Forest management and silvicultural responses to projected climate change impacts on European broadleaved trees and forests

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SUMMARY

Broadleaved trees represent 37 % of the forest resource of Europe; equating to 9 % of the world's forest resource. The high number of broadleaved species (c. 80), many of which are 'minor', is reflected in a lack of adequate information on their distribution and state of health. Existing and projected impacts of climate change on the broadleaved resource are reviewed, as are future possible socio-economic drivers for forest management. Assisting the European forest resource and the sector to adapt to change, and to exploit opportunities, may take the form of broader species and provenance choice, new approaches to forest design, and more support for research, particularly tree breeding. Production forestry may benefit in some regions with changes in yield and the development of stronger markets for hardwoods as a substitute for tropical hardwoods or fossil fuel-derived materials in construction, and for bio-energy markets.

Keywords: broadleaves, climate change, silviculture, European forests

Gestion forestière et réponses de la sylviculture aux impacts prévus du changement climatique sur les forêts et arbres feuillus européens

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Les arbres feuillus représentent 37% de la ressource forestière européenne, représentant 9% de la ressource forestière mondiale. Le nombre élevé d'espèces de feuillus (environ 80), dont beaucoup sont "mineures", est reflété dans la carence d'information adéquate sur leur distribution et leur état de santé. Les impacts existants, et ceux prévus du changement climatique sur la ressource des feuillus sont examinés, ainsi que les motivations socio-économiques potentielles futures pour la gestion forestière. Aider la ressource forestière européenne et son secteur à s'adapter au changement prendra peut-être la forme d'un choix plus important d'espèces et de leur provenance, de nouvelles approches d'organisation de la forêt, et d'un soutien plus important pour la recherche, particulièrement dans le domaine de la reproduction des arbres. La foresterie de production pourrait bénéficier de changements dans la récolte et d'un développement de marchés plus résistants pour les feuillus, en substitut des feuillus tropicaux, et de matériaux dérivés du carburant fossile dans la construction, ainsi que de marchés de l'énergie-bio dans certaines régions.

Gestión forestal y respuestas silviculturales al impacto proyectado del cambio climático sobre los árboles y bosques de hoja caduca en Europa

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Los árboles de hoja caduca representan un 37% de los recursos forestales europeos, y esta cifra equivale a un 9% de la cobertura forestal mundial. El alto número de especies de hoja caduca (alrededor de 80), muchas de las cuales son de importancia 'menor', se refleja en una escasez de información sobre su distribución y estado de salud. Se analizan los impactos actuales y proyectados del cambio climático sobre los bosques de hoja caduca, además de factores posibles de cambio socioeconómico que puedan afectar la gestión forestal en el futuro. Un plan para ayudar al sector a adaptarse al cambio y a explotar las oportunidades puede tener en cuenta la posibilidad de tener una gama mayor de especies con qué elegir, además de aprovechar nuevas metodologías de planificación forestal y un mayor apoyo a la investigación, sobre todo el cultivo de nuevas variedades de árboles. El manejo forestal orientado hacia la producción puede beneficiarse en algunas regiones de cambios en el rendimiento y el desarrollo de mercados más significativos para maderas nobles que sustituyan en la construcción y en el mercado bioenergético a las maderas duras de origen tropical y a los materiales derivados de combustibles fósiles.

INTRODUCTION

Forests in Europe are likely to be widely impacted by the projected changes in climate. The effects will be a complex interaction of factors; for example a combination of stress from drought resulting in reduced tree health, or large-scale disturbances such as increased incidences of pathogens or fire, increased frequency of severe wind events, and seasonal temperature fluctuations. These effects are likely to be compounded by anthropogenic factors that may include trends in rural abandonment in some areas, or in others by development pressures that may lead to accentuated physical barriers and increased habitat fragmentation. Forest management across Europe must address these challenges 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 must address temporal uncertainties (*e.g.* 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 may be more successful in the long run.

The projected impacts of climate change on European forests, together with a judgement of the benefits that may be demanded of forests by society in the future, provide the necessary framework to plan their management in the 21st Century.

