particular valuable tree species, problematic.

This chapter reviewed the impacts of environmental change with special focus on temperature changes, CO_2, fire, drought, wind, frost, and extreme precipitation. The difficulties in predicting some of these stochastic or extreme events and their impact on the European tree resource is challenging the scientific community. Hand in hand with changes expected in tree distributions, it seems apparent that the distribution of pests and pathogens will also change. Their impact may increase due to lower tree health caused by stress from, for example, drought or changes in temperature.

The need to better understand forest ecosystem dynamics was reviewed with a view to gaining a better understanding of natural processes, and to stress the importance of accurate modelling using concepts such as functional traits. The results of these approaches will inform both conservationists concerned with biodiversity, and forest managers seeking to conduct close-to-nature forest management.

Scientific studies concerning mapping and understanding phenophase transitions are providing evidence for change in many tree species. Phenology undoubtedly plays a major role in adaptation to future environmental change. Interaction of phenophases with light levels and altitude complicates this science, whilst some current studies are revealing contrary responses amongst different species. Such responses further confound our ability to predict and model the affects of climate change on our forests, as species-specific responses and resulting changes in interaction between species will fundamentally alter forest communities.

Evolutionary mechanisms provide another fundamental element in understanding and predicting the affects on climate change. A key question is whether Europe's tree species can adapt quickly enough to the changes predicted. The role of adaptation by pollen migration may have been underestimated. Geneticists suggest that evidence from three sources, namely evolutionary biology, provenance tests, and observations on behaviour of exotic species, should provide more insight but that greater collaboration across Europe is required.

Three contrasting approaches to modelling change were presented in case studies illustrating approaches in France, the UK and the USA. The degree of divergence in approach, even between these three case studies, suggests that more collaboration would be advantageous. The Climate Change Tree Atlas for the USA is particularly impressive and invites the view that a similar model, were it to be developed collaboratively for Europe, would be an extremely valuable tool for foresters, scientists, conservationists and policy makers. Certainly the call for a collaborative approach which transcends national boundaries is intuitive, as the impacts of climate change and the resulting response of Europe's forest resource have little relevance to these arbitrary manmade geographic distinctions. The readily-accessible format of the Tree Atlas database and outputs (and background scientific literature) on a dedicated website is an exemplar.

[20] Advanced Terrestrial Ecosystem Analysis and Modelling http://www.pik-potsdam.de/ateam/ateam_objectives.html

4. THE CONTEXT FOR EUROPEAN FORESTS, WOODLANDS AND TREES IN THE 21ST CENTURY

4.1. Introduction

Forests and forest managers are required to deliver on an increasing range of outputs. For centuries, mankind's main use/purposes for forests were economics (*e.g.* materials for construction and burning) and survival (*e.g.* food and shelter). Towards the end of the 20th Century, social (*e.g.* health, recreation, access) and environmental (*e.g.* biodiversity, landscape, water management) were foremost priorities.

Now, in the early 21st Century, whilst ecosystem services remain a major output, the issue of climate change has created an additional theme, namely contributing to society's aim for a carbon-lean economy. Essentially this aim may be met by providing wood for heat and energy production, and by managing the forest resource as a carbon sink. Such aims will clearly alter sustainable forest management practice, from choice of species (Figure 8), site location, crop management, and harvesting.

This chapter provides an overview of the current and future context for growing valuable broadleaves in Europe. Any economic production objectives must account for global trade and markets, whilst the policy contexts for broadleaved forests in the 21st Century will clearly be focussed on the provision of ecosystem services and forestry's contribution to a carbon-lean society.

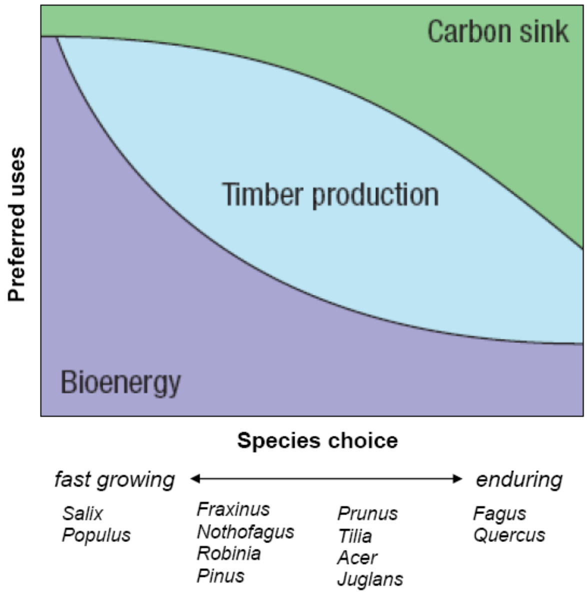


Figure 8 Example options for selection of crops and tree species to meet different objectives (adapted from Matthews and Robertson, 2005).

4.2. World timber trends

In a review of world timber trade, Lawson and Hemery (2007) conclude that forest areas and productivities in Western Europe expanded by 11 % and 30 % respectively since 1950 but around 30 % less of the annual forest increment is being utilised. The forest resource in Eastern Europe and Russia is large and will continue to dominate markets in Western Europe. Lawson and Hemery (2007) also recognised that temperate timber and wood products are increasingly traded in globalised markets but noted that trade in tropical hardwood logs is declining. Increasing timber demands in China, India, and other Asian countries will reduce roundwood availability for Europe, and, together with a 50 €/m^3 tax on exports from Russia, will drive up softwood prices.

There appear to be four major trends in future world timber production: i.) a continuing decrease in hardwood roundwood exports from the tropics as old-growth forests are reduced in size and quality, and as tropical countries impose export restrictions; ii.) increasing importance of tropical and temperate plantations; iii.) increasing exploitation of massive timber resources in Russia; iv.) increasing consumption of timber in China, India and other ‘industrialising’ countries (Lawson and Hemery, 2007).

The mantra that “quality sells” is important in this context as the majority of world timber trade projections naturally centre on the bulk timber markets, not those relevant to forest managers producing quality timber in smaller quantities. Concern regarding unsustainable forest management in developing countries has also begun to reduce imports of tropical and temperate hardwoods in to Europe. Current trends are decreases in hardwood log export from developing countries, and increases in exports of processed wood products (UNECE-FAO, 2005). Furthermore, increasing concern about timber miles may also favour domestic hardwood supplies in the future. Overall, the outlook for valuable broadleaved species, capable of producing diverse and high quality timber products, may therefore be viewed with some optimism. However, the growing conditions in the Mediterranean (Schröter *et al.*, 2005) and Pannonian regions of Europe are likely to reduce in suitability for some tree species, particularly drought-prone species.

Results from a global dynamic model suggest that markets are likely to benefit from climate change (Sohngen *et al.*, 1998). In this, benefits occurred as prices declined relative to the baseline case, and timber supply expanded (forests were predicted to expand by approximately 20 %). In temperate regions, the total area of land in forests was predicted to expand by 6 %, less than in tropical and boreal regions. Forest productivity is also expected to increase by 18 to 44 % depending on the climate scenario. In temperate regions, more productive timber types are expected to replace less productive timber types as species migrate. In the model, climate change permitted southern species to survive in regions farther to the north. It is possible that market development will quicken the pace of migration as forest managers respond to changing conditions.

The future of Europe’s forests will be driven by many wide-ranging factors beyond a changing climate, including population change, economic growth, social interest, technological development, policy interests. In the ATEAM project, long-term modelling was undertaken combining these factors. Current trends in forestry and forests were assumed to continue until 2020. ‘Storylines’ were developed for scenarios covering 2020–2050 and 2050–2100. The long rotation times of forests in some regions was an added complication, as trees planted today may only reach their harvesting age in 2080 or 2100. The analysis was undertaken for country groups with similar characteristics in terms of forest policy: Group 1 (Norway, Sweden, Finland), Group 2 (Austria, Switzerland), Group 3 (Portugal, Spain, Italy, Greece), Group 4 (France, Germany, Luxembourg, U.K.), Group 5 (Belgium, Ireland), and Group 6 (Denmark, Netherlands).

The general trends shown by the ATEAM scenarios are of small increases in urban areas with different spatial patterns, large reductions in agricultural areas for food production (except for B1 and B2) partly compensated for by increases in bioenergy production, forests and areas protected for conservation and/or recreation with surplus land in the A1f and A2 scenarios.

Assuming that the relative change in felling levels would be constant throughout Europe wood demand was modelled to increase strongly in the A1f scenario and, to a lesser extent, in the A2 scenario. In the B1 scenario, wood demand decreased, while it remained relatively constant in the B2 scenario (Schröter *et al.*, 2005).

4.3. Ecosystem services

The concept of ecosystem services was developed to aid our understanding of the human use and management of natural resources. Humankind's health and wellbeing is reliant upon the services provided by ecosystems and their components: water, soil, nutrients and organisms (Diaz *et al.*, 2006).

Ecosystem services have been defined in various ways, the most comprehensive of which was developed by the Millennium Ecosystem Assessment[21]:

- **supporting services** that are necessary for the production of all other ecosystem services, including soil formation, photosynthesis, primary production, nutrient cycling and water cycling;
- **provisioning services** are the products obtained from ecosystems, including food, fibre, fuel, genetic resources, biochemicals, natural medicines, pharmaceuticals, ornamental resources and fresh water;
- **regulating services** are the benefits obtained from the regulation of ecosystem processes, including air quality regulation, climate regulation, water regulation, erosion regulation, water purification, disease regulation, pest regulation, pollination, natural hazard regulation;
- **cultural services** defined as the non-material benefits people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation and aesthetic experiences – thereby taking account of landscape values.

The chief challenges at a global scale (Millennium Ecosystem Assessment, 2005) are: human-induced changes in land cover at the global scale lead to clear losers and winners among species in biotic communities; that these changes have large impacts on ecosystem processes and, thus, human well-being; and, that such consequences will be felt disproportionately by the poor, who are most vulnerable to the loss of ecosystem services.

Evidently, forests play a key role in delivering on all of the four key services identified above. This section reviews the services provided by forests and therefore the context for their management and for political support.

4.3.1. *Adaptation provision for associated biodiversity*

Mitigation in response to climate change can be viewed primarily as activities *to protect nature from society*, whilst adaptation constitutes *ways of protecting society from nature* [although 21st Century climate change is not natural] (Stehr and von Storch, 2005). There is now a tangible shift in science and policy interest, from a focus on mitigation, to adaptation. Forests, in conjunction with our management decisions, will provide critical adaptation potential for all associated biodiversity.

European forests are the largest single area of nature supporting biodiversity and contain many of Europe's threatened species. The EU forestry strategy considers that the conservation and enhancement of biodiversity in forests is key to their sustainable management. A recent Resolution of the EU Forestry Strategy[22] calls for action concerning the use of sustainable forest management practices and the multifunctional role of forests. Use of forests for carbon sequestration and climate regulation may conflict with achieving the objective of biodiversity conservation.

Conservationists need to develop management strategies to reduce the impact of climate change on global biodiversity (*e.g.* Hannah *et al.*, 2002). Traditionally, protection of habitats and species has largely relied upon the designation of sites, or a 'protectionist' approach but this is now questioned (*e.g.* Araújo *et al.*, 2004). Results from predictive models indicate that changes in suitable climate space for individual species will be seen at regional and national scales over the coming decades. Therefore it is important that nature conservation policies and practices should consider the likely impacts of climate change on species, habitats and protected areas, but still remain flexible enough to cope with any surprise event.

Hossell *et al.*, (2003) suggest that management options may need to include dynamic solutions such as strategically positioning new sites for

[21] http://www.maweb.org/en/index.aspx

[22] 16th February 2006 – Strasbourg: see INI/2005/2054 at http://www.europarl.europa.eu/

climate-sensitive species as their climate space changes and implementing more flexible wider-countryside measures to enable species to disperse across an otherwise inhospitable landscape. More radically, in some situations, a valid management strategy may be to recognise that the magnitude of climate change will overwhelm any effort to protect the species or habitat type and that little can be done to prevent responses to climate change. However, preservation is expected to continue to have an important role in ensuring the protection of some habitats and species, but is expected to become increasingly untenable.

It seems clear that taking measures to enhance the flexibility of the forest resource to adapt to climate change might have net benefits that exceed costs. The incremental costs of adaptation strategies could create a serious burden for developing countries, whilst some adaptation strategies may result in cost savings for others. There are significant uncertainties about the capacity of different regions to adapt successfully to projected climate change (IPCC, 2007a). In some cases, application of measures can make sense without considering climate change because they might assist in meeting current climate challenges (Smith and Lenhart, 1996). In other cases, the measures should be implemented in anticipation of climate change because they would be ineffective if implemented as a reaction to climate change.

Under the sixth framework programme a two year project entitled 'Minimisation of and Adaptation to Climate change Impacts on biodiverSity' (MACIS) was established in 2006 to assess the potential impacts of climate change and of proposed climate change adaptation and mitigation measures on biodiversity, and options available to prevent and minimise negative impacts[23].

In spite of repeated commitments at the highest political levels to halt or reduce significantly the loss of biodiversity the implementation of action towards meeting this goal is very slow, often hindered by a lack of adequate financial and other resources. A key problem in developing policies to stop biodiversity loss is translating threats into a tangible factor for decision making. A recent EU project RUBICODE[24] will contribute to solving this by examining what biodiversity does for society (RUBICODE, 2006). The project is seeking to identify the specific services that biological units provide and their value, so that they can be compared with more traditional economic valuations. This will give decision-makers a more rational base and will help the understanding of the need for adequate conservation policies, which are essential to halting biodiversity loss.

4.3.2. Landscape connectivity

The predicted impacts of climate change on biodiversity, particularly the isolation of species and communities, are likely to be amplified due to ever increasing habitat fragmentation arising from mankind's direct impact on the countryside through development activities. Rising interest in landscape scale approaches to biodiversity conservation and population dynamics has resulted in connectivity being frequently proposed as an effective strategy to address biodiversity decline within fragmented habitats. Many researchers have associated declines in woodland species with fragmentation (Bailey, 2007). Currently, there is a concerted effort to increase connectivity (through increasing the number of physical links) between woodlands, often through the development of habitat networks, with the aim of increasing biodiversity. Bailey (2007) also assesses the evidence behind the assumption that increasing connectivity will increase biodiversity and proposes alternative approaches to enhancing woodland biodiversity in fragmented landscapes.

In relation to forests and landscape connectivity, the principal debate in recent years has tended to revolve around two key issues: how much, and what sort of, forest land needs to be set aside in order to attain an adequate network of protected forest areas; and what constitutes best management practice in timber production forests. In the UK, concern regarding what is a relatively small and fragmented woodland resource, combined with patterns of large scale afforestation with exotic conifers, has led to the development of a tool termed 'Biological and Environmental Evaluation Tools for Landscape Ecology' (BEETLE) (Watts *et al.*, 2005). The aim of this tool is to enable forest and land managers to make informed choices at a landscape scale in order to provide sustainable forest landscapes for the future.

4.3.3. Soil and water protection

Soil protection is a prime concern, not only to preserve slope stability, prevent erosion, maintain nutrition status for crop systems and to maintain biodiversity, but also due to the role for soil as a

[23] http://macis-project.net/

[24] http://www.rubicode.net/rubicode/index.html

carbon sink. The global potential of soil carbon is estimated to off-set about 15 % of the world's fossil fuel emissions (Lal, 2007). There is a concern that climate change may have a negative effect on soil properties and processes. Forests and trees are therefore a crucial element in the drive to protect the world's soils and maintain carbon storage. In turn, how we manage (Markewitz, 2006b) and design (Jose *et al.*, 2006) our forests will impact their functionality as carbon stores.

Soils that are in equilibrium with a natural forest ecosystem have high carbon (C) density (Lal, 2005). Furthermore, afforestation of agricultural soils and management of forest plantations can enhance soil organic carbon stock through C sequestration. Increasing production of forest biomass *per se* may not necessarily increase the soil organic carbon stocks. Fire, natural or managed, is an important perturbation that can affect soil C stock for a long period after the event. Climate change may also stimulate forest growth by enhancing availability of mineral N and through the CO_2 fertilization effect, which may partly compensate release of soil C in response to warming (Nisbet, 2002). Soil C sequestration in boreal and temperate forests may be an important strategy to ameliorate changes in atmospheric chemistry (Lal, 2005).

Forests and trees also provide a crucial function in controlling water quality, flood amelioration, water catchment management and conserving water biodiversity (*e.g.* shade provision). They can also have an unwelcome effect of decreasing water yields, although broadleaved woodland has a much lower water use compared to conifers and is less of a threat where water resources are limited (Nisbet, 2002). Compared to other land uses, forestry provides many additional benefits. For example, Pattanayak *et al.,* (2005) modelled advantages of reduced pollutant run-off through the conversion of arable land to forest.

4.4. Supporting a carbon-lean society

There is growing demand for society to transform to a low carbon economy, which will influence land use, planning, food production, energy, buildings, transport, waste management and many other aspects of human society.

Deforestation worldwide accounts for 20 % of greenhouse gas emissions. It is likely that carbon conserved in forest protection schemes will be added to the Kyoto Convention in 2009, or certainly in its successor starting in 2013. The value of forests, forest vegetation and forest soils as an increasing pool of carbon is stressed in the latest UNFCCC[25] returns.

Forests, and how we manage them, can contribute significantly to a carbon-lean society of the future. Four main contributory themes are summarised here: growing Europe's domestic supply, utilising wood for bioenergy, substituting wood for carbon-rich materials, and managing forests as carbon sinks.

4.4.1. Domestic timber supply

International logistics lead to higher costs and additional energy losses compared to local or regional utilisation (Schlamadinger *et al.*, 2006). A strengthened domestic timber market would reduce both unsuitable deforestation abroad and promote a lower carbon footprint through, by example, reducing wood miles and encouragement of material substitution through branding and marketing.

A number of issues are apparent under this theme, most notably international trade conventions that might hinder domestic timber supply ambitions. However, environmental legislation may alter the political landscape over coming decades. It is also evident that cost-benefit analyses, both carbon and financial, are required to inform this debate.

4.4.2. Bioenergy

The EU has ambitious targets for 12 % of total energy to be comprised of renewables and 5.75 % of transport fuel to be composed of biofuel by 2010 (CEC, 1997). It is assumed that wood energy will provide sufficient resource to meet these

[25] United Nations Framework Convention on Climate Change: http://unfccc.int.

targets across member states. However, a study of the 'environmentally compatible bioenergy potential' of existing forests predicts that the amount of additional harvestable resource is insufficient to meet these targets without significant environmental impact, or without disrupting existing timber markets (Lindner *et al.*, 2006). Lawson and Hemery (2007) point out that the calculations seem to point to a shortage of wood resource.

Forest plantations are currently excluded from the EU emissions trading scheme, but parliament has asked the commission to consider their inclusion in the near future. Forest plantations in developing countries are included in carbon offset schemes covered by the two Articles of the Kyoto Convention.

The main context for valuable broadleaves in terms of bioenergy is in relation to arisings from forest management. Indeed, there is a natural synergy between quality timber management and biomass production. Chiefly, promotion of quality in stand management will lead to increased yield (*e.g.* through use of improved genotypes) and crucially, arisings from pruning of stems and thinning activities. These issues are addressed in Chapter 5.

4.4.3. Material substitution

Product substitution for carbon-rich materials (*e.g.* brick, concrete, plastic) can make substantial carbon savings. For example, substituting wood for concrete in building construction can make significant savings (Gustavsson *et al.*, 2006b). Currently in England, only around 10 % of new buildings are built with timber-framed techniques compared to 80 % in Sweden and 55 % in Scotland. Timber and wood products are carbon-lean (not quite carbon neutral) and therefore can directly and indirectly contribute to reducing carbon emissions. A report for Forestry Commission Scotland estimated that GHG emissions could be reduced by up to 86 % if timber for internal and external construction were specified wherever possible rather than typical practice Scottish building materials (Edinburgh Centre for Carbon Management, 2006). Another study calculated that replacing steel or concrete utility poles could make a significant, if small contribution, to reducing GHG emissions in the USA (Sedjo, 2002).

Two key issues need to be emphasised:

- carbon mitigation efficiency, expressed in terms of biomass used per unit of reduced carbon emission, may be considerably better if the wood is used to replace carbon-rich construction materials than if the wood is used directly as biofuel;

however,

- when any residues, from forest management aimed at producing quality timber for construction purposes, are also utilised for bioenergy then overall savings are enhanced.

In other words, there is a strong logical case for enhancing existing forest management to deliver greater output of quality timber. This point is revisited in more detail in the next chapter.

4.4.4. Forests as a carbon sink

There are sufficient wood resources to substantially increase the use of wood for material and energy purposes. However, a number of factors hinder a wider use of wood for energy and material purposes. An analysis of wood substitution is a complex issue, since the substitution influencing factors are to be found along the entire wood supply chain and involve several industries, socio-economic and cultural aspects, traditions, price dynamics, and structural and technical change (Gustavsson *et al.*, 2006a). Furthermore, Gustavsson *et al.*, (2006a) suggest that to improve our knowledge regarding wood as a substitute for other resources and any arising implications, it would be beneficial to better integrate research from different disciplines on the subject and to cover different scales from project-scale to an economy-wide level.

There are also complicated worldwide policy issues surrounding this issue. Both the EU and the USA are currently defining the role that agricultural soil sequestration of carbon will play in their overall strategies to reduce greenhouse gas emissions. Young *et al.*, (2007) explain how these decisions have important ramifications, as recent research indicates that soil sequestration of carbon may have the potential to reduce the need for reductions in greenhouse gas emissions. The EU ratified the Kyoto Protocol in 2002, but chose not to use soil sequestration of carbon in its strategy to address climate change, and has excluded it from the EU's new carbon market. The EU's strategy can be explained by uncertainties surrounding soil sequestration calculations and by the importance of its international leadership on climate change. As both the science and international protocols for carbon sequestration proceed, the EU may reconsider the use of agricultural sequestration of carbon as a means for achieving its Kyoto Protocol commitments. There are some indications that the EU's position on the use of agricultural sinks may be softening with the realisation that inclusion of sink activities may reduce the cost of meeting commitments. As Young *et al.,* (2007) point out, while the EU has yet not embraced the use of soil sequestration of carbon, it has provided the foundations necessary for success should it choose to do so.

Matthews *et al.,* (2002) highlight that few, if any, studies have addressed the impacts or benefits on biodiversity from carbon-centred forestry, typically focussing on economic benefits or wider environmental benefits. They conclude that assessments of the biological consequences of afforestation for carbon sequestration must consider current land cover and distributional patterns of organisms, as well as any carbon sequestration conversion goal.

In an insightful paper, Romero *et al.,* (1998), consider the role of carbon uptake as a public good, identifying a divergence between private and social interests. In a case study of a *Fagus* forest in Spain, the authors present a methodology to determine optimal forest rotation ages in the context of this multiple use and to remove divergence between these two interests.

The role of European forests and forest management in the carbon balance is a topical discussion point amongst modellers and scientists, and of keen interest to policy shapers. This was particularly motivated by the recognition that forest management is a possible measure that countries may adopt in the framework of the Kyoto Protocol to reduce concentration of greenhouse gases in the earth's atmosphere.

The main method to assess the carbon budget in forests is based on traditional forest inventories. This method requires the conversion of measured stem volume to carbon pools. However, this conversion has been identified as a large source of uncertainty in past assessments (Lindner and Karjalainen, 2007). Both aboveground (*e.g.* Vallet *et al.*, 2006), and belowground (*e.g.* Jose *et al.*, 2006) carbon estimates are required, and these are reliant on good understanding of forest ecosystem dynamics.

Monitoring and transparent reporting of forest carbon sinks are currently needed under the Climate Convention and, from 2005 onwards, national GHG inventories should also provide uncertainty estimates of the reported emissions and removals. An example of a detailed uncertainty estimate is provided by Peltoniemi *et al.,* (2006) for Finnish forests and soils, where estimates of the forest carbon stock and carbon sink were obtained by combining forest inventory data, models of biomass and turnover, and a dynamic decomposition model for soil organic matter and litter. Other studies have been conducted in temperate areas and on different forest types (*e.g.* Karjalainen *et al.*, 2002; Knohl *et al.*, 2003).

Another dimension of carbon sequestration and sinks is the impact from any increases in silvicultural activity, which may arise due to increased interest in managing the forest resource across Europe. Markewitz (2006a) provides such an estimate, concluding that carbon stored in forest soils and in forest products outweigh any carbon produced by fossil fuels or fertilisers used in forest management.

The ATEAM project[26] modelled carbon stocks in trees and forecast that they increased from 2000 to 2100 by between 76 % (HadCM3 A1f) and 176 % (HadCM3 B1), reflecting the changes in growing stock. The carbon sink in trees remained at the present level in the B1 and B2 scenarios. In the A1f and A2 scenarios, carbon sink capacity started to decrease around 2050 and, in the A1f scenario with HadCM3 climate, trees turned into a carbon source in 2080. Without land use change, carbon stocks in soils increased by 19 – 25% between 2000 and 2100, both for the current climate model runs, and for the simulations with climate change. (Schröter *et al.*, 2005). In the simulations undertaken by Schröter *et al.*, (2005) climate change dominated the overall trend climate change in European-wide net carbon exchange. However, the EFISCEN model used in the forestry sector to simulate the growth of managed forests indicates that forest management may be at least as important a driver as climate change and land use in Europe.

[26] http://www.pik-potsdam.de/ateam/

4.5. Summary

This chapter was introduced with the statement that forests and forest managers are required to deliver on an increasing range of outputs. However, far from viewing this as a negative proposition, the forestry sector is now presented with unparalleled opportunities to contribute to society's needs. Achieving greater profile for the sector in the public conscious will inevitably lead to more political support and business development opportunities.

Long-term forecasts for world timber trends indicate a continuing decrease in hardwood roundwood exports from tropical forests and increasing consumption of timber in industrialising countries such as China and India.

Forests provide many ecosystem services and these are likely to be increasingly important in the future as climate change impacts biodiversity and society. The role of forests in the provision of habitats for adaptation of biodiversity was discussed, in the context of Europe's forests being the single largest natural land-type supporting biodiversity. Landscape connectivity is a related important role for forests and trees, in linking habitats and species in an increasingly fragmented landscape. A forest's function in protecting and conserving soil and water resources was highlighted.

Society's drive towards a carbon-lean economy was highlighted here as a major opportunity for forestry in Europe. An overarching concept for all forestry is the provision of a carbon sink to assist in meeting international mitigation targets. Quality timber production can fulfil roles in increasing domestic timber supply, contributing by-products to bioenergy demand, and by providing materials for product substitution.

Support and encouragement of domestic timber markets may bring multiple benefits to society:

- encouragement of appropriate management that, under SFM, will deliver ecosystem services required locally;
- generation of by-products from forest management, for use in bioenergy production;
- supply of timber for use in material substitution, hence lowering our carbon footprint;
- domestic sourcing might reduce procurement from vulnerable global forest resources (deforestation contributes 20 % of the world's GHG emissions), and thus assist in delivery of global ecosystem services;
- local and regional procurement will reduce timber miles, hence lowering our carbon footprint;
- an economically viable domestic (local, regional or European) forestry sector will drive SFM and underpin management of the forest resource as a carbon sink, and possibly assist in meeting member nation's Kyoto Protocol commitments in the future.

5. Forest management and silvicultural options for the future

5.1. Introduction

The predictive impacts on European forests (Chapter 3), together with the context for forests in the future (Chapter 4), provide the necessary framework to predict what forests may be required, and how they should be managed, in the 21st Century. This chapter provides a speculative outline of forest design, management and silvicultural options for the future, and reviews evidence where available.

The effects of climate change are likely to be compounded by trends of rural abandonment (*e.g.* increased fire risk) in some areas of Europe or elsewhere, and development pressures (*e.g.* habitat fragmentation, physical barriers). In combination with stress from drought and resulting reduced tree health, increased incidences of pathogens, fire and other large-scale disturbances will further impact our forests. Forest management across Europe must rise to these challenges to mitigate from threat whilst encompassing opportunities from new markets, maintaining ecosystem functioning and maximising carbon sequestration.

Forest management will need to adapt to needs and opportunities at local, regional and national scales, and to address temporal uncertainties (Perez-Garcia *et al.*, 2002). For example the needs of Mediterranean forests (*e.g.* Resco de Dios *et al.*, 2007) will differ widely from those of boreal forests (*e.g.* Kellomäki *et al.*, 2005; Ministry of Forests and Range, 2006), whilst temperate regions will face their own challenges (*e.g.* Laurent, 2003). As Skinner (2007) highlights, management strategies that ignore the uncertainties associated with climate change are likely to fall short of expectations, whereas, strategies that acknowledge ongoing climate change, incorporate relevant monitoring, and include capacity for adaptation will likely be more successful in the long run.

5.2. Assisting forests adapt to change

During the course of the 21st Century, climate change will have direct impacts on forest biodiversity and tree distribution, reproduction, growth and health. The forestry sector needs to evaluate these impacts and determine its short and longer term responses. In short, we must develop adaptation policies.

Given the uncertainty of change, particularly timing, clearly a suite of readily available solutions are required. Spittlehouse and Stewart (2003) provide a summary of adaptation priorities:

- establish objectives for the future forest under climate change;
- increase awareness and education within the forestry community;
- determine present and future cost-effective adaptive actions;
- manage the forest to reduce vulnerability and enhance recovery;
- monitor to determine the state of the forest and identify when critical thresholds are reached;
- manage to reduce the impact when it occurs, speed recovery, and reduce vulnerability to further climate change.

Facing the uncertainty concerning growth of forests in the future can be a potential advantage, provided that forest managers are able to maintain flexibility, keep decisions open, and there is a chance that climatic change will benefit some species. Jacobsena and Thorsen (2003) modelled a mixed stand under different uncertainty assumptions and demonstrated that the larger the changes, the higher the option value at any time during the stand's life. In other words, maintaining a mixture of tree species in the stand for a longer period of time had the greatest advantage.

5.2.1. Summary of adaptive actions

Spittlehouse and Stewart (2003) provide a very valuable summary of adaptive actions that is worth repeating and enhancing here. The original article provides referenced evidence in support of the actions summarised below.

Gene management

Adapt seed zones and provenance transfer guidelines to account for northward migration of species and for new assemblages in space and time. Activities recommended include:

- determine responses of species and genotypes, and their transferability, and develop climate-based zones that will change over time. Test provenance at their ecological range limit;
- breed for pest resistance and wider tolerance of climate stresses;
- re-evaluate seed orchard locations to ensure supply in the future;
- plant a mixture of provenances at a site;
- re-evaluate conservation and recovery programmes.

Forest protection

Increased disturbances in combination with change in forest age class distribution and landscape patterns suggest the following actions:

- to deal with increased fire risk, develop 'fire-smart' landscapes (*e.g.* planting Aspen to retard fire progress in boreal forests), focus effort appropriately (*e.g.* allow wildfires to run their course if little socio-economic threat), alter forest structure to reduce risk;
- to combat pests and pathogens, encourage thinning (may increase stand vigour and lower susceptibility), improve sanitation (*i.e.* remove infected trees), shorten rotation length in plantations to change age structure, and also facilitate change to more suitable species, use genotypes with more resistance.

Forest regeneration

Existing forests will be quite resilient to climate change but it is their regeneration that is threatened. Natural forest disturbances may facilitate change with human intervention but non-commercial species might have to migrate without human intervention. Actions include:

- identify drought-tolerant genotypes;
- assist migration of commercial species to projected future ranges but account for local environmental conditions;
- plant provenances that grow over an adequately wide range of conditions, or plant a range of provenances at a site;
- control undesirable species (plant and animal) which may become more competitive.

Silvicultural management

Increased productivity for some forests in some regions can be expected, at least in the short to medium term. However, such benefits are unlikely to be maintained in the future and other impacts (*e.g.* temperature, drought) mean that maintaining forest ecosystems will require silvicultural systems that assist declining and disturbed stands. Adaptive actions will include:

- thinning or selectively removing suppressed, damaged or poor quality individuals (even before economic maturity) to increase resources available to remaining trees;
- reducing vulnerability to future disturbances by managing stand density, composition, structure, and location/timing of management activities;
- underplanting with other species or genotypes where current regeneration is insufficient as a source for future forest development;
- reducing the rotation age followed by planting to speed the establishment of better-adapted forest types.

Forest operations

Changes to temperature (*e.g.* shorter frozen period) and water regimes (*e.g.* waterlogging) may impact site accessibility for maintenance or harvesting. Increased environmental restrictions are likely to impede some traditional activities. Adaptive activities may include:

- maintaining or developing forest roads to minimise sediment runoff;
- managing forests to maintain or enhance water regimes (*e.g.* controlling stream flow, flood management, water quality);
- including adaptation planning with forest certification schemes as part of a risk management strategy;

– maintaining forests as carbon sinks, and evaluating risk to carbon stocks;
– increase use of forests for biomass energy;
– develop policies that support adaptive management responses to climate change.

Other non-timber resources

To enhance the provision of ecosystem services, we should:

– minimise fragmentation of habitat and maintaining connectivity;
– maintaining representative forest types across environmental gradients;
– protecting primary forests, thereby permitting an extended time period over which adaptation may occur;
– maintaining diversity of functional groups as well as species within groups.

Before developing adaptation strategies, it is essential to learn from the actual difficulties faced by foresters to cope with risk management at the forest level (Salinger *et al.*, 2005).

Adaptive management experiments can be used to evaluate the success of management manipulations. These experiments should include manipulations of species distributions and performance through planting and release projects, habitat modification, genetic engineering, and eradication of undesirable desirable species (Hansen *et al.*, 2001). In addition, species limits banks or refuges for colonisation could be developed (Hansen *et al.*, 2001).

5.3. Species and provenance choice

The choice of species and provenances will clearly be increasingly important as climate change impacts in the future. However, EU and nation policies for broadleaved tree and provenance selection in Europe have strongly advocated native and local provenance.

The Helsinki Guidelines (Second Ministerial Conference on the Protection of Forests in Europe, 1993) state:

- H1. 8 Tree species should be well suited to local conditions and be capable of tolerating other stresses and potential climate changes. Genetic selection which is commonly practised in Europe should not favour performance traits at the expense of adaptive ones;
- H1. 9 Native species and local provenances should be preferred where appropriate. The use of species, provenances, varieties or ecotypes outside their natural range should be discouraged where their introduction would endanger important/valuable indigenous ecosystems, flora and fauna.

These have been based on the assumption that over time, natural selection has led to adaptation. The Helsinki Guidelines have been interpreted in various ways by different nations. In the UK, the Forestry Commission developed regions of provenance and local seed zones (Herbert *et al.*, 1999), stating that "all planting stock should be of a local provenance". The policy was welcomed by UK conservation NGOs and was easy to advocate (*e.g.* Flora Locale[27] and Woodland Trust[28] but not welcomed by the forestry sector due to an increased economic and administrative burden on tree nurseries among others, but more fundamentally by forest scientists citing lack of evidence.

A recent review of scientific evidence (Boshier, 2007) argues that in the face of a lack of extensive trials of native British trees that the precautionary principle, previously cited as the basis for this policy, is potentially dangerous. Specifically,

27 www.floralocale.org

28 www.woodland-trust.org.uk/campaigns/briefingsmore/seed.htm

inbreeding depression and the loss of genetic diversity should be given greater consideration, where extensive gene flow and adaptation at a broad scale would be advantageous to develop the capacity to adapt to current and future conditions. The review by Boshier (2007) concludes that the emphasis on local seed sources may also cause problems, in that given the long life of trees and predicted climate change, the environment of a site may no longer experience the conditions under which the trees evolved.

A more controversial extension of this position may be to question the concept and definitions of "nativeness", since the creation and maintenance of robust future-proof woodlands may require using a variety of sources of native species in combination with introduced species where appropriate. Valuable but 'non-native' broadleaved species currently considered less appropriate in some countries such as *Acer pseudoplatanus*, *Castanea sativa*, *Fagus orientalis*, *Juglans regia*, *Nothofagus* spp., *Ostrya carpinifolia*, *Sorbus domestica*, and *Quercus pubescens* and *Q. rubra*, may come to play an important role in the productive and healthy forests of the future.