Broadleaved forests in Europe

Forests cover 44 % of the land area of Europe, and correspond to 25 % of the world's forested area (MCPFE 2007). The European Environment Agency have mapped European forests and classified 14 forest categories (12 of which contain broadleaves) and 75 forest types (European Environment Agency 2007). At a more detailed level, Pan-European tree species maps (Päivinen *et al.* 2001, Schuck *et al.* 2002) provide information of the current composition of European forests by main tree species. Preliminary European species maps have been modelled by combining three pan-European data sets by Köble and Seufert (2001). Unpublished data provided by Renate Köble (*pers. comm.*) behind the work of Köble and Seufert (2001) provided more information on the broadleaved component (Table 1). This data permitted the author to estimate that the broadleaved component (c. 80 species) represents 37 % of the forest area in Europe (EU34) (Table 1), and therefore approximately 9 % of the global forest resource. It is important to note that the uncertainties in the data, especially for 'minor' tree species, might be quite high (Renate Köble, *pers. comm.*) and unfortunately, national forest statistics very often do not provide data for minor species or only in an aggregated way (*e.g.* as 'other broadleaves').

In this paper, forests are defined by five main bioclimatic zones. Boreal forests are those in the European part of the boreal zone (*e.g.* Finland, Iceland, Latvia, Lithuania, northern Norway, Sweden). Temperate forests in central Europe can be divided into Atlantic (*e.g.* Belgium, Denmark, northern France, far northern Germany, Ireland, far southern Sweden, UK) and Continental forests (*e.g.* Austria, southern France, Germany, northern Italy, Poland, Romania, Slovakia, Slovenia, Switzerland), which emphasises differences in water availability. Mediterranean forests (*e.g.* Albania, Bulgaria, Greece, Italy, Portugal, Spain, Turkey) grow in a climate characterised by rainfall in winter and dry summers in the Mediterranean Basin. Alpine refers to high altitude forests within some of Europe's countries but especially so in larger areas of Austria and Switzerland.

Projected impacts of climate change

Scientists agree that natural disturbances are likely to increase in frequency and intensity in response to climate change 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).

The sensitivity of forest growth to climate change and management will vary across Europe. Kellomäki and Leinonen (2005) considered that the limitations and potential for forest production in the main bioclimatic zones of Europe would be:

- **northern boreal** - production is currently limited by low temperature, and often by nutrient availability. Precipitation is normally not limiting. The higher air temperature predicted by scenarios in the future will prolong the growing season and thereby increase production.
- **southern boreal** - production is currently limited by water availability, and less by temperature and nutrients, which results in higher production than in the North.
- **temperate maritime** - production is currently 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 currently water-limited at low altitudes, but not at higher altitudes where

TABLE 1 *Estimated forest area (km2) and percentage forest component for broadleaved species across the EU34. Based on unpublished data (Renate Köble, pers. comm.)*