Evidently consideration may be needed towards appropriateness of these non-native species, in terms of their social and historical context, associated biodiversity-richness, environmental protection benefits (*e.g.* flood alleviation, soil protection), productiveness (*e.g.* timber, short-rotation forestry, bioenergy), climatic suitability (climate matching), economic potential, along with any potential negative impacts (*e.g.* invasiveness). Accepting such a concept is likely to be a greater challenge for nature conservation NGOs and policy makers.

Tree species choice should form the basis for an appropriate adaptive management strategy (as detailed in Section 5.2 Assisting forests adapt to change), which must then include issues such as the adjustment of thinning intensity, intervals, and patterns with changing productivity (Kellomäki and Leinonen, 2005b).

The following changes in tree species composition may be considered in implementing adaptive management strategies (from Kellomäki and Leinonen, 2005b):

- incorporation of other indigenous tree species, currently of minor importance in forestry, but with high potential for timber production or carbon sequestration under climate change;
- increased share of broadleaved species, because broadleaved species are assumed to perform better under climate change;
- substitution of species sensitive to drought and to late spring frosts with more drought-tolerant and frost-resistant tree species or provenances;
- replacement of low productivity tree populations with high productivity ones whenever the current population does not make full use of the potential productivity of a site.

5.4. Yield

Globally, commercial timber productivity is forecast to rise modestly with climate change in the short to medium term, with large regional variability around the global trend (IPCC, 2007a). Across much of Europe, the majority of forests are growing faster now than they did in the early 20th Century, which can be attributed to improvements in silviculture and genetic improvement (Cannell, 2002).

The evidence reviewed above indicates that, during the coming decades, there may be increases in yield with rising CO_2. However, later decreases in precipitation, and increased incidence of drought, will lead to lower yield in many species. Climate change may also impact forest growth by limiting soil nutrient availability or by prolonged soil waterlogging.

Nabuurs *et al.*, (2002) present the results of a modelling study of future net annual increment changes in stemwood of European forests owing to climate change. They applied seven process-based growth models to 14 representative forest sites across Europe under one climate change scenario (HadCM2: 2.5°C increase in mean temperature between 1990-2050 and a 5-15 % increase in annual precipitation). Data from this were subsequently incorporated with a large-scale forest resource scenario model, EFISCEN (European forest information scenario). Nabuurs *et al.*, (2002) were able to model European scale forest resource impacts for 28 countries covering 131.7 Mha of forest under two management scenarios for the period until 2050. Their results indicated that net annual increments in stemwood of European forests under climate change will further increase by an additional 0.90 $m^3\ ha^{-1}yr^{-1}$ in 2030, compared to the ongoing increase under a current climate scenario, *i.e.* an extra 18 % increase. After 2030 the extra increment increase is reduced to 0.79 $m^3\ ha^{-1}yr^{-1}$ in 2050. Under the modelled climate change scenario, absolute net annual increments would increase from the present 4.95 $m^3\ ha^{-1}yr^{-1}$, on average for Europe, to 5 $m^3\ ha^{-1}yr^{-1}$ in 2025. After 2025, increments in all scenarios start to decline owing to ageing of the forest and maximum growing stocks being attained.

Nabuurs *et al.*, (2002) highlight that there are many significant uncertainties in this model. These uncertainties are caused by unknown emissions in the future, unknown extent of climate change, uncertainty in process-based models, uncertainty in inventory data, and uncertainty in inventory projection. However, the results do indicate, climate change may lead to extra felling opportunities in European forests of 87 million m^3yr^{-1}.

Modellers have also developed regional scale analyses and applied them to national models. In the case of a regional model applied to the Finnish large-scale forestry model (MELA), this was shown to be a valuable tool for planning regional management (*e.g.* yield forecasts and thinning regimes) and mitigation activities (Nuutinen *et al.*, 2006).

Modellers have developed site specific models in an attempt to gain more understanding of predicted yields with a changing climate. A case study conducted by Forest Research in the UK applied a process model (GroMIT) to predictions of future oak growth in southern England[29]. The model simulations for oak growth indicated that during the 21st Century, there is likely to be an increase in productivity, raising site indices.

Models such as these are valuable but are incapable of estimating the effects of stochastic events such as drought on tree growth and yield. In addition, the many indirect consequences of climatic change have not been addressed such as changing distributions of pests and pathogens, and nutrient availability. These may become limiting factors as a result of increased growth rates, management practice or reductions in atmospheric deposition.

29 http://www.forestresearch.gov.uk/website/forestresearch.nsf/ByUnique/INFD-626MXH

5.5. Quality

Broadleaved forestry, particularly when involving valuable hardwoods, is chiefly concerned with *quality* rather than *quantity*. Such quality (phenotype) is a product of interactions between genetic factors (*i.e.* the genotype) and the growing environment (*e.g.* forest management and site conditions). Often this is expressed as:

$$P = G \times E$$

where *P* is phenotype, *G* genotype, and *E* environment.

5.5.1. Genetic improvement

Genetic improvement can provide many benefits such as increased establishment rates, growth rates and improving timber quality without the need for additional silvicultural inputs. However, genetic improvement cannot alter the presence of traits that are mainly under control of the environment (*e.g.* compression wood), or alter a stand once it is established (Hubert and Lee, 2005).

Examples where tree breeding could improve the quality and value of broadleaved tree species include stem straightness and vigour in *Betula* (Koski and Rousi, 2005), reducing forking in *Fraxinus* (Kerr and Boswell, 2001), reducing likelihood of shake and/or spiral grain in *Castanea* (Mutabaruka *et al.*, 2005) or *Quercus* (Kanowski *et al.*, 1991), late flushing to avoid frost damage in *Juglans* (Hemery *et al.*, 2005b), and increased resistance to bacterial canker in *Prunus* (Russell, 2002).

However, getting improved stock adopted by forest owners can be problematic as the higher investment necessary for quality stock is difficult to justify when timber prices are low (Hubert and Lee, 2005). The wider influence of forestry regulations (*e.g.* planting grants) that limit or control forest reproductive materials also affect uptake.

Stakeholder interest and commitment to quality is also affected by performance of existing forest systems and species. Where stakeholder perceptions persist that either of these elements are problematic, interest or uptake will be limited. Cameron (1996) provide an example where interest in *Betula* spp. has greatly increased in recent years partly as a result of pressures to restore and expand native woodlands but also due to renewed interest in birch as a tree capable of producing quality timber. Despite the many advantages of birch as a commercial timber tree, such as ease of establishment, fast growth on good sites, high value timber and a short rotation, it has a poor reputation in Britain largely as a result of the poor form of the existing, mainly unmanaged resource. Anecdotal evidence for other species, *Juglans regia*, *J. nigra* and hybrids, also demonstrates barriers to stakeholder uptake. Despite growing recent evidence that in the UK very high establishment rates can be achieved followed by good early growth rates (Hemery and Russell, 2005), the widespread perception amongst landowners in the UK is that these species are 'difficult' to grow.

In recent decades the funding of genetic improvement programmes has not been attractive, through either public or private funding mechanisms, due to the foci for research being centred on social and environmental themes. Hubert and Lee (2005) recognise that tree breeders must:

- reduce the number of years required to complete a generation of testing and its deployment;
- make improved planting material available to the industry as quickly as possible;
- improve understanding of the genetic control of desirable timber traits to meet the needs of the industry;
- work closely with silviculturists in order to optimise systems.

5.5.2. Silviculture

Good silvicultural practice can increase establishment success, increase growth rates (*e.g.* by improving drainage, and herbicide/fertiliser applications), decrease knot size, alter crop straightness, reduce compression wood (*i.e.* by thinning), and extend rotations to produce a greater volume of mature wood (Hubert and Lee, 2005). However, silviculture cannot increase growth and wood density simultaneously, change wood properties such as spiral grain, or improve a stand beyond the quality of the final crop trees (Hubert and Lee, 2005).

There are many publications on the subject of broadleaved silviculture, and an excellent review is provided by (Savill *et al.*, 1997). However, in the context of growing quality timber, it is worth emphasising the key elements of silviculture here.

Pruning

Pruning is fundamentally important for the production of quality timber, and becomes increasingly necessary if genetic quality is poor or plantation design/management unsuitable. Correction of early problems, 'formative pruning', is applied to young trees before canopy closure to encourage the development of a single straight stem at least 6 m in height. It can be particularly beneficial for young trees damaged by frost, because as frost damage is usually more extreme closer to the ground, resulting damage can spoil a tree before the tree even grows *in situ*. *Fraxinus* is especially prone, as damage to the terminal bud by frost when flushing will cause a pair of lateral buds to grow, forming a quality-destroying fork (Kerr and Boswell, 2001).

Kerr and Morgan (2006) experimented on the effects of four levels of formative pruning on precanopy closure stands of *Fraxinus excelsior*, *Prunus avium*, *Fagus sylvatica*, and *Quercus robur*. Form and growth were assessed for up to nine years after the last pruning treatment. A moderate intensity of formative pruning that removed forks and large branches showed some potential to improve the form of *Quercus* and *Fagus*. Interestingly however, there were no form improvements for any level of formative pruning applied to *Fraxinus* or *Prunus*. Kerr and Morgan (2006) suggest that attempting to produce quality timber by minimizing the number of trees planted and applying formative pruning is risky and likely to fail. A more secure way of obtaining quality improvement is to use traditional pruning after a period of canopy closure.

High pruning

The increased value from a defect-free log usually justifies the resources required in high pruning. Piat (2004) suggests that crops should be assessed at three key stages: early form pruning when trees are at 3 m height stage, cutting of large (up to 30 mm) branches when trees are at the 7-8 m height stage, and a later final pruning of large branches to create a clean bole up to 6-7 m. High pruning, above 6 to 7 m is a difficult and time consuming operation requiring suitable climbing equipment.

The amount of canopy retained when high pruning is important, as is when to prune, which differs amongst species (Savill *et al.*, 1997).

Thinning

Thinning operations are applied to stands to reduce density and therefore reduce competition. It also has the potential to provide revenue for the forest owner but more importantly, is carried out in expectation of greater return later in the rotation (Savill *et al.*, 1997). Thinning offers an opportunity to remove less valuable trees, for example trees that are leaning, (*i.e.* with compression wood), unstraight, or more unusually those (*Quercus* spp.) prone to shake following a simple assessment of flushing (Savill and Mather, 1990).

To summarise, silvicultural operations undertaken to improve quality are more efficient in combination with good stand design and the use of quality genetic stock. Looking to the future, a fundamentally important outlook is that these operations will produce by-products for bioenergy. If the bioenergy market develops as hoped by many in the sector, revenue for such by-products may encourage more forest owners to prune and to thin their stands. In such cases, the production of quality timber and subsequent generation of markets for broadleaves may become a viable proposition. Technology transfer will continue to be important to ensure good silviculture across Europe. Good stand management will also be beneficial in limiting risk to certain events, such as fire and pests.

5.6. Forest design and management systems

5.6.1. *Mixed forests*

Nearly all forest plantations are established as monocultures, but research has shown that there are potential advantages to be gained by using carefully designed species mixtures, or 'polycultures' in place of monocultures. Mixed forests are present across 40 % of the total forest area in Europe but this varies widely from 5 % (UK) to 68 % (Germany) (Bartelink and Olsthoorn, 1999). Often one tree species may naturally dominate the stand, but in most cases other tree species make up a certain proportion of the stand. In light of predicted impacts of climate change, mixed stands may be considered more 'natural', and more resilient to changing environmental conditions. The diversity of stand types at the landscape level also has a mitigating influence on the proliferation of forest fires and insect infestations (Kellomäki and Leinonen, 2005b). Mixed stands may also provide an insurance policy for forest owners, in that diversity of species provides a range of potential timber products for different markets, in combination with a robust resource (Bodin and Wiman, 2007). Furthermore, mixtures of tree species and stand types are likely to deliver efficient ecosystem services.

About 2 % of English-language literature on plantations deals with mixed-species plantations, but only a tiny proportion (<0.1 %) of industrial plantations are polycultures (Nichols *et al.*, 2006). Financial analyses suggest that a yield stimulus of 10 %, depending on product and rotation length, may be sufficient to offset increased costs associated with planting and managing a mixed-species plantation, a stimulus that has been demonstrated in many field trials. Nichols *et al.*, (2006) conclude that the main obstacle to commercial uptake of polycultures in industrial plantations may be the lack of operational scale demonstrations coupled with reliable financial analyses.

There are many challenges in designing and managing mixed stands. An understanding of crown growth amongst different species is important in terms of initial design and subsequent thinning regimes in mixed stands (Hemery *et al.*, 2005a). Silvicultural operations such as pruning may need to be repeated at different times of the year to suit different species.

Kelty (2006) reviewed recent studies that compared stand development and productivity of mixed and pure plantations. Higher stand-level productivity in mixtures has been found with two kinds of species interactions:

- complementary resource use between species that arises from development of a stratified canopy and possibly root stratification;
- facilitative improvement in nutrition of a valuable timber species growing in mixture with a nitrogen-fixing species (but only if combined with complementary resource use as well).

Mixed stands can therefore improve economic returns through greater individual-tree growth rates and the provision of multiple commercial or subsistence products.

For ecological restoration projects more complex plantation mixtures (5–70 species) have been used, where large numbers of species of different successional stages are combined to reduce the need for a series of sequential plantings.

Section 3.5.3. Phenology highlighted the role of phenology in adapting to climate change. If tree species respond differently to climate change, the competitive relationships between species will alter, affecting species composition within forests and possibly the geographic distribution of species (Kramer, 1999).

Another dimension to planning and implementing mixed-species silviculture are the below-ground components of competitive and complementary interactions. Jose *et al.*, (2006) conclude that our ability to design successful mixed-species systems is constrained by limited information on belowground interactions.

Innovative planting designs have been developed to reduce the land area needed for mixed-species plantation experiments, by focusing on individual-tree analysis rather than plot-level analysis (Kelty, 2006). It is evident however, that future research should focus on many more tree species across a wider range of sites.

5.6.2. *Uneven-aged silviculture*

Silvicultural systems can be applied where the canopy is maintained at varied levels without clear-felling, using varied tree species and utilising natural regeneration where possible. Alternative silvicultural systems, such as shelterwood and selection (and their variants such as Continuous Cover Forestry (CCF), femel, jardinage and plenter systems), generally involve retaining some mature trees on the site during the regeneration phase. It is not a new practice (e.g. Schlich, 1923) but a resurgence began in the 1990s in line with growing interest in conserving ancient semi-natural woodlands.

Kerr (2002) reviewed the potential for conversion of even-aged stands to an uneven-aged system, concluding that three criteria were important:

- basal area;
- size distribution of trees;
- amount, height and species present in natural regeneration.

O'Hara *et al.*, (2007) reviewed long-term research plots in uneven-aged stands, managed with the plenter system, Central Europe. They assessed sustainability using four criteria: stand density, tree species diversity, basal area increment, and stand structure. Their results suggest that the plenter system is still evolving and is not the model of sustainability often assumed.

Hekhuis and Wieman (1999) analysed and modelled delivery of multifunctional objectives in The Netherlands. Compared to large-scale / clear cutting forest management, small-scale / close to nature forestry demonstrated better:

- financial-economic performance (but only if interest was included);
- nature function fulfilment on most criteria;
- recreation function.

Most practitioners agree that uneven-aged silviculture is simpler when natural regeneration of desirable species is successful (Kerr, 2002). In the context of climate change, this suggests that impacts on seed viability and seedling growth (*e.g.* drought and light) and viability/stress (*e.g.* distributional changes of pests), may be profound. Certainly such systems may become more complicated if natural regeneration is negatively affected. However, there may also be new opportunities if acceptability of 'desirable' species is reviewed in the light of maintaining robust and 'fit for purpose' woodlands.

5.6.3. Close to nature forestry

The silvicultural philosophy of the mixed forest was advocated by Gayer (1886) over 120 years ago but subsequently adapted and amended by foresters in some areas of Europe, particularly Slovenia and Switzerland (Schütz, 1999). Definition of this philosophy varies but fundamentally concerns the relative emphasis that is placed on 'culture' or 'nature'.

Schütz (1999) provides an excellent review with a purpose of extending the original concepts of close to nature forestry to embrace modern requirements from forest management. In summary, Schütz (1999) recommends:

- learning from experience;

  silviculturists must accept and learn from failures as well as celebrating successes. The slow development of forests makes analysis and learning problematic (erosion of practical and literature evidence). Insufficient progress has been made in establishing mixed stands, and promotion of stand irregularity.

- tendency of natural succession to result in single-species stands;

  mixed stands need more silvicultural intervention. If these are not undertaken, nature will be expressed through domination of a few competitive species, forming relatively unmixed forests. These two processes occur more under good site conditions. Naturally mixed forests are only found where site and climatic factors deteriorate.

- tendency of natural succession to result in structural regularity;

  a similar tendency is observed in terms of stand irregularity. In virgin forests, tendency toward mixtures is only found in the 'regenerative' phase, when disrupted by senescence.

- difficulties of creating long-term irregularity.

  the need to initiate intensive and repetitive silvicultural intervention is demanding on resources.

Since Schütz's (1999) review focussing on the need to include biodiversity in forest management, the emerging contexts for 21st Century forests revealed in this report now add more dimensions to this silvicultural philosophy. The genuine multi-functionality now demanded from our forests may be well served by revisiting the concept of close to nature forestry.

Efforts in Denmark to transform forestry practice to uneven-aged silviculture revealed a lack of settled long-term goals in terms of stand structure and dynamics of the ''future'' forests (Larsen and

Nielsen, 2007). Forest Development Types (FDT) were developed in the form of profile diagrams as tools for steering forest planning, and as a participatory process involving people both inside and outside the organisation. FDT describes long-term goals for forest development on a given locality (*e.g.* climate and soil conditions) in order to accomplish specific long-term aims of functionality, combining analysis of silvicultural possibilities with the aspirations of future forest functions. The FDT profile diagrams were viewed as being integrative, flexible and an easily comprehensible concept for communicating long-term goals for stand development in nature-based forest management.

5.7. Forest health and protection

Section 3.4 reviewed Environmental change impacts on forests and trees. The question that needs to be addressed here is how forest owners and managers can respond to these impacts, particularly when there is so much uncertainty surrounding these predictions.

Recent extreme events have increased interest in adaptation strategies in forestry, particularly concern regarding European forests becoming a carbon source rather than a carbon sink, for example following the 2003 European heatwave and drought, and the 'Godrun' storm that wind-felled 75 Mm^3 of forest in Sweden (Bodin and Wiman, 2007).