Species	**km^2**	**%**	**Species**	**km^2**	**%**
Acer campestre	733	0.04	*Populus canascens*	978	0.06
Acer monspessulanum	329	0.02	*Populus hybrides*	3003	0.18
Acer opalus	743	0.04	*Populus nigra*	741	0.04
Acer platanoides	5623	0.34	*Populus tremula*	9957	0.60
Acer sp.	2021	0.12	*Prunus avium*	2514	0.15
Alnus cordata	1188	0.07	*Prunus padus*	24	0.00
Alnus glutinosa	5745	0.34	*Prunus serotina*	87	0.01
Alnus incana	3137	0.19	*Pyrus communis*	78	0.00
Alnus viridis	53	0.00	*Quercus cerris*	17186	1.03
Arbutus andrachne	140	0.01	*Quercus coccifera*	3613	0.22
Arbutus unedo	739	0.04	*Quercus faginea*	3762	0.23
Betula pendula	38594	2.32	*Quercus frainetto*	8474	0.51
Betula pubescens	77863	4.67	*Quercus fructosa*	783	0.05
Buxus sempervirens	407	0.02	*Quercus ilex*	36239	2.18
Carpinus betulus	16097	0.97	*Quercus macrolepsis*	290	0.02
Carpinus orientalis	200	0.01	*Quercus patraea*	38342	2.30
Castanea sativa	17935	1.08	*Quercus pubescens*	24814	1.49
Cercis siliquastrum	183	0.01	*Quercus pyrenaica*	10303	0.62
Ceratonia siliqua	44	0.00	*Quercus robur*	48726	2.93
Corylus avellana	165	0.01	*Quercus rotundifolia*	3357	0.20
Erica arborea	201	0.01	*Quercus rubra*	2191	0.13
Erica manipuliflora	2	0.00	*Quercus suber*	13877	0.83
Erica scoparia	4	0.00	*Quercus trojana*	682	0.04
Eucalyptus sp.	14040	0.84	*Robinia pseudoacacia*	7741	0.46
Fagus moesiaca	2488	0.15	*Salix alba*	54	0.00
Fagus orientalis	243	0.01	*Salix caprea*	617	0.04
Fagus sylvatica	118248	7.10	*Salix cinerea*	18	0.00
Fraxinus angustifolia	828	0.05	*Salix eleagnos*	11	0.00
Fraxinus excelsior	9959	0.60	*Salix* sp.	396	0.02
Fraxinus ornus	1509	0.09	*Sorbus aria*	611	0.04
Ilex aquifolium	99	0.01	*Sorbus aucuparia*	775	0.05
Juglans nigra	13	0.00	*Sorbus domestica*	165	0.01
Juglans regia	47	0.00	*Sorbus torminalis*	268	0.02
Laurus nobilis	0	0.00	*Tilia cordata*	3521	0.21
Malus domestica	26	0.00	*Tilia platyphyllos*	722	0.04
Olea europaea	672	0.04	*Ulmus glabra*	490	0.03
Ostrya carpinifolia	4803	0.29	*Ulmus laevis*	96	0.01
Other broadleaves	2726	0.16	*Ulmus minor*	204	0.01
Phillyrea latifolia	459	0.03	Forest area, no species classification possible		
Pistacia lentiscus	28	0.00		38130	2.29
Pistacia terebinthus	233	0.01			
Platanus orientalis	1114	0.07			
Populus alba	524	0.03			
			TOTAL	**614,043 km^2**	**37 %**

precipitation is significantly higher. In the future, the climate at low altitudes is likely to lead to a loss in production if not counteracted by elevated CO_2. Production at higher altitudes is likely to increase in the future, mainly because of a prolonged growing season.

- **Mediterranean** - production is currently limited by high evaporative demand and soilwater content. Productivity under the projected future climate is likely to be lower than under current conditions.

Climate changes are likely to impact first and most notably at the extreme limits of a tree species' range in boreal, Alpine and Mediterranean regions, and perhaps less severely in continental regions. For example, Mediterranean forests are susceptible in many ways and impacts are already evident (Lavergne *et al.* 2006, Resco de Dios *et al.* 2007), with specific studies in the region identifying impacts from insects (Battisti 2004) and 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 on Boreal forests identify the importance of phenology (Heide 2003, Kramer 1999, Kramer *et al.* 2000, Partanen 2004).

The impact of climate change on all European forests and trees will result from changes in the frequency and magnitude of key abiotic and biotic factors. These are well-reviewed in the scientific literature and can be summarised:

- temperature changes will alter photosynthesis and respiration, soil organic matter decomposition and mineralisation, phenology and frost hardiness, species distributional changes, and adaptation and evolution (Saxe *et al.* 2001). Species and populations will adapt and evolve in response to temperature changes but the rate of change is likely to be a challenge for long-lived immobile tree species. Winter temperature will impact 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 during mild spells in mid-winter resulting in heavy frost damage during subsequent periods of frost (*e.g.* Hänninen 1996);
- increases in the greenhouse gas CO_2 not only affect the global climate but directly impact plant photosynthesis and respiration. Research has indicated increased growth rates but with impacts on water use, carbon, nutrient allocation and timber quality (Broadmeadow and Randle 2002). Higher photosynthetic rates are a main consequence of elevated CO_2 levels but the effects are also complicated by temperature, nutrient availability, and vary with tree age and forest type (Hyvönen *et al.* 2007);
- forest fire incidences in Europe are predicted to increase, as suggested by climate records elsewhere (*e.g.* Carvalho *et al.* 2006, Groisman *et al.* 2007, Loacker *et al.* 2007);
- drought frequency and magnitude are projected to increase and are likely to affect tree species composition and diversity. However, few studies have assessed the impact of summer droughts on forest biodiversity and ecosystem functioning (Archaux and Wolters 2006), and any response will vary between species (Fuhrer *et al.* 2006). A notable study suggested that relictual taxa are more drought tolerant than extinct taxa (Svenning 2003);
- extreme wind events are a major cause of natural disturbance in forests (*e.g.* Peterson 2000). Windthrow damage in Europe increased in the 20th Century but loss of timber was typically smaller than annual timber harvests (Schelhaas *et al.* 2003). 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, and;
- 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 (*e.g.* Fuhrer *et al.* 2006). 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), and;
- tree pathogens, in response to climate-induced changes in their reproduction, dispersal and winter activity, will effect host tree species and the interaction between host and pathogen (Lonsdale and Gibbs 2002), furthermore, stressed trees will be more susceptible to damage. The direct impact on forests from herbivorous mammals (*e.g.* deer and grey squirrel *Sciurus carolinensis* Gmelin.) in light of a changing climate does not seem to have been considered in depth by the scientific community.