Some of the risks to broadleaves and appropriate responses by foresters are summarised in Table 6. Perhaps the most problematic, in terms of uncertainty and potential threat, is the risk from new or more destructive pests and pathogens. As Savill *et al.*, (1997) summarise, one good reason for the good health and high productivity of many exotic species introduced to Europe, is the lack of specialised pathogens. Conversely, pests and pathogens often are more successful (from their viewpoint) when introduced to new territory. The partial solution here may be tighter sanitary controls. However, in principle if robust forests are created (*e.g.* species choice, age distribution, genetic variation), then the risk will be lowered.

Table 6 Generalised predictions of impact risk to European broadleaved tree species and possible responses.

risk	impacts	responses
temperature	– increased growth rates but linked with drought	Species selection according to new growth potential (economics).
CO_2	– increased growth rates until other risks impact – Intraspecific variation in response will alter forest ecosystems and stands dynamics	Adjust yield estimates and develop flexible stand management to account for altering competition, interaction and regeneration.
fire	– mortality – few species fire resilient – European forests mostly not natural wildfire ecosystems	Landscape scale planning necessary. At local scale, incorporate firebreaks, resilient species (non-natives?). Improve management (*e.g.* thinning, forest floot maintainance).
drought	– mortality or stress. – landscape scale. – increased susceptibility to pests/pathogens	Account for altitude and aspect. Species selection. Utilise small-scale site features to suit species.
wind	– damage to tree form – reduction in growth – mortality	More use of shelterbelts, around woods to control valuable crops, and to reduce wind speeds at a landscape scale.
extreme precipitation	– reduction in growth. – waterlogging	No specific response. Potential role for forestry in reducing runoff and minimising flood risk.
frost	– damage to tree form. – timber quality reduced	Avoid frost sensitive species or breed/use selected genotypes. Account for small-scale site variability.
pests & pathogens	– health reduction. – mortality	Genetic breeding to reduce susceptibility. Genetic variability (provenance) and species mixtures for robustness. Pest control where feasible. Careful control of exotic species.

5.8. Future markets

5.8.1. Timber

Markets for timber from valuable broadleaved species are currently diverse and are likely to continue to be so. Indeed, in our drive for a carbon-lean society product substitution may expand markets for wood products to replace carbon-rich materials where reasonable. In contrast to coniferous forestry where large scale substitution in building and construction may create large demand in the future, the potential market for valuable broadleaves (*i.e.* excluding oak that is commonly used in timber-framing), is fundamentally different. For these species, quality will count for more than quantity. The points raised in this chapter in terms of combining superior (quality or robustness) genotypes with good silvicultural practice cannot be overemphasised.

5.8.2. Biofuel

Markets for biofuel, for example wood fuel or tree-ethanol, are not discussed in detail here. However, the context for biofuels in relation to growing valuable broadleaves has been stated clearly above: namely, that markets for the by-products of good stand management (*i.e.* pruning and thinning) may encourage forest managers to practise good silviculture.

5.8.3. Ecosystem services

Currently, the main barrier to forest owners adopting forest management activities that deliver ecosystem services, such as biodiversity, social benefit (*e.g.* health and recreation), and environmental protection, is an economic one. Legislative tools and/or public incentives may be necessary to secure and enhance the delivery of ecosystem services in the future. This may particularly be the case where no direct revenue is available to the forest owner when undertaking to deliver a service, or even more so when there is a net cost.

5.8.4. Carbon storage

Management of European forests as carbon sinks will only be viewed as a market when remuneration is available for forest owners. As discussed in sub-Section 4.4.4 Forests as a carbon sink, international negotiations in relation to the Kyoto Protocol commitments may create the necessary redefinition of purpose and support for forestry in the future. In relation to valuable broadleaves, there is a strong case that these species will satisfy the various elements required.

5.9. Summary

A number of large EU-funded projects are currently addressing issues raised in this chapter.

Understanding complex interactions between site conditions and growth, yield and timber quality for current and future scenarios of atmospheric change is the main aim for the EU-wide MEFYQUE project[30]. MEFYQUE will develop a prototype modelling system operating at an appropriate forestry management scale (the forest stand) to forecast timber growth, yield, quality and marketability suitable for application in the EU (Randle, 2004).

A comprehensive review of options for mitigation and adaptation was undertaken within the SilvStrat project (Chapter 9: Kellomäki and Leinonen, 2005b), although this focussed on timber production and carbon storage, rather than ecosystem services (Figure 9).

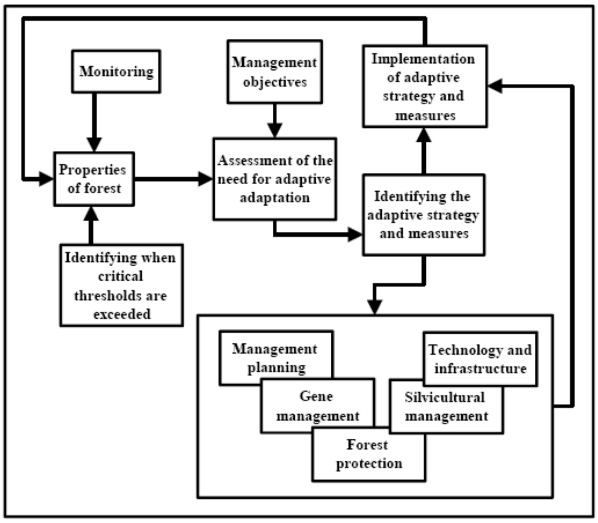


Figure 9Outlines for identifying the needs for adaptation, with defining adaptive strategy and measures (Kellomäki and Leinonen, 2005b).

The key points raised in this chapter were:

- the need to develop and maintain European forest markets;
- manage the forest resource at different scales appropriate to these markets and to adapt to predicted climate change, *i.e.* EU-wide, bioregional and micro-site scales.

[30] http://www.efi.int/projects/mefyque/index.html

- develop forest adaptation strategies and consider including these as a pre-requisite in certification schemes. These must address: gene management, forest protection, forest regeneration, silvicultural management, forest operations, and delivery of ecosystem services;
- species and provenance choice is increasingly important to facilitate adaptation (*i.e.* deliver ecosystem services) and provide product for markets. Seed zones need to be re-evaluated regularly. Initiate informed debate on the notion of 'nativeness';
- develop better understanding of forest growth and yield projections to improve long-term stand management and marketing strategies;
- encourage forest owners to aim for quality by combining good genetics with best silvicultural practice;
- appropriate forest design and management may create a more robust forest resource, possible options include mixed forests and close to nature forestry. Forest owners should embrace true functionality under 'sustainable forest management', addressing ecosystem service provision, economic production, and carbon-lean (stock and bioenergy) priorities;
- forest health and protection in the future will be high priority. Forest management strategies must combat long term trends (*e.g.* temperature and CO_2) and be flexible to meet uncertain stochastic events.

6. DISCUSSION

This chapter summarises and amalgamates the species-specific information discussed above for each of the species of interest to COST Action E42. In general there is a lack of information, at least in an accessible form, for these valuable broadleaved species. However, many of the specific threats and impacts to Europe's forests and tree species are applicable to the broadleaved species of interest to this Action.

Implications for forest policy are covered including economics, climate policy, technology transfer and biodiversity. Finally, five key challenges and recommendations are provided as a forward-looking output from this STSM.

6.1. Species impacts and opportunities

Due to the dearth of data regarding tree distributions at the species level for Europe, projections for individual trees species at this scale are difficult to assimilate. Information for some species, compiled by members of the EUFORGEN networks based on existing bibliography provide some map projections[31].

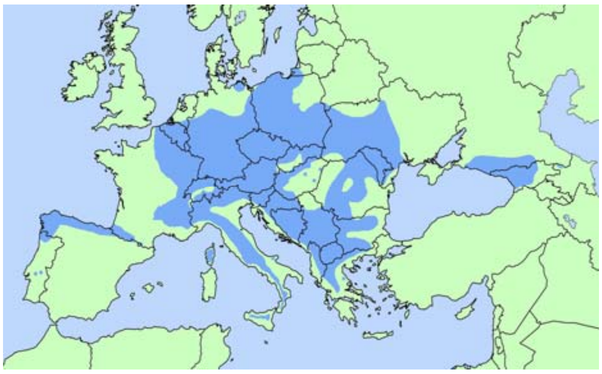
The case studies (Section 3.7 Modelling change) revealed that various effective steps have been taken to model and predict future distributions for various species within national borders. The USDA Climate Change Tree Atlas provided an exemplar to which scientists and policy shapers should aspire to for Europe. In the light of the range shifts predicted for many tree species (that will not respect national borders!), clearly an international collaborative approach is required to provide to develop a similar tool for Europe. In the process of such collaboration, expertise, modelling tools and experimental results would be shared which is likely to reduce duplication of effort at national level. In addition, many nations need to look to other areas of Europe to model predicted changes to their existing bioclimatic regions (*e.g.* the UK should look to France for genetic performance and silvicultural options, France to Spain/Portugal to understand drought and fire modelling).

The species tables presented below attempt to summarise information provided above in this report. Citations for new (*i.e.* to this report) evidence is provided. Timber properties were sourced from Savill (1991).

31 http://www.bioversityinternational.org/Networks/Euforgen/Euf_Distribution_Maps.asp

6.1.1. *Acer species*

Acer pseudoplatanus



Current range: Rusanen and Myking (2003).

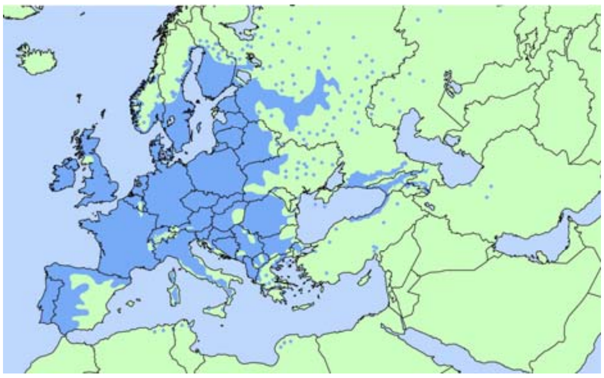
Impacts

factor	comments
disease	Sooty bark disease for *A. pseudoplatanus.*
pests	Grey squirrel targets *A. pseudoplatanus*
drought	generally species are resistant but stress may increase disease susceptibility.
other	

Opportunities

factor	comments
carbon-sink	Fast growing and moderately long-lived. Rapid growth and high biomass for wood energy.
ecosystem services	Non-native status in some countries. Not favoured by ecologists due to effects on woodland biodiversity. Wind stable. Product substitution.
stand design and management	Good natural regeneration. Vigorous and strong apical dominance. High prune.
timber	Decorative and valuable timber . Uses - cabinet making, furniture, musical instruments.

6.1.2. *Alnus glutinosa*



Current range: Kajba and Gračan (2003).

Impacts

factor	comments
disease	*Phytophthora* (Gibbs et al., 2003)
pests	-
drought	Intolerant. Other *Alnus* spp. more tolerant.
other	Fire resilient.

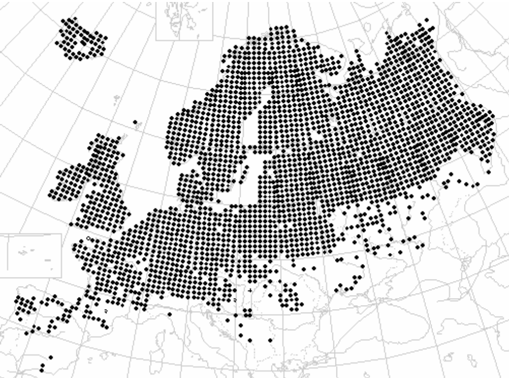
Opportunities

factor	comments
carbon-sink	-
ecosystem services	River bank stability, flood management.
stand design and management	Good nurse species and *N*-fixing. Useful in mixed forests. Good natural regeneration.
timber	Water resistant but soft. Uses – light furniture, turnery, pulp and turnery.

6.1.3. Betula *species*

Betula pendula

Betula pubescens



Current ranges: (Jalas and Suominen, 1976).

Impacts

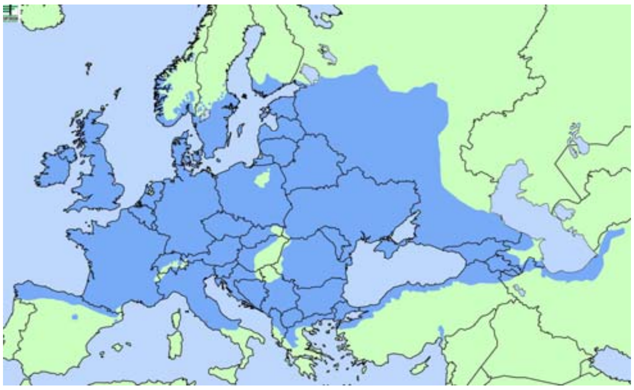
factor	comments
disease	-
pests	-
drought	Intolerant.
other	Range changes at altitudinal and latitudinal limits.

Opportunities

factor	comments
carbon-sink	-
ecosystem services	High associated biodiversity value. Pioneer species. Good natural regeneration. Landscape connectivity. Product substitution.
stand design and management	Useful nurse species and important in mixed forestry.
timber	Strong but not durable. Uses – furniture, plywood, veneers, turnery.

6.1.4. Fraxinus *species*

Fraxinus excelsior



Current range: Pliüra and Heuertz (2003).

.Impacts

factor	comments
disease	-
pests	Ash bud moth (Kerr and Boswell, 2001).
drought	Tolerant (deep rooted).
other	Frost sensitive.

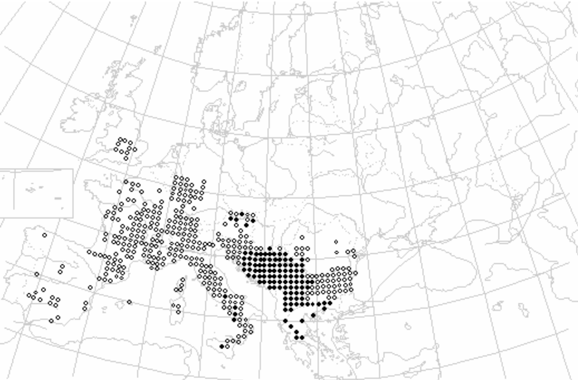
Opportunities

factor	comments
carbon-sink	Fast growing and good longevity, range of durable products to lock carbon.
ecosystem services	Wide native distribution and high associated biodiversity. Product substitution.
stand design and management	Productive species, grows well in mixed forests. Shade tolerant. Formative pruning and high pruning required. Good soil nutrient status required.
timber	Valuable, tough, flexible, decorative. Uses – sports goods, toll handles, furniture. High calorific value (wood fuel).

Further detailed and excellent information for *Fraxinus* is available in FRAXIGEN (2005).

6.1.5. *Juglans species and hybrids*

Juglans regia



Current range: (Jalas and Suominen, 1976)

Other species - no data available.

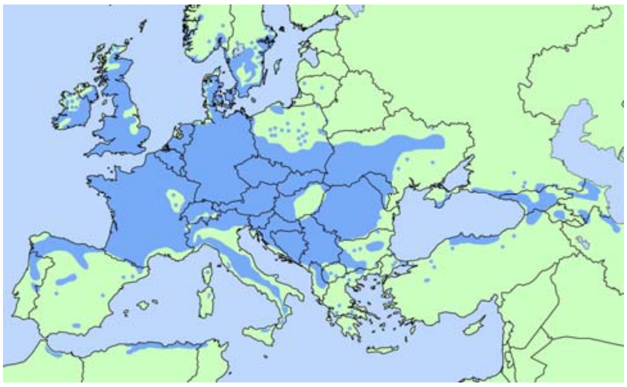
Impacts

factor	comments
disease	Various foliar diseases worsened by wet climatic conditions, therefore impact may lessen.
pests	Few.
drought	Tolerant (deep rooted).
other	Frost prone. Temperature will increase vigour. Range expansion expected.

Opportunities

factor	comments
carbon-sink	Fast growing and good longevity, range of durable products to lock carbon.
ecosystem services	Non-native for all Europe (*J. regia* and *J. nigra*). Low associated biodiversity. Good for slope and soil stability. Product substitution.
stand design and management	Vigorous, particularly hybrids. Light demanding. Benefits in mixed forests, particularly with *N*-fixing species (Hemery, 2001) but large crown size (Hemery *et al.*, 2005a).
timber	Stable, strong and decorative. Uses – furniture, flooring, veneer. Also fruit crops.

6.1.6. Prunus avium



Current range: (Russell, 2003)

Impacts

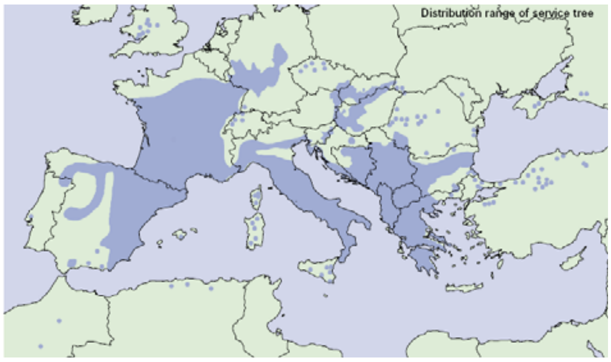
factor	comments
disease	Bacterial cankers.
pests	Deer.
drought	Resistant.
other	Temperature will increase vigour.

Opportunities

factor	comments
carbon-sink	Fast growing and good longevity, range of durable products to lock carbon.
ecosystem services	Native to much of Europe. High associated biodiversity. High landscape value.
stand design and management	Genetic stock important (canker resistance and form). Good in mixed forests. Light demanding. High pruning necessary.
timber	Highly decorative and valuable. Uses – furniture, turnery, veneer.

6.1.7. Sorbus *species*

Sorbus domestica



Current range: Rotach (2003).

Sorbus torminalis

Current range: Demesure-Musch and Oddou-Muratorio (2004).