Possible socio-economic drivers for European forestry

Introduction

For many centuries, mankind's main demands for forests were focussed on economic (*e.g.* materials for construction and burning) and survival (*e.g.* food and shelter) goals. Towards the end of the 20th Century, social (*e.g.* health, recreation, access) and environmental (*e.g.* biodiversity, landscape, water management) were foremost priorities. Today, 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, site location, crop management, and harvesting.

Timber forecasts

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 authors identified four major trends in future world timber production over the course of the 21st Century: 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). Results from a global dynamic model suggest that markets are likely to benefit from climate change (Sohngen *et al.* 1998). 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, such as much of Europe, the total area of land under forest was predicted to expand by 6 %, less than in tropical and boreal regions (Sohngen *et al.* 1998). However, a likely impact of increased human pressure on land resources may be increased fragmentation. Forest productivity is also expected to increase by 18 to 44 % depending on the climate scenario, and in temperate regions, more productive timber types are expected to replace less productive timber types as species migrate.

Biodiversity

Forested areas are the largest single land cover type in Europe and contain many of the continent'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[1] calls for action concerning the use of sustainable forest management practices and the multifunctional role of forests. However, use of forests for carbon sequestration and climate regulation may conflict with achieving the objective of biodiversity conservation. 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.

Soil and water management

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 soil's role as a carbon sink. 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 soils and maintain carbon storage, and some broadleaved species have particularly valued roles, for example in reducing river bank erosion (*Alnus* spp.) and maintaining slope stability (*Juglans regia* L.).

To improve carbon management we require good quality information on which to base management decisions. 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. Broadleaved trees 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 water management benefits. For example, Pattanayak *et al.,* (2005) modelled advantages of reduced pollutant run-off through the conversion of arable land to forest.

Carbon lean society

There is growing demand by 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[2] returns. Forests, and how we manage them, can contribute significantly to a carbon-lean society of the future. The four main contributory themes are likely to be growing

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[1] 16th February 2006 – Strasbourg: see INI/2005/2054 at http://www.europarl.europa.eu/

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

Europe's domestic supply, utilising wood for bioenergy (*e.g.* CEC 1997), substituting wood for fossil-fuel based materials (*e.g.* Edinburgh Centre for Carbon Management 2006, Sedjo 2002), and managing forests as carbon sinks (*e.g.* Gustavsson *et al.* 2006, Romero *et al.* 1998, Young *et al.* 2007). High timber strength species such as *Fraxinus excelsior* L., *Quercus* spp. and *Ulmus* spp. could provide more material for construction as a substitute for carbon-rich materials (*i.e.* aluminium, brick and steel). Decorative hardwoods such as *Juglans regia, Prunus avium* L.*, Sorbus torminalis* L. could provide more high value material as a substitute for tropical hardwoods. *Populus* spp. and *Salix* spp. are already valuable species for bio-energy production, whilst fast growing broadleaves such as *Acer* spp., *Fraxinus* spp., *Prunus* spp. and *Robinia pseudoacacia* L. may be more widely used in short rotation forestry.

Assisting forests to 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 will need to evaluate these impacts and determine short and longer term responses, and develop adaptation strategies. 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 forest growth in the future can be a potential advantage, provided that forest managers are able to maintain flexibility, and recognise that climatic change is likely to benefit some species. Jacobsena and Thorsen (2003) modelled a mixed stand under different uncertainty assumptions and demonstrated that the larger the changes in thinning regimes, 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. Spittlehouse and Stewart (2003) provide a review of adaptive actions that are summarised and enhanced in Table 2.