Impacts

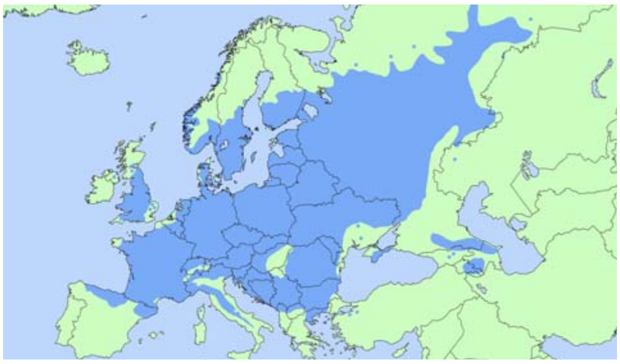
factor	comments
disease	-
pests	-
drought	Resistant.
other	-

Opportunities

factor	comments
carbon-sink	Small contribution.
ecosystem services	Wide native range. High associated biodiversity. High landscape value.
stand design and management	Natural component in mixed forests.
timber	Decorative. Uses – furniture, veneer, turnery, (*S. torminalis* fine tools and instruments).

6.1.8. Tilia *species*

Tilia cordata



Current range: Svejgaard Jensen (2003).

Tilia platyphyllos

Current range: Svejgaard Jensen (2003).

Impacts

factor	comments
disease	-
pests	-
drought	Intolerant. *T. cordata* more resistant than other species. Stools very resilient.
other	-

Opportunities

factor	comments
carbon-sink	-
ecosystem services	Wide native range. Product substitution.
stand design and management	Excellent in mixed forests.
timber	Soft, light and resists splitting. Uses – turnery, carving, furniture (replacing plastic in many products).

6.1.9. *Ulmus procera*

Current range: no data available.

Impacts

factor	comments
disease	Dutch elm disease *Ophiostoma* spp.
pests	-
drought	In combination with disease, vulnerable.
other	-

Opportunities

factor	comments
carbon-sink	Durable and good potential to lock carbon.
ecosystem services	High social and landscape values. Product substitution.
stand design and management	Genetic resistance to disease required.
timber	Strong and resistant to strain. Uses – pipes, chairs, wheels, furniture, flooring.

6.2. Implications for forest policy in Europe

Sustainable forest management (SFM) is currently widely accepted as the overriding objective for forest policy and practice in Europe. The Ministerial Conference on the Protection of Forests in Europe (MCPFE) is the high level forest policy process, addressing all dimensions of SFM in the pan-European region. MCPFE involves the 44 countries of the European continent, the European Community and 41 observer countries and international organisations[32].

The main forces that will shape the European forest sector in the future can be divided into two factors (UNECE-FAO, 2006). Firstly, there are external factors that will drive the sector in one direction or another (*i.e.* socio-economic and environmental trends). Linked to these are the future changes in demands placed upon the sector that can be expected in response to these trends. Secondly, there are changes in policies and market frameworks that may be implemented by those working in the sector in an attempt to steer the sector in a particular direction. This framework is used by UNECE and FAO in scenario planning.

6.2.1. *Forestry economics*

A recently completed pan-European project 'Modelling the Impact of Climate Extremes' (MICE) assessed the potential impacts of climate change on a range of economic sectors important to the region (Hanson *et al.*, 2006). The main conclusions of the project were:

1. the next 10 to 20 yr are important to stakeholders, whilst projections for the 2080s have limited relevance for decision-makers;
2. the reliability of climate models needs to be increased and uncertainties decreased;
3. scientific results should be made accessible to the non-specialist, and stakeholders should be involved in relevant projects, preferably from the design stage;
4. there is the need to recognise and work to bridge the gap between what scientists can realistically achieve and what stakeholders require.

[32] http://www.mcpfe.org

The economic consequences of climate change received global policy attention with the publication of the Stern Report (Stern, 2006). In the UK, the Forestry Commission responded by issuing a response (Forestry Commission, 2005) highlighting forestry's contribution:

- promotion and protection of the role of forests and woodlands in stabilising atmospheric carbon dioxide by sequestering and storing carbon in biomass and soils;
- provision of wood products that provide alternatives to materials such as concrete and steel which involve high energy use in their production;
- development of the use of wood fuel as a renewable source of energy to substitute for fossil fuels.

6.2.2. Forestry climate policy

Motha (2007) advocates the development of an agricultural weather policy to be pro-active in assisting sector in preparedness for future change. Close analogies for forestry can be drawn from the proposals, particularly:

- more understanding on the influence of climate change conditions on SFM, given the increasing limitations and restrictions on natural resource management;
- agrometeorologists can play a leading role in bridging the gaps between the diverse multi-disciplinary fields of science, by reaching out to foresters, extension service personnel, and the forestry industry;
- the forestry sector must learn to adapt to issues arising from climate variability and long term climate change;
- the challenge for agrometeorologists is to develop a coordinated pan-European agricultural/forestry climate policy to assist the land-based sectors deal with these issues.

Motha (2007) states that preparedness must be the essential foundation of an agricultural weather policy that builds upon mitigation measures and adaptation strategies to cope with climate variability and climate change as it affects agriculture, forestry, rangelands, and fisheries.

6.2.3. Technology transfer and advocacy

The need for action to assist forests and forest ecosystems to adapt to change has been highlighted here. However, inherently there is difficulty in persuading forest managers, conservationists and planners to take action, particularly when predictions are so long term and when actions may conflict within existing guidelines or protocols. The contentious issue of seed transfer guidelines and native species is one example, discussed above. A more specific example is provided by Wesche *et al.*, (2006) where, a questionnaire survey of individuals involved in forestry and conservation management in Britain suggested that whilst climate change was recognised as a factor that will affect future conservation management, there was less acceptance to date of a need to modify current policies and practice to take account of possible future range changes.

Involvement of stakeholders is important if adaptation measures are to be translated from planning, to action on the ground. The multi-service provision of forests and their management adds great complexity in impact assessment planning, making stakeholder participation crucial (e.g. Lindner *et al.*, 2002). From an ecological perspective, a conservation strategy would be preferable under all climate scenarios, but the business as usual management would also fit expectations under the current climate due to high biodiversity and carbon sequestration in the forest ecosystem (Fürstenau *et al.*, 2007). In contrast, a forest manager or owner might prefer a management strategy with an intermediate thinning intensity and suitable high quality phenotypes to enhance income from timber production while maintaining other forest functions.

6.2.4. Biodiversity

Adaptation of species to climate change can occur through phenotypic plasticity, evolution, or migration to suitable sites, with the latter probably the most common response in the past. Forest management in Europe is likely to play a pivotal role in providing ecological niches for species, and large scale landscape connectivity. Modelling and planning at regional and local scales will also play important roles in assisting biodiversity (e.g. Lindner *et al.*, 1997). Noss (2001) provides a review of the properties of forest ecosystems and management options for assisting forests to adapt to climate change.

- representing forest types across environmental gradients in reserves;
- protecting climatic refugia at multiple scales;
- protecting primary forests;
- avoiding fragmentation and providing connectivity, especially parallel to climatic gradients;
- providing buffer zones for adjustment of reserve boundaries;
- practicing low-intensity forestry and preventing conversion of natural forests to plantations;
- maintaining natural fire regimes;
- maintaining diverse gene pools;
- identifying and protecting functional groups and keystone species.

Despite repeated commitments at the highest political levels to halt or reduce significantly the loss of biodiversity, the implementation of action towards meeting this goal has been slow, often hindered by a lack of adequate financial and other resources. A key problem in developing policies to stop biodiversity loss is translating threats into a tangible factor for decision making. The RUBICODE project (described above) will address these issues by examining what biodiversity does for society (RUBICODE, 2006). This will give decision-makers a more rational base and will help the understanding of the need for adequate conservation policies, which are essential to halting biodiversity loss.

6.2.5. Policy summary

Kellomäki and Leinonen (2005a) summarise policy implications for European forests and their management from the SilvStrat report. In short, these are that:

- forestry decision making must account for the effects of alternative stand treatments on forest multi-functionality, whilst incorporating ecological, social and economic values. More emphasis may be placed on anyone of these values but balance must be sought;
- balanced decision making will inevitably result in some trade offs;
- guidelines for close-to-nature silviculture (including preference for indigenous species, mixed and structurally diverse stands, continuous cover forestry, refraining from site manipulation), place more constraints on forest management, and are particularly important in central Europe.;
- in order to implement international policy developments at the national and local levels, policy measures are needed in three main categories:
  (i) legal and regulatory measures (*e.g.* revision of legislation, regulations and guidelines);
  (ii) financial and economic measures (*e.g.* incentives for specific management activities and education, revision of taxation systems), and;
  (iii) educational and informational measures (training and expert advice). These policy measures should be dependent on the specific regional and local socio-economic and ecological context.

6.3. Five challenges and recommendations

1. **Develop and implement a pan-European climate change tree atlas, as a scientific and advocacy tool for the forestry and related sectors.**

   The collaborative effort required to develop such a tool would enable the adoption of the best science methodologies and facilitate sharing of data and modelling approaches into the future.

   The atlas and supporting data should be made freely available on the worldwide web.

2. **Gather distribution and abundance data for all European tree species.**

   Some nations have comprehensive data for many species but many have ignored valuable species with smaller distributions or abundance. A European-wide approach would be required to plan and co-ordinate this work.

   This data will underpin the climate change atlas and other predictive work at the European scale. It is crucial for forest scientists, environmental adaptation strategy development and carbon-energy-timber forecasting.

3. **Encourage the forest sector and those engaged in related policy work to develop forestry adaptation strategies.**

   These must address gene management, forest protection, forest regeneration, silvicultural management, forest operations, and delivery of ecosystem services.

4. **Encourage and provide more support for scientific research programmes.**

   Evolutionary mechanism research needs support to enable long-term studies, and to encourage more international collaboration. These will want to use evidence from evolutionary biology, provenance tests and observation on behaviour of exotic species to understand and model the effects of climate change on European trees species and forests.

   Observational research is important to underpin modelling work, and to improve the accuracy of predicting impacts. Phenological studies, and altitudinal, temperature and CO_2 responses, are some examples.

   Monitoring of pest and disease distributions, and developing understanding of natural defence mechanisms.

   Tree breeding work to develop quality wood for material substitution in shorter rotations, or increased disease resistance, are two important examples.

   Silvicultural research into mixed forests and close to nature forestry.

5. **Develop and coordinate advocacy and outreach programmes for the forestry sector.**

   The long generation times for trees and their probable medium-term resistance to climate change (the main threat is to regeneration), in combination with the long term nature of forestry practice, provides a challenge for the forestry sector if it is to disseminate information effectively and attract interest.

   Scientific information is often widely dispersed and inaccessible to those outside academia or scientific institutes. Widely accessible and well designed tools for practitioners, scientists and policy makers are necessary (*e.g.* a climate change tree atlas for Europe).

   The multi-functionality of sustainable forestry management needs to be promoted. The contexts for forestry in the 21st Century will be provision of ecosystem services and support for a carbon-lean society. Broader collaboration with other sectors will increase interest in forestry and attract more political support.

7. CONCLUSIONS

At the highest political and scientific levels it is recognised that forestry practices can make a significant contribution at low cost to increasing soil carbon sinks, to GHG emission reductions, and by contributing biomass feedstocks for energy use.(medium agreement, medium evidence: IPCC, 2007b). There is stronger evidence than ever before that climate change impacts are detectable in natural systems and that these are attributable to anthropogenic factors.

In the future, Europe's forests will be driven and influenced by many wide-ranging factors in addition to a changing climate, including population change, economic growth, social interest, technological development, policy interests.

Predicted change and impacts on European forests are wide-ranging. Some impacts such as rising CO_2 and temperature are easier to forecast (and positive), whilst others such as stochastic events (*e.g.* fire, drought, wind, pests/pathogens) and more difficult to model (and potentially damaging). The Mediterranean and Pannonian regions of Europe are likely to most affected, as are those forests and species at altitudinal limits. Different models and approaches adopted among countries across Europe provides diversity but greater collaboration would be beneficial. The case study discussion revealed an opportunity for developing a pan-European climate change tree atlas, and the multiple benefits such an exercise would bring to forestry practice, science and policy.

Timber yields are forecast to improve during the early 21st Century. Land use modelling also predicts increase interest and potential for forests within Europe land-use. Combined with current forecast trends in timber indicating decrease in available hardwoods and increasing consumption by industrialising countries, the outlook for the European forest sector seems positive. However, regional differences will become more apparent in time, as climate change impacts. The context for European forests will be supporting a carbon-lean society (domestic timber production, material substitution, bioenergy, carbon storage) and ecosystem services (biodiversity adaptation, landscape connectivity, soil and water protection and management).

Adaptation to predicted impacts will be critically important. Adaptation strategies must be developed to promote and manage the forest resource. Given the long generation times of forest tree species, and the inherent lag times, immediate adaptation measures are required by the forestry sector. A key point however is that climate change will impact the existing resource less than future generations, as it is the regeneration capability of forest tree species that will be most impacted. In other words, there will be an apparent persistence of trees even once the climate becomes unsuitable. Clearly there is a difference between autonomous adaptation (either natural adaptation by the species or unplanned human influence) and planned adaptation strategies.

Forest management and silvicultural practice must rise to the challenge of managing the forest resource for emerging markets, whilst meeting changing policy demands and adapting to climate change. It will need to develop adaptation strategies at EU-wide, bioregional and micro-site scales, and these must address gene management, forest protection and regeneration, silvicultural management, forest operation and delivery of ecosystem services. The possibility of including adaptation strategies within certification schemes should be explored.

Species and provenance choice will be important in delivering priorities but without a more flexible approach in the future, progress and delivery may be hindered. For example, provenance and seed transfer policy guidelines should be reviewed regularly. In the interests of developing robust woodlands, wider acceptance of non-native species may be required, providing full impact evaluations on SFM delivery are undertaken.

Without question a robust forest resource is required to combat climate change so that SFM (including ecosystem services) can continue to be delivered effectively. Possible future management and design options may favour mixed forests and close to nature practice. Such systems, in combination with the promotion of genetic diversity, will assist in forest health and protection, and in ecosystem service delivery. Strategies must be flexible and meet uncertain future demands and impacts.

8. REFERENCES

Ackerly, D. and Cornwell, W., (2007). A trait-based approach to community assembly: partitioning of species trait values into within- and among-community components. *Ecology Letters*, 10(2): 135-145.

Araújo, M.B., Cabeza, M., Thuiller, W., Hannah, L. and Williams, P.H., (2004). Would climate change drive species out of reserves? An assessment of existing reserve-selection methods. *Global Change Biology*, 10: 1618-1626.

Archaux, F. and Wolters, V., (2006). Impact of summer drought on forest biodiversity: what do we know? *Annals of Forest Science*, 63: 645-652.

Badeau, V., Dupouey, J., Cluzeau, C. and Drapier, J., (2005). Aires potenielles de répartition des essences forestières d'ici. *Fôret Entreprise*, 162: 25-29.

Badeck, F.-W., Bondeau, A., Böttcher, K., Doktor, D., Lucht, W., Schaber, J. and Sitch, S., (2004). Responses of spring phenology to climate change. *New Phytologist*, 162: 295–309.

Bailey, S., (2007). Increasing connectivity in fragmented landscapes: investigation of evidence for biodiversity gain in woodlands. *Forest Ecology and Management*, 238: 7-23.

Bartelink, H. and Olsthoorn, A., (1999). Introduction: mixed forest in western Europe. In: A. Olsthoorn, H. Bartelink, J. Gardiner, H. Pretzsch, H. Hekhuis and A. Franc (Editors), Management of mixed-species forest: silviculture and economics, Wageningen, pp. 9-16.

Battisti, A., (2004). Forests and climate change - lessons from insects. *Forest@*, 1(1): 17-24.

Bergh, J., Freeman, M., Sigurdsson, B., Kellomäki, S., Laitinen, K., Niinistö, S., Peltola, H. and Lindera, S., (2003). Modelling the short-term effects of climate change on the productivity of selected tree species in Nordic countries. *Forest Ecology and Management*, 183: 327-340.

Berry, P., Harrison, P., Dawson, T. and Walmsley, C., (2005). Monarch 2: modelling natural resource responses to climate change www.UKCIP.org.uk.

Bodin, P. and Wiman, B., (2007). The usefulness of stability concepts in forest management when coping with increasing climate uncertainties. *Forest Ecology and Management*, 242: 541-552.

Boshier, D., (2007). Tree improvement and genetic diversity of British broadleaves, Policy paper. British & Irish Hardwoods Improvement Programme.

Botkin, D., Saxe, H., Araújo, M., Betts, R., Bradshaw, R., Cedhagen, T., Chesson, P., Dawson, T., Etterson, J., Faith, D., Ferrier, S., Guisan, A., Skjoldborg Hansen, A., Hilbert, D., Loehle, C., Margules, C., New, M., Sobel, M. and Stockwell, D., (2007). Forecasting the Effects of Global Warming on Biodiversity. *BioScience*, 57(3): 227-236.

Briceño-Elizondo, E., Garcia-Gonzalo, J., Peltola, H., Matala, J. and Kellomäki, S., (2006). Sensitivity of growth of Scots pine, Norway spruce and silver birch to climate change and forest management in boreal conditions. *Forest Ecology and Management*, 232: 152-167.

Broadmeadow, M., (2000). Climate change - Implications for forestry in Great Britain, Forestry Commission, Edinburgh.

Broadmeadow, M. and Randle, T., (2002). The impacts of increased CO_2 concentrations on tree growth and function. In: M. Broadmeadow (Editor), Climate change: impacts on UK forests. Forestry Commission Bulletin 125, Edinburgh, pp. 119-140.

Broadmeadow, M., Ray, D. and Samuel, C., (2005). Climate change and the future for broadleaved tree species in Britain. *Forestry*, 78(2): 145-161.

Brooker, R., (2006). Plant–plant interactions and environmental change. *New Phytologist*, 171: 271-284.

Brooker, R., Kikvidze, Z., Pugnaire, F., Callaway, R., Choler, P., Lortie, C. and Michalet, R., (2005). The importance of importance. *Oikos*, 109: 63-70.

Cameron, A., (1996). Managing birch woodlands for the production of quality timber. *Forestry*, 69(4): 357-371.

Cannell, M., (2002). Impacts of climate change on forest growth. In: M. Broadmeadow (Editor), Climate change: impacts on UK forests. Forestry Commission Bulletin 125, Edinburgh, pp. 141-149.

Cannell, M. and Smith, R., (1986). Climate warming, spring budburst and frost damage on trees. *Journal of Applied Ecology*, 23: 177-191.

Carvalho, A., Flannigan, M., Logan, K., Miranda, A. and Borrego, C., (2006). Future fire activity in Portugal. *Forest Ecology and Management*, 234S: S214.

CEC, (1997). Energy for the Future: renewable sources of energy, a white Paper for a Community Strategy and Action Plan. COM(97)599 final (26/11/1997).

Chuine, I., (2000). A unified model for budburst of trees. *Journal of Theoretical Biology*, 207(3): 337-347.

Chuine, I., Belmonte, J. and Mignot, A., (2000). A modelling analysis of the genetic variation of phenology between tree populations. *Journal of Ecology (Oxford)*, 88(4): 561-570.

Cleland, E., Chuine, I., Menzel, A., Mooney, H. and Schwartz, M., (in press). Shifting plant phenology in response to global change. *TRENDS in Ecology and Evolution*.

Coultherd, P., (1978). The effect of the 1976 drought on established and recently-planted trees is discussed with particular reference to their greater susceptibility to disease and to the fire danger. *Quarterly Journal of Forestry*, 72(2): 67-80.

Daubree, J. and Kremer, A., (1993). Genetic and phenological differentiation between introduced and natural populations of *Quercus rubra* L. *Annales des Sciences Forestieres*, 50(Suppl.1): 271s-280s.

Demesure-Musch, B. and Oddou-Muratorio, S., (2004). EUFORGEN technical guidelines for genetic conservation and use for wild service tree (*Sorbus torminalis*), International Plant Genetic Resources Institute, Rome, Italy, pp. 6.

Desprez-Loustau, M., Marçais, B., Nageleisen, L.M., Piou, D. and Vannini, A., (2006). Interactive effects of drought and pathogens in forest trees. *Annals of Forest Science*, 63(6): 597-612.

Diaz, S., Fargione, J., Chapin, F. and Tilman, D., (2006). Biodiversity loss threatens human well-being. *PLoS Biology* 4(8): 1300-1305.

Dorland, C., Tol, R. and Palutikof, J., (1999). Vulnerability of the netherlands and northwest europe to storm damage under climate change. A Model Approach Based on Storm Damage in the Netherlands. *Climate Change*, 43: 513-535.

Ducousso, A., Guyon, J.P. and Kremer, A., (1996). Latitudinal and altitudinal variation of bud burst in western populations of sessile oak (*Quercus petraea*

(Matt.) Liebl.). *Annales des Sciences Forestieres*, 53(2/3): 775-782.

Edinburgh Centre for Carbon Management, (2006). Forestry Commission Scotland greenhouse gas emissions comparison - carbon benefits of timber in construction. A report by the Edinburgh Centre for Carbon Management Ltd., http://www.forestry.gov.uk/pdf/Carbonbenefitsoftimberinconstruction.pdf/$FILE/Carbonbenefitsoftimberinconstruction.pdf, pp. 26.

European Environment Agency, (2006). European forest types. Categories and types for sustainable forest management reporting and policy. EEA Technical report No 9/2006, http://reports.eea.europa.eu/technical_report_2006_9/en/eea_technical_report_9_2006.pdf.

Forestry Commission, (2005). Stern review on economics of climate change - response from the Forestry Commission, http://www.hm-treasury.gov.uk/media/FC3/89/climate_change__forestry.pdf, pp. 6.

FRAXIGEN, (2005). Ash species in Europe: biological characteristics and practical guidelines for sustainable use. Oxford Forestry Institute, University of Oxford, UK, pp. 128.

Frei, C., Davies, H., Gurtz, J. and Schär, C., (2000). Climate dynamics and extreme precipitation and flood events in Central Europe. *Integrated Assessment*, 1: 281-299.

Fuhrer, J., Beniston, M., Fischlin , A., Frei , C., Goyette, S., Jasper, K. and Pfister, C., (2006). Climate risks and their impact on agriculture and forests in Switzerland. *Climate Change*, 79: 79-102.

Fürstenau, C., Badeck, F., Lasch, P., Lexer, M., Lindner, M., Mohr, P. and Suckow, F., (2007). Multiple-use forest management in consideration of climate change and the interests of stakeholder groups. *European Journal of Forest Research*, 126: 225-239.

Gayer, K., (1886). Der gemischte Wald, seine Begründung und Pflege, insbesondere durch Horst- und Gruppenwirtschaft. Parey, Berlin, 168 pp.

Gibbs, J., van Dijk, C. and Webber, J., (2003). *Phytophthora* disease of Alder in Europe, Forestry Commission Bulletin 126. Forest Commission, Edinburgh, pp. 82.

Granier, A., Reichstein, M., Bréda, N., Janssens, A., Falge, E., Ciais, P., Grünwald, T., Aubinet, M., Berbigier, P., Bernhofer, C., Buchmann, N., Facini, O., Grassi, G., Heinesch, B., Ilvesniemi, H., Keronen, P., Knohl, A., Köstner, B., Lagergren, F., Lindroth, A., Longdoz, B., Loustau, D., Mateus, J., Montagnani, L., Nys, C., Moors, E., Papale, D., Peiffer, M., Pilegaard, K., Pita, G., Pumpanen, J., Rambal, S., Rebmann, C., Rodrigues, A., Seufert, G., Tenhunen, J., Vesala, T. and Wang, Q., (2007). Evidence for soil water control on carbon and water dynamics in European forests during the extremely dry year: 2003. *Agricultural and Forest Meteorology*, 143: 123-145.

Groisman, P., Sherstyukov, B., Razuvaev, V., Knight, R., Enloe, J., Stroumentova, N., Whitfield, P., Førland, E., Hannsen-Bauer, I., Tuomenvirta, H., Aleksandersson, H., Mescherskaya, A. and Karl, T., (2007). Potential forest fire danger over Northern Eurasia: changes during the 20th century. *Global and Planetary Change*, 56: 371-386.

Gustavsson, L., Madlener, R., Hoen, H.-F., Jungmeier, G., Karjalainen, G., KlÖhn, S., Mahapatra, K., Pohjola, J., Solberg, B. and Spelter, H., (2006a). The role of wood material for greenhouse gas mitigation *Mitigation and adaptation strategies for global change*, 11(5-6): 1097-1127.

Gustavsson, L., Pingoud, K. and Sathre, R., (2006b). Carbon dioxide balance of wood substitution: comparing concrete- and wood-framed buildings. *Mitigation and adaptation strategies for global change*, Volume 11(3): 667-691.

Hampe, A., (2004). Bioclimate envelope models: what they detect and what they hide. *Global Ecology & Biogeography* 13(5): 469-471.

Hamrick, J., (2004). Response of forest trees to global environmental changes. *Forest Ecology and Management*, 197: 323-335.

Hannah, L., Midgley, G.F., Lovejoy, T., Bond, W.J., Bush, M., Lovett, J.C., Scott, D. and Woodward, F.I., (2002). Conservation of biodiversity in a changing climate. *Conservation Biology*, 16(1): 264-268.

Hänninen, H., (1996). Effects of climatic warming on northern trees: testing the frost damage hypothesis with meteorological data from provenance transfer experiments. *Scandinavian Journal of Forestry Research*, 11: 17-25.

Hansen, A., Neilson, R., Dale, V., Flather, C., Iverson, L., Currie, D., Shafer, S., Cook, R. and Bartlein, P., (2001). Global change in forests: responses of species, communities, and biomes. *BioScience*, 51(9): 765-779.

Hanson, C., Palutikof, J., Dlugolecki, A. and Giannakopoulos, C., (2006). Bridging the gap between science and the stakeholder: the case of climate change research. *Climate Research*, 31: 121-133.

Heide, O., (2003). High autumn temperature delays spring bud burst in boreal trees, counterbalancing the effect of climate warming. *Tree Physiology*, 23: 931-936.

Heikkinen, R., Luoto, M., Araújo, M., Virkkala, R., Thuiller, W. and Sykes, M., (2006). Methods and uncertainties in bioclimatic envelope modelling under climate change. *Progress in Physical Geography*, 39(6): 751-777.

Hekhuis, H. and Wieman, E., (1999). Costs, revenues and function fulfilment of nature conservation and recreation values of mixed, uneven-aged forests in The Netherlands. In: A. Olsthoorn, H. Bartelink, J. Gardiner, H. Pretzsch, H. Hekhuis and A. Franc (Editors), Management of mixed-species forest: silviculture and economics, Wageningen, pp. 331-346.

Hemery, G.E., (2001). Growing walnut in mixed stands. *Quarterly Journal of Forestry*, 95(1): 31-36.

Hemery, G.E. and Russell, K., (2005). Advances in walnut breeding and culture in the United Kingdom. *Acta Horticulturae*, 705: 95-101.

Hemery, G.E., Savill, P. and Pryor, S.N., (2005a). Applications of the crown diameter - stem diameter relationship for different species of broadleaved trees. *Forest Ecology and Management*, 215(1-3): 285-294.

Hemery, G.E., Savill, P. and Thakur, A., (2005b). Height growth and flushing in common walnut (*Juglans regia* L.): 5-year results from provenance trials in Great Britain. *Forestry*, 78(2): 121-133.

Herbert, R., Samuel, S. and Patterson, G., (1999). Using local stock for planting native trees and shrubs, Forestry Commission Practice Note 8. Forestry Commission, Edinburgh, pp. 8.

Hossell, J.E., Ellis, N.E., Harley, M.J. and Hepburn, I.R., (2003). Climate change and nature conservation: Implications for policy and practice in Britain and Ireland. *Journal for Nature Conservation*, 11(1): 67-73.

Hubert, J. and Lee, S., (2005). A review of the relative roles of silviculture and tree improvement: the example of Sitka spruce in Britain and possible lessons for hardwood breeding. *Forestry*, 78(2): 109-120.

IPCC, (2007a). Climate Change 2007: Impacts, Adaptation and Vulnerability, Working Group II Contribution to the Intergovernmental Panel on Climate Change Fourth Assessment Report. Summary for policy makers. , http://www.ipcc-wg2.org/.

IPCC, (2007b). Climate Change 2007: Mitigation of Climate Change, Working Group III Contribution to the Intergovernmental Panel on Climate Change Fourth Assessment Report. Summary for policy makers. , http://www.ipcc.ch/.

IPCC, (2007c). Climate Change 2007: The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Summary for policy makers, http://www.ipcc.ch/.

Iverson, L., Prasad, A., Matthews, S. and Peters, M., (in preparation). Estimating potential suitable habitat for 134 tree species in the eastern United States with tree ensemble methods and six possible future climate scenarios. *Forest Ecology and Management*.

Iverson, L., Schwartz, M. and Prasad, A., (2004). How fast and far might tree species migrate under climate change in the eastern United States? Global Ecology and Biogeography 13:209-219. *Global Ecology and Biogeography*, 13: 209-219.

Jacobsena, J. and Thorsen, B., (2003). A Danish example of optimal thinning strategies in mixed-species forest under changing growth conditions caused by climate change. *Forest Ecology and Management*, 180: 375-388.

Jalas, J. and Suominen, J., (1976). Atlas Florae Europaeae. Distribution of Vascular Plants in Europe Vol 3. The Committee for Mapping the Flora of Europe & Societas Biologica Fennica, Vanamo, Helsinki

Jose, S., Williams, R. and Zamora, D., (2006). Belowground ecological interactions in mixed-species forest plantations. *Forest Ecology and Management*, 233: 231-239.

Kajba, D. and Gračan, J., (2003). EUFORGEN technical guidelines for genetic conservation and use for black alder (*Alnus glutinosa*), International Plant Genetic Resources Institute, Rome, Italy, pp. 6.

Kanowski, P., Mather, R. and Savill, P., (1991). Short note: genetic control of oak shake; some preliminary findings. *Silvae Genetica*, 40: 166-168.

Karjalainen, T., Pussinen, A., Liski, J., Nabuurs, G.-J., Erhard, M., Eggers, T., Sonntag, M. and Mohren, G., (2002). An approach towards an estimate of the impact of forest management and climate change on the European forest sector carbon budget: Germany as a case study. *Forest Ecology and Management*, 162: 87-103.

Kellomäki, S. and Leinonen, S., (2005a). Chapter 6: Policy Objectives in Relation to Adaptive Forest Management, Management of European Forests Under Changing Climatic Conditions. SilviStrat Final Report. Tiedonantoja/Research Notes No. 163. University of Joensuu, Faculty of Forestry. ISBN: 952-458-652-5. , pp. 253-314.

Kellomäki, S. and Leinonen, S., (2005b). Management of European Forests Under Changing Climatic Conditions. SilviStrat Final Report. Tiedonantoja/Research Notes No. 163. University of Joensuu, Faculty of Forestry. ISBN: 952-458-652-5. , pp. 427.

Kellomäki, S., Strandman, H., Nuutinen, T., Peltola, H., Korhonen, K. and Väisänen, H., (2005). Adaptation of forest ecosystems, forests and forestry to climate change. FINADAPT Working Paper 4, Finnish Environment Institute Mimeographs 334, Helsinki, pp. 44.

Kelty, M., (2006). The role of species mixtures in plantation forestry. *Forest Ecology and Management*, 233: 195-204.

Kerr, G., (2002). The potential for sustainable management of semi-natural woodlands in southern England using uneven-aged silviculture. *Forestry*, 75(3): 227-243.

Kerr, G. and Boswell, C., (2001). The influence of spring frosts, ash bud moth (*Prays fraxinella*) and site factors on forking of young ash. *Forestry*, 74: 29-40.

Kerr, G. and Morgan, G., (2006). Does formative pruning improve the form of broadleaved trees? *Canadian Journal of Forest Research*, 36(1): 132-141.

Knohl, a., Schulze, E.-D., Kolle, O. and Buchmann, N., (2003). Large carbon uptake by an unmanaged 250-year-old deciduous forest in Central Germany. *Agricultural and Forest Meteorology*, 118: 151-167.

Köble, R. and Seufert, G., (2001). Novel maps for forest tree species in Europe. In: . (Editor), Proceedings of the conference "A changing atmosphere" 8th European symposium on the Physico-Chemical Behaviour of Atmosperic Pollutants, 17 - 20 Sept. 2001, Torino. JRC Ispra, Institute for Environment and Sustainability, T.P.051, I-21020 Ispra, Paper online: http://ccu.jrc.it/Pubblications/tree_species_maps.pdf.

Koski, V. and Rousi, M., (2005). A review of the promises and constraints of breeding silver birch (*Betula pendula* Roth) in Finland. *Forestry*, 78(2): 187-198.

Kramer, K., (1999). The role of phenology for impact assessments of climate change on growth in boreal, temperate and Mediterranean forest ecosystems. In: A. Olsthoorn, H. Bartelink, J. Gardiner, H. Pretzsch, H. Hekhuis and A. Franc (Editors), Management of mixed-species forest: silviculture and economics, Wageningen, pp. 278-291.

Kramer, K., Leinonen, L. and Loustau, D., (2000). The importance of phenology for the evaluation of impact of climate change on growth of boreal, temperate and Mediterranean forests ecosystems: an overview. *International Journal of Biometeorology*, 44: 67-75.

Kremer, A., (in preparation). How well can existing forests withstand climate change?, Proceedings of IPGRI conference on Climate change and forest genetic diversity: implications for sustainable forest management in Europe.

Lal, R., (2005). Forest soils and carbon sequestration. *Forest Ecology and Management*, 220: 242-258.

Lal, R., (2007). Carbon Management in agricultural soils. *Mitigation and Adaptation Strategies for Global Change*, 12(2): 303-322.

Langvatn, R., Albon, S., Borkey, T. and Clutton-Brock, T., (1996). Climate, plant phenology and variation in age of first reproduction in a temperate herbivore. *Journal of Animal Ecology*, 65: 653-670.

Lapenis, A., Shvidenko, A., Shepaschenko, D., Nilsson, S. and Aiyyer, A., (2005). Acclimation of Russian forests to recent changes in climate. *Global Change Biology*, 11(12): 2090-2102.

Larsen, J. and Nielsen, A., (2007). Nature-based forest management—Where are we going? Elaborating forest development types in and with practice. *Forest Ecology and Management*, 238: 107–117.

Laurent, C., (2003). Forest management and climate change in the Walloon region of Belgium In: A. Perlis

(Editor), Unasylva 214/215 - Forest Management at the XII World Forestry Conference. FAO, Rome, Italy.

Lavergne, S., Molina, J. and Debussche, M., (2006). Fingerprints of environmental change on the rare Mediterranean flora: a 115-year study. *Global Change Biology*, 12(8): 1466-1478.

Lavorel, S., Diaz, S., Cornelissen, J., Garnier, E., Harrison, S., McIntyre, S., Pausas, J., Pérez-Harguindeguy, N., Roumet, C. and Urcelay, C., (2007). Plant functional types: are we getting any closer to the Holy Grail? In: J. Canadell, D. Pataki and L. Pitelka (Editors), Terrestrial ecosystems in a changing world. Springer, New York, pp. 149-164.

Lavorel, S. and Garnier, E., (2002). Predicting changes in community composition and ecosystem functioning from plant traits: revisiting the Holy Grail. *Functional Ecology*, 16(5): 545-556.

Lawson, G. and Hemery, G., (2007). World timber trade and implementing sustainable forest management in the UK, Report to the Woodland Policy Group, pp. 86.

Leathwick, J. and Austin, M., (2001). Competitive interactions between tree species in New Zealand's old-growth indigenous forests. *Ecology*, 82: 2560-2573.

Lindner, M., Bugmann, H., Lasch, P., Flechsig, M. and Cramer, W., (1997). Regional impacts of climatic change on forests in the state of Brandenburg, Germany. *Agricultural and Forest Meteorology*, 84: 123-135.

Lindner, M. and Karjalainen, T., (2007). Carbon inventory methods and carbon mitigation potentials of forests in Europe: a short review of recent progress. *European Journal of Forest Research*, 126: 149–156.

Lindner, M., Meyer, J., Eggers, T. and Moiseyev, A., (2006). Bioenergy potential from forestry. In: EEA (Editor), How much bioenergy can Europe produce without harming the environment?, European Environment Agency, Copenhagen, pp. 31-42.

Lindner, M., Sohngen, B., Joyce, L., Price, D., Bernier, P. and Karjalainen, T., (2002). Integrated forestry assessments for climate change impacts. *Forest Ecology and Management*, 162: 117-136.

Lloret, F., Peñuelas, J. and Estiarte, M., (2004). Experimental evidence of reduced diversity of seedlings due to climate modification in a Mediterranean-type community. *Global Change Biology*, 10: 248–258.

Loacker, K., Kofler, W., Pagitz, K. and Oberhuber, W., (2007). Spread of walnut (*Juglans regia* L.) in an Alpine valley is correlated with climate warming. *Flora*, 202: 70-78.

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. Forestry Commission Bulletin 125, Edinburgh, pp. 83-97.

Loustau, D., Bosc, A., Colin, A., Davi, H., François, C., Dufrêne, E., Déqué, M., Cloppet, E., Arrouays, D., Le Bas, C., Saby, N., Pignard, G., Hamza, N., Granier, A., Breda, N., Ciais, P., Viovy, N., Ogée, J. and Delage, J., (2005). Modelling the climate change effects on the potential production of French plains forests at the sub regional level. *Tree Physiology*.

Markewitz, D., (2006a). Fossil fuel carbon emissions from silviculture: Impacts on net carbon sequestration in forests. *Forest Ecology and Management*, 236: 153–161.

Markewitz, D., (2006b). Fossil fuel carbon emissions from silviculture: Impacts on net carbon sequestration in forests *Forest Ecology and Management*, 236: 153-161.

Matthews, R. and Robertson, K., (2005). Answers to ten frequently asked questions about bioenergy, carbon sinks and their role in climate change, IEA Bioenergy. Task 38, http://www.ieabioenergy-task38.org/publications/faq/, pp. 8.

Matthews, S., O'Connor, R. and Plantinga, A.J., (2002). Quantifying the impacts on biodiversity of policies for carbon sequestration in forests. *Ecological Economics*, 40(1): 71-87.

McGill, B., Enquist, B., Weiher, E. and Westoby, M., (2006). Rebuilding community ecology from functional traits. *TRENDS in Ecology and Evolution*, 21(4): 178-185.

McLachlan, J., Clark, J. and Manos, P., (2005). Molecular indicators of tree migration capacity under rapid climate change. *Ecology*, 86(8): 2088-2098.

Michalet, R., Petetin, A. and Souchier, B., (1995). Catalogue detaille des Stations Forestieres du Sud-Isere, Labaratoire des Ecosystèmes Alpins, Centre de Biologie Alpine, Université Joseph Fourier, Grenoble, pp. 346 plus Annexes.

Miles, P., Brand, G., Alerich, C., Woudenberg, S., Glover, J. and Ezzell, E., (2001). The forest inventory and analysis database: database description and users manual version 1.0, GTR NC-218. North Central Research Station, USDA Forest Service, St. Paul, MN.

Millennium Ecosystem Assessment, (2005). Ecosystems and human well-being: biodiversity synthesis. . Washington D. C: World Resources Institute, pp. 86.

Ministry of Forests and Range, (2006). Preparing for climate change: adapting to impacts on British Columbia's forest and range resources, http://www.for.gov.bc.ca/mof/Climate_Change/Preparing_for_Climate_Change.pdf, pp. 92.

Motha, R., (2007). Development of an agricultural weather policy. *Agricultural and Forest Meteorology*, 142: 303–313.

Mutabaruka, C., Woodgate, G. and Buckley, G., (2005). External and internal growth parameters as potential indicators of shake in sweet chestnut (*Castanea sativa* Mill.). *Forestry*, 78(2): 175-186.

Nabuurs, G.-J., Pussinen, A., Karjalainen, T., Erhard, M. and Kramer, K., (2002). Stemwood volume increment changes in European forests due to climate change - a simulation study with the EFISCEN model. *Global Change Biology*, 8(4): 304-316.

Nichols, J., Bristow, M. and Vanclay, J., (2006). Mixed-species plantations: Prospects and challenges. *Forest Ecology and Management*, 233: 383–390.

Nisbet, T., (2002). Implications of climate change: soil and water. In: M. Broadmeadow (Editor), Climate change: impacts on UK forests. Forestry Commission Bulletin 125, Edinburgh, pp. 53-68.

Noss, R.F., (2001). Beyond Kyoto: forest management in a time of rapid climate change. *Conservation Biology*, 15(3): 578-590.

Nuutinen, T., Matala, J., Hirvelä, H., Härkönen, K., Peltola, H., Väisänen, H. and Kellomäki, S., (2006). Regionally optimized forest management under changing climate. *Climate Change*, 79(3-4): 315-333.

O'Hara, K., Hasenauer, H. and Kindermann, G., (2007). Sustainability in multi-aged stands: an analysis of long-term plenter systems. *Forestry*, 80(2): 163-181.

Orshan, G., (1989). Plant pheno-morphological studies in Mediterranean type ecosystems, vii. Kluwer Academic, Dordrecht, 404 pp. pp.

Päivinen, R., Lehikoinen, M., Schuck, A., Häme, T., Väätäinen, S., Kennedy, P. and Folving, S., (2001). Combining Earth Observation Data and Forest Statistics. EFI Research Report 14. European Forest Institute, Joint Research Centre - European Commission. EUR 19911 EN pp. 101.

Parmesan, C., (2006). Ecological and evolutionary responses to recent climate change. *Annual Review of Ecology, Evolution and Systematics*, 37: 637-669.

Parmesan, C. and Yohe, G., (2003). A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, 421: 37-42.

Partanen, J., (2004). Dependence of photoperiodic response of growth cessation on the stage of development in Picea abies and Betula pendula seedlings. *Forest Ecology and Management*, 188: 137–148.

Pattanayak, S.K., McCarl, B.A., Sommer, A.J., Murray, B.C., Bondelid, T., Gillig, D. and DeAngelo, B., (2005). Water quality co-effects of greenhouse gas mitigation in US agriculture. *Climatic Change*, 71(3): 341-372.

Pearson, R. and Dawson, T., (2004). Bioclimate envelope models: what they detect and what they hide - response to Hampe. *Global Ecology & Biogeography*, 13(5): 471-473.

Peltoniemi, M., Palosuo, T., Monni, S. and Mäkipää , R., (2006). Factors affecting the uncertainty of sinks and stocks of carbon in Finnish forests soils and vegetation. *Forest Ecology and Management*, 232: 75-85.

Peñuelas, J. and Marti, B., (2003). A global change-induced biome shift in the Montseny mountains (NE Spain). *Global Change Biology*, 9: 131-140.

Perez-Garcia, J., Joyce, L. and McGuire, A., (2002). Temporal uncertainties of integrated ecological/economic assessments at the global and regional scales. *Forest Ecology and Management*, 162: 105-115.

Peterken, G.F. and Mountford, E.P., (1996). Effects of drought on beech in Lady Park Wood, an unmanaged mixed deciduous woodland. Forestry. 69 (2), 125-136. *Forestry*, 69(2): 125-136.

Peterson, C., (2000). Catastrophic wind damage to North American forests and the potential impact of climate change. *The Science of the Total Environment*, 262: 287-311.

Petit, R., Brewer, S., Bordács, S., Burge, K., Cheddadi, R., E, C., J, C., UM, C., van Dam, B., JD, D., Espinel, S., Fineschi, S., Finkeldey, R., Glaz, I., Goicoechea, P., Jensen, J., König, A., Lowe, A., Madsen, S., Mátyás, G., Munro R.C., Popescu, F., Slade, D., Tabbener, H., de Vries, S., Ziegenhagen, B., de Beaulieu, J. and Kremer, A., (2002). Identification of refugia and post-glacial colonisation routes of European white oaks based on chloroplast DNA and fossil pollen evidence. *Forest Ecology and Management*, 156: 49-74.

Piat, J., (2004). Le diagnostic: un préalable indispensable à la taille ou l'élagage des feuillus à objectif de production. *RenDez-Vous Techniques*, 6: 8-12.

Pliüra, A. and Heuertz, M., (2003). EUFORGEN technical guidelines for genetic conservation and use for common ash (*Fraxinus excelsior*), International Plant Genetic Resources Institute, Rome, Italy, pp. 6.

Prasad, A. and Iverson, L., (1999-ongoing). A Climate Change Atlas for 80 Forest Tree Species of the Eastern United States [database] Northeastern Research Station, USDA Forest Service, Delaware, Ohio, http://www.fs.fed.us/ne/delaware/atlas/index.html

Prasad, A., Iverson, L. and Liaw, A., (2006). Newer classification and regression tree techniques: bagging and random forests for ecological prediction *Ecosystems*, 9: 181-199.

Pyatt, G., Ray, D. and Fletcher, J., (2001). An ecological site classification for forestry in Great Britain, Bulletin 124. Forestry Commission, Edinburgh, pp. 74.

Rameau, J.-C., Gauberville, C. and Drapier, N., (2000). Gestion forestière et diversité biologique. Identification et gestion intégrée des habitats et espèces d'intérêt communautaire. France Domaine continental. IDF, Paris, France, pp. 114.

Randle, T., (2004). Forest and timber quality in Europe: modelling and forecasting yield and quality in Europe. MEFYQUE Final Report, pp. 245.

Ray, D., Pyatt, G. and Broadmeadow, M., (2002). Modelling the future climatic suitability of plantation forest tree species. In: M. Broadmeadow (Editor), Climate change: impacts on UK forests. Forestry Commission Bulletin 125, Edinburgh, pp. 151-168.

Resco de Dios, V., Fischer, C. and Colinas, C., (2007). Climate change effects on mediterranean forests and preventive measures. *New Forests*, 33: 29-40.

Romero, C., Ros, V. and Daz-Balteiro, L., (1998). Optimal forest rotation age when carbon captured is considered: theory and applications. *Journal of the Operational Research Society*, 49(2): 121-131.

Rotach, P., (2003). EUFORGEN technical guidelines for genetic conservation and use for service tree (*Sorbus domestica*), International Plant Genetic Resources Institute, Rome, Italy, pp. 6.

Rötzer, T., Grote, R. and Pretzsch, H., (2004). The timing of bud burst and its effect on tree growth. *International Journal of Biometeorology*, 48: 109-118.

RUBICODE, (2006). Global Change and Ecosystems Area: Shaping biodiversity strategies for terrestrial and freshwater ecosystems, Technical Annex. RUBICODE Project no: 036890, Sixth Framework Programme., pp. 77.

Rusanen, M. and Myking, T., (2003). EUFORGEN technical guidelines for genetic conservation and use for sycamore (*Acer pseudoplatanus*), International Plant Genetic Resources Institute, Rome, Italy, pp. 6.

Russell, K., (2002). Wild cherry programme gets star rating. *Forestry and Timber News*, 1(Woodland Owner Supplement): 4-6.

Russell, K., (2003). EUFORGEN technical guidelines for genetic conservation and use for wild cherry (*Prunus avium*), International Plant Genetic Resources Institute, Rome, Italy, pp. 6.

Salinger, M., (2007). Agriculture's influence on climate during the Holocene. *Agricultural and Forest Meteorology*, 142: 96–102.

Salinger, M.J., Sivakumar, M.V.K. and Motha, R., (2005). Reducing vulnerability of agriculture and forestry to climate variability and change: Workshop summary and recommendations. *Climatic Change*, 70(1-2): 341-362.

Savill, P., Evans, J., Auclair, D. and Falck, J., (1997). Plantation silviculture in Europe. Oxford University Press, Oxford.

Savill, P. and Mather, R., (1990). A possible indicator for shake in oak: relationship between flushing dates and vessel sizes. *Forestry*, 63: 355-362.

Savill, P.S., (1991). The silviculture of trees used in British forestry. CAB International, Wallingford, 143 pp.

Saxe, H., Cannell, M., Johnsen, Ø., Ryan, M. and Vourlitis, G., (2001). Tree and forest functioning in response to global warming. Tansley review no. 123. *New Phytologist*, 149: 369-400.

Schelhaas, M., Nabuurs, G. and Schuck, A., (2003). Natural disturbances in the European forests in the 19th and 20th centuries. *Global Change Biology*, 9: 1620-1633.

Schlamadinger, B., Faaij, A., Junginger, M., Woess-Gallasch, S. and Daugherty, E., (2006). Options for trading bioenergy products and services, Tasks 38 and 40. IEA Bioenergy, http://www.ieabioenergy-task38.org/publications/T38-40-biotrade.pdf, pp. 12.

Schlich, W., (1923). The regulated selection forest. *Empire Forestry Journal*, 2(1): 76-82.

Schlyter, P., Stjernquist, I., Bärring, L., Jönsson, A. and Nilsson, C., (2006). Assessment of the impacts of climate change and weather extremes on boreal forests in northern Europe, focusing on Norway spruce. *Climate Research*, 31: 75–84.

Schröter, D., L. Acosta-Michlik, Arnell, A.W., Araújo, M.B., Badeck, F., Bakker, M., Bondeau, A., Bugmann, H., Carter, T., Vega-Leinert, A.C.d.l., Erhard, M., Espiñeira, G.Z., Ewert, F., Fritsch, U., Friedlingstein, P., Glendining, M., Gracia, C.A., Hickler, T., House, J., Hulme, M., Kankaanpää, S., Klein, R.J.T., Krukenberg, B., Lavorel, S., Leemans, R., Lindner, M., Liski, J., Metzger, M.J., Meyer, J., Mitchell, T., Mohren, F., Morales, P., Moreno, J.M., Reginster, I., Reidsma, P., Rounsevell, M., Pla, E., Pluimers, J., Prentice, I.C., Pussinen, A., Sánchez, A., Sabaté, S., Sitch, S., Smith, B., Smith, J., Smith, P., Sykes, M.T., Thonicke, K., Thuiller, W., Tuck, G., Werf, G.v.d., Vayreda, J., Wattenbach, M., Wilson, D.W., Woodward, F.I., Zaehle, S., Zierl, B., Zudin, S. and Cramer, W., (2005). ATEAM (Advanced Terrestrial Ecosystem Analysis and Modelling). Final Report. Section 5 and 6 (2001-2004). Detailed report, related to overall project duration reporting period: 01.01.2001 - 30.06.2004. Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany, http://www.pik-potsdam.de/ateam/ateam_final_report_sections_5_to_6.pdf.

Schuck, A., Van Brusselen, J., Päivinen, R., Häme, T., Kennedy, P. and Folving, S., (2002). Compilation of a calibrated European forest map derived from NOAA-AVHRR data. . European Forest Institute. EFI Internal Report 13, pp. 44 plus Annexes

Schueler, S. and Schlünzen, K., (2006). Modeling of oak pollen dispersal on the landscape level with a mesoscale atmospheric model. *Environmental Modeling and Assessment*, 11(3): 179-194.

Schütz, J.-P., (1999). Close to nature silviculture: is this concept compatible with species diversity? *Forestry*, 72(4): 359-366.

Second Ministerial Conference on the Protection of Forests in Europe, (1993). Resolution H1 General guidelines on the sustainable management of forests in Europe, Part 1: General Guidelines 8 & 9. 16-17 June 1993, Helsinki, Finland.

Sedjo, R., (2002). Wood materials used as a means to reduce greenhouse gases (GHGs): an examination of wooden utility poles. *Mitigation and Adaptation Strategies for Global Change*, 7(2): 191-200.

Semenov, M., (2007). Development of high-resolution UKCIP02-based climate change scenarios in the UK. *Agricultural and Forest Meteorology*, 144: 127–138.

Shugart, H., Sedjo, R. and Sohngen, B., (2003). Forests and global climate change. Potential impacts on U.S. forest resources, Pew Center on Global Climate Change, Arlington, VA.

Skinner, C., (2007). Silviculture and forest management under a rapidly changing climate. USDA Forest Service General Technical Report PSW-GTR-203.

Smith, J.B. and Lenhart, S.S., (1996). Climate change adaptation policy options. *Climate Research*, 6(2): 193-201.

Sohngen, B., Mendelsohn, R. and Sedja, R., (1998). The effect of climate change on global timber markets.

Soja, A., Tchebakova, N., French, N., Flannigan, M., Shugart, H.H., Stocks, B., Sukhinin, A., Parfenova, E., Chapin, F. and Stackhouse, P., (2006). Climate-induced boreal forest change: predictions versus current observations. *Global and Planetary Change*, 56(3-4): 274-296.

Spittlehouse, D. and Stewart, R., (2003). Adaptation to climate change in forest management. *BC Journal of Ecosystems and Management*, 4(1): 1-11.

Stehr, N. and von Storch, H., (2005). Introduction to papers on mitigation and adaptation strategies for climate change: protecting nature from society or protecting society from nature? *Environmental Science and Policy*, 8: 537-540.

Stern, N., (2006). Stern review: the economics of climate change, http://www.hm-treasury.gov.uk.

Sultan, S., (2000). Phenotypic plasticity for plant development, function and life history. *Trends in plant science*, 5(12): 537-542.

Sultan, S. and Spencer, H., (2002). Metapopulation structure favors plasticity over local adaptation. *The American Naturalist*, 160(2).

Svejgaard Jensen, J., (2003). EUFORGEN technical guidelines for genetic conservation and use for lime (*Tila* spp.), International Plant Genetic Resources Institute, Rome, Italy, pp. 6.

Svenning, J., (2003). Deterministic Plio-Pleistocene extinctions in the European cool-temperate tree flora. *Ecology Letters*, 6: 646-653.

Thuiller, W., (2003). BIOMOD – optimizing predictions of species distributions and projecting potential future shifts under global change. *Global Change Biology*, 9: 1353-1362.

Thuiller, W., Albert, C., Araújo, M., Berry, P., Guisan, A., Hickler, T., Midgley, G., Paterson, J., Schurr, F., Sykes, M. and Zimmermann, N., (in preparation). Predicting global change impacts on plant species distributions: where to go from here? *Plant Ecology, Evolution and Systematics*, Special Issue: 51.

Thuiller, W., Lavorel, S., Araújo, M., Sykes, M. and Prentice, I., (2005). Climate change threats to plant diversity in Europe. *Proceedings of the National Academy of Sciences*, 102(23): 8245-8250.

Thuiller, W., Lavorel, S., Sykes, M. and Araújo, M., (2006). Using niche-based modelling to assess the impact of climate change on tree functional diversity in Europe. *Diversity and Distributions*, 12(1): 49-60.

Truong, C., Palme, A. and Felber, F., (2007). Recent invasion of the mountain birch *Betula pubescens* ssp. *tortuosa* above the treeline due to climate change: genetic and ecological study in northern Sweden. *European Society for Evolutionary Biology*, 20: 369-380.

UNECE-FAO, (2005). UN/ECE Timber Committee and FAO European Forestry Commission statement on forest products markets in 2005 and prospects for 2006. UN Economic Commission for Europe, http://unece.org/pub_cat/topics/annual_report_2005-2006.pdf, pp. 4.

UNECE-FAO, (2006). European Forest Sector Outlook Study - Executive Summary, UN Economic Commission for Europe, Food and Agriculture Organisation, Geneva.

Vallet, P., Dhôte, J.-F., Le Moguédec, G., Ravart, M. and Pignard, G., (2006). Development of total aboveground volume equations for seven important forest tree species in France. *Forest Ecology and Management*, 229: 98-110.

Violle, C., Navas, M.-L., Vile, D., Kazakou, E., Fortunel, C., Hummel, I. and Garnier, E., (2007). Let the concept of trait be functional! *Oikos*, 116(5): 882-892.

Vitasse, Y., (in preparation). Impact of climate change on mountain forests – a study of phenological clines and biological interactions along an altitudinal gradient. Genetic versus environmental factors., PhD research programme. UMR BIOGECO, University of Bordeaux and INRA.

Vitasse, Y., Delzon, S., Dufrene, E., Pontailler, J.-Y., Louvet, J.-M., Kremer, A. and Michalet, R., (in prep). Altitudinal trends in leaf phenology of six temperate woody species.

Walmsley, C.A., Smithers, R.J., Berry, P.M., Harley, M., Stevenson, M.J. and Catchpole, R., (2007). MONARCH – Modelling Natural Resource Responses to Climate Change – a synthesis for biodiversity conservation. UKCIP, Oxford, pp. 207.

Watts, K., Humphrey, J., Griffiths, M., Quine, C. and Ray, D., (2005). Evaluating biodiversity in fragmented landscapes: principles, Forest Research Information Note, http://www.forestresearch.gov.uk/pdf/fcin073.pdf/$FILE/fcin073.pdf, pp. 8.

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.

Young, L., Weersink, A., Fulton, M. and Deaton, B., (2007). Carbon Sequestration in Agriculture: EU and US Perspectives. *EuroChoices*, 6(1): 32-37.

9. APPENDICES

9.1. Appendix I Field study visit to southern France.

Field study visit to assess phenology in a Pyrenean Reciprocal Transplant Experiment and Common Garden experiment near Bordeaux, southern France.

Introduction

A study visit to France, hosted by UMR BIOGECO[33] University of Bordeaux and INRA, was conducted for this STSM. The author accompanied PhD student Yann Vitasse in the field for data collection during early May 2007. Vitasses' PhD research programme, now in its second year, is entitled *Impact of climate change on mountain forests – a study of phenological clines and biological interactions along an altitudinal gradient. Genetic versus environmental factors* (Vitasse, in preparation). The research programme has established both Reciprocal Transplant Experiments (RTEs) in and near the Pyrenees (Table 7), and a Common Garden experiment near Bordeaux. This section presents some personal observations made in the field, in late April and early May 2007, and presents some unpublished data.

Pyrenean RTEs

Experimental design and assessment

The RTEs utilise five sites situated at different altitudes: 100, 400, 800, 1200 and 1600 metres above sea level (asl) (Table 7). Seedlings were raised from three provenances each of beech (*Fagus sylvatica*) and oak (*Quercus petraea*), from three different altitudes: 400, 800 and 1200 m asl. At each site, two treatments were applied, incorporating four replicates each, under tree canopy and in forest gaps (8 plots). Four replicates of each provenance were present within each plot.

Table 7 **Pyrenean RTE site details.**

Site	Altitude (metres asl)	Location	
Forêt domaniale de Laveyron	100	N 43°45’55”	W 00°13’26”
Forêt communale de Lourdes	400	N 43°05’45”	W 00°05’07”
Forêt communale d’Arras-Sireix	800	N 42°58’37”	W 00°08’33”
Forêt de Gez	1200	N 43°00’06”	W 00°12’50”
Forêt de L’Ayre et Lisey	1600	N 42°53’38”	E 00°04’59”

The phenology of the transplants were observed at each site every 10 days during late winter and spring. Beech was assessed using a four point scoring system, oak with five different scores (Table 8).

[33] Unité Mixte Researche, Biodiversité genès & ecosystems

Table 8 Scoring systems adopted for beech and oak phenological assessments.

SCORE	*Fagus sylvatica*	*Quercus petraea*
1	Buds elongated and green apparent at extremities	Buds swollen and a little green
2	Bud burst	Buds elongated and green (>0.5 cm)
3	Leaves visible but not exposed	Bud burst and start to leaves expanding
4	Leaves exposed and expanded	A little of leaves exposed
5	- -	Internodes commencing elongation and leaves at the tip mature

Observed results

Data are not presented here as the research programme is still underway. However, general observations can be reported.

Beech transplants from the highest altitude (1200 m asl) provenance were the earliest to flush. At the highest altitude site where flushing was occurring (1200 m asl)[34], the four transplants from the highest altitude provenance were immediately obvious to the eye, being green and in leaf (score 4). Other provenances at this location were either score 1 or 2. No similar trends were present in the oak provenances.

It was observed that for beech, phenology was more advanced for provenances of higher altitudinal origin. Assessments during April 2007 indicated that trees from lower altitudes displayed greater divergence for phenology in plots with canopy and open conditions (Figure 10).

Common Garden experiment, Bordeaux

Experimental design and assessment

The author visited a common garden experiment established between 2005-06 on the banks of the River Garronne, 38 km south east of Bordeaux (N 44°34’27” / W 00°16’21”), at INRA’s Unité Expériemental Arboricole, Domaine des Jarres. The experiment aims to provide information on tree phenology and growth for six species as part of the same PhD programme described above and in addition, over a longer ten year period. It is laid out in a complete randomised design, arranged in 16 rows each containing 98 trees spaced at 3 × 2 metres, and incorporating at least 15 replicates per provenance.

Six woody species (Table 9) which have widespread distributions in Europe, were selected to represent both conifers and broadleaves, and to include different water transport characteristics (ring porous, diffuse porous and tracheid bearing), leaf ecology (evergreen vs. deciduous) and nutrient use efficiency (conservative *vs.* exploitative).

Provenance seed collections were made from natural populations for the six species at between four and nine different altitudes, and at each altitude from two different valleys (Table 9). Phenology assessments were made for the apical bud only using different scoring systems for each of the species (Table 9).

[34] At the highest altitude site (1600 m asl), the site had only recently become clear of snow and no flushing was evident.

Figure 10 Observations for beech phenological development for three days in April 2007 in response to altitude of origin and light conditions at one site (Lourdes at 400 m asl) of a multi-site experiment in the Pyrenees, France (Vitasse, in preparation). Error bars indicate standard errors.

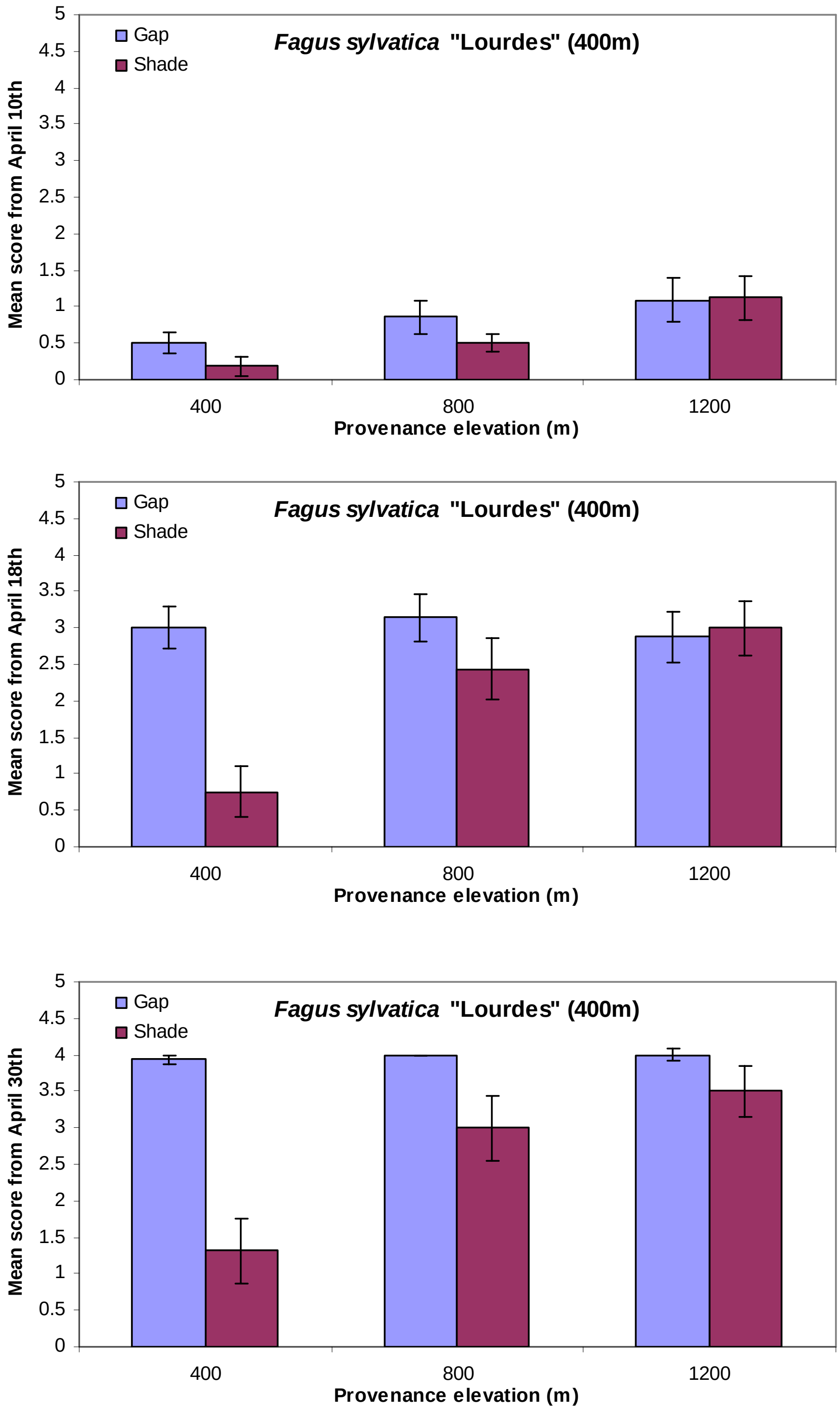


Table 9 Summary of material included in the Bordeaux Common Garden Experiment.

Species	Number of provenance locations (× 2 valleys at each)	Altitude range (m asl)			Number of phenological stages recorded
		min	max	range	
Abies alba	3	422	1604	1182	3
Acer pseudoplatanus	4	450	1614	1164	5
Fagus sylvatica	5	131	1604	1473	5
Fraxinus excelsior	5	130	1533	1403	5
Ilex aquifolium	5	131	1614	1483	3
Quercus petraea	9	131	1630	1499	6

Observed results

For beech and oak clear differences for phenological development were evident with provenance altitude of origin. For ash the lowest altitude provenance (130 m) had flushed earlier (2 to 3 weeks) than those from the highest altitude (1533 m). In combination with those provenances of intermediate altitude, there was a clear evidence for clinal response of flushing with altitude of origin. For oak, a clinal response was also evident but interestingly the relationship was the opposite of ash, *i.e.* the highest altitude provenance was most phenologically advanced. This observation is in agreement with Ducousso *et al.*, (1996) although that work only studied a limited range of material, therefore for the first time this research programme is providing information for such a relationship over a much wider range of altitudes.

Figure 11 **Ash phenological variation in the Bordeaux Common Garden Experiment on the same day (May 3rd 2007) illustrating (left) a fully dormant apical bud on a transplant from a high altitude (1200 m asl) source and (right) a fully-flushed low altitude source (400 m asl). Researcher Yann Vitasse.**

Abies had demonstrated good survival but not immediate trends were directly observable. Holly had a very poor (approximately 50 %) survival rate.

Discussion and conclusions

The visit by the author permitted the observation of research in progress assessing phenological response of trees to temperature and light in the Pyrenees, France. There appears to be a strong relationship between phenological progression and increasing altitude of origin. Phenological responses differed from one species to the other, with oak trees contrary to beech trees. It is possible that climate warming could alter the competitive balance between species and thus affect species distributions. A fundamental question arises with regard to these results: to what extent are these phenological responses determined by genetic differences or by phenotypic modifications resulting from environmental conditions (Vitasse *et al.*, in prep)? Under rapid climate change, phenological plasticity will be important in allowing trees to respond quickly to temperature change.

9.2. Appendix II Glossary and definitions

adaptive forest management	the management regimes that can be applied to mitigate adverse impacts of climate change on forest ecosystems, forest production and carbon sequestration, and utilization the opportunities, which the climate change may provide.
carbon sequestration	the amount of carbon that is sequestered from the atmosphere and stored temporarily in the forest ecosystem in the biomass of trees and in the soil profile (soil organic matter).
ecosystem services	the processes by which the environment produces resources utilised by humans such as clean air, water, food and materials.
functional trait	morpho-physio-phenological traits which impact fitness indirectly via their effects on growth, reproduction and survival (Violle *et al.*, 2007).
fundamental niche	the subset of n-dimensional environmental space of all possible conditions in which a species can maintain itself in the absence of competition (Figure 1c,d, main text).
habitat modelling	the development of a regression model (usually nonlinear) that predicts the abundance (or presence versus absence) of a species given a set of environmental conditions by estimating model parameters from observations of abundance versus environment in the field.
Pannonian	a topographically discrete area in Europe consisting of a basin remaining after the Pliocene Pannonian Sea dried out, now bounded by the Carpathian mountains, the Alps, the Dinaric Alps and the Balkan mountains. The basin consists mainly of the Great Hungarian Plain (in the south and east) and the Little Alföld (in the northwest).
phenology	the science of recurring events in nature.
phenophase	a particular stage of development, such as bud burst, flowering, fruiting, leaf-out, or senescence.
plasticity	the ability of a single genotype to produce different phenotypes in different environments.
physiological response curve	or *environmental response curve*. A relationship giving fitness (or a component of fitness) as a function of one (occasionally several) environmental variables.
phytophagous	feeding on plants, usually used for describing insect behaviour.
realized niche	the subset of n-dimensional environmental space where a species is present. It is usually assumed that the realized niche is a subset of (smaller than) the fundamental niche.
relictual	the geographic distribution of a species or group that persists in localities that it occupied at an earlier time but which is extinct over much of its former range
serotinous	species that retain non-dormant seeds, releasing them after exposure to fire.
trait	a well-defined, measurable property of organisms, usually measured at the individual level and used comparatively across species. A functional trait is one that strongly influences organismal performance.
sustainable forest management	the stewardship and use of forests and forest lands in a way, an at a rate, that maintains their biological diversity, productivity, regeneration capacity, vitality and their potential to fulfil, now and in the future, relevant ecological economic and social functions, at local, national and global levels, and that does not cause damage on other ecosystems.
thermophilous	an affinity for warm places, specifically sunny and sheltered ground conditions

9.3. Appendix III COST E42 and the work of WG1

Action E42 of the EU COST framework[35] is entitled '*Growing valuable broadleaved tree species*'. The main objective of the Action is to increase the knowledge of growing valuable broadleaved tree species, with emphasis on the production of valuable wood and with the intent to promote non-wood products that can be produced in parallel with, or in addition to, the main product. In respect to wood production the goal is to maximise the share of highly valuable wood in a short production time and low investment of work, energy and capital. The action was launched in November 2004 and will be finished in October 2008. More information is available on the Action's website[36].

The Memorandum of Understanding[37] of COST E42 outlines the rationale for the framework, and lists the main species under consideration (Table 1).

Working Group 1 (WG1) considers the '*Basics of growing valuable broadleaved tree species*', and covers the following tasks:

- Selection of species and provenances while considering site conditions and management targets;
- Harmonisation of terms, units, methods and practices for the research;
- Presentation and discussion of currently running personal projects, which could be a part of this Action;
- Identification of value-relevant wood properties;
- Identification of non-wood goods and services;
- Spacing, species mixture, weed control and tending the stands;
- Interspecific and intraspecific competition;
- Growth dynamics in respect to site and species.

35 European cooperation in the field and scientific and technology research: http://www.cost.esf.org/index.php?id=168

36 http://www.valbro.uni-freiburg.de/index.php

37http://www.cost.esf.org/typo3conf/ext/bzb_securelink/pushFile.php?cuid=253&file=fileadmin/domain_files/FFP/Action_E42/mou/E42-e.pdf

9.4. Appendix IV The author

Gabriel Hemery is currently Director of an independent forestry think-tank, Forestry Horizons. He is a forest scientist, environmental programme manager and forestry policy-thinker.

Gabriel has practical hands-on experience in land management, extensive knowledge of the forest sector and is a specialist in hardwood forestry research. He was responsible for planning and creating a unique 30 hectare woodland and field research centre in Oxfordshire, England. Personally planting over 25,000 trees in the woodland, he developed Britain's first research centre dedicated to hardwood trees, also co-ordinating the establishment of more than 25 field trials across the UK and Ireland. Gabriel has been the secretary of an international forestry science group, BIHIP, and collaborated widely with scientists from Europe and North America in tree research and agroforestry programmes.

Gabriel has held several senior positions in the UK environmental sector including Head of Land Science and Director of Land Operations for the Northmoor Trust in Oxfordshire and Director of Development for the Botanical Society of the British Isles. He has conducted a range of consultancies for Government, NGOs and the private forestry sector and worked widely in collaborative international research programmes. The author of 35 papers and articles, he has acted as editor for an international forestry journal, and is a member of the international editorial board of the CABI Forest Science Database. He is a trustee for Woodland Heritage and a committee member of the Forestry Commission's Regional Assembly for the South East. He is a Chartered Forester (and ICF assessor for professional membership and Council member), a member of the Institute of Ecology and Environmental Management and a Chartered Environmentalist (and member of the SocEnv Board). Gabriel gained a DPhil from the University of Oxford on walnut genetics and silviculture.