Species and provenance choice

The choice of species and provenances will clearly be increasingly important as climate change impacts in the future. 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 guidelines 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". 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, 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. 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.

Species choice may also need to be extended. The concept and definitions of "nativeness" may need to be challenged, given that 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* L., *Castanea sativa* Mill., *Fagus orientalis* Lipsky., *Juglans regia*, *Nothofagus* spp., *Ostrya carpinifolia* Scop., *Sorbus domestica* L., and *Quercus pubescens*Willd. and *Q. rubra* L., may come to play an important role in the productive and healthy forests of the future. For some countries, many of these may be 'near-native' (*i.e.* native to neighbouring European countries) or from the same genus as a native species, and may become more acceptable in the future.

Evidently consideration may be needed towards appropriateness of these non-native species, in terms of their social and historical context, associated biodiversity-

TABLE 2 *Summary of adaptive actions (adapted from Spittlehouse and Stewart 2003)*

Management area	Adaptive action
Gene management Adapt seed zones and provenance transfer guidelines to account for northward migration of species and for new assemblages in space and time.	• 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.	• 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	• 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.	• 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.	• 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.	• 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).

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).

Tree species choice should form the basis for an appropriate adaptive management strategy, which must include issues such as the adjustment of thinning intensity and timing with changing productivity (Kellomäki and Leinonen 2005). The following changes in tree species composition may be considered in implementing adaptive management strategies (from Kellomäki and Leinonen 2005):

- 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.

Forest design

Mixed forests

Monoculture plantation forestry is most common in Europe 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 may also have a mitigating affect on the proliferation of forest fires and insect infestations (Kellomäki and Leinonen 2005). 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.

Individual tree species will respond differently to climate change, therefore interspecific relationships 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.

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

Close to nature forestry

Close to nature forestry is a silvicultural philosophy that advocates close observation of, and learning from, natural processes. It recognises that mixed-stands and uneven-aged stands require silvicultural intervention (Schütz 1999). It was first advocated by Gayer (1886) over 120 years ago but subsequently adapted and amended by foresters in some areas of Europe, particularly Slovenia and Switzerland. 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' were developed as an easily comprehensible concept that was integrative and flexible, and capable of communicating long-term goals for stand development in nature-based forest management to forest owners/managers. The philosophy of close observation and adapting management approaches to suit natural processes is likely to be a valued concept in the light of climate change. Given the uncertainty of projections, forest managers need to be able to react quickly and effectively to challenges as they arise in the future.

Forest health and protection

Forest owners and managers need to plan for and respond to projected impacts, although this is problematic when there is so much uncertainty surrounding these forecasts. 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).

Pests and pathogens

For various broadleaved species, certain specific pests and pathogens may be expected to become more damaging with projected climate change including: *Cryptostroma corticale* on *Acer* spp. as this is often caused by summer drought and high temperatures, *Erwinia amylovora* (fireblight) on *Sorbus* spp. in the Mediterranean due to warmer conditions and wetter periods, and ash (*Fraxinus excelsior*) dieback caused by *Chalara fraxinea* due to increased stress on trees from drought. For many broadleaved species, increased frequency and intensity of wet periods in some regions may exacerbate impacts from *Phytopthora* species. Perhaps the greatest problem, 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. Similarly, pests and pathogens are also more successful when introduced to new territory. One partial solution may be tighter sanitary controls however, in principle, if robust forests are created (*e.g.* through appropriate species choice, age distribution, genetic variation) then the risk will be reduced.

Abiotic threats

Abiotic threats, including fire, drought, extreme precipitation and wind, will need targeted specific measures, and these must be developed at local and regional scales. Two examples are considered below.

In respect to fire the main concern is the impact on the forest environment which, in the most part, is neither adapted (*e.g.* serotinous) nor dependent on wildfires. Mediterranean regions may be most affected, for example, a 100 % estimated increase in fire incidence for most districts of Portugal (Carvalho *et al.* 2006). 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.

The direct impacts of drought on forest health have been reviewed above but drought can also have a lasting impact on woodland communities when sensitive species are adversely affected. For example, a detailed study of *Fagus sylvatica* L. in an English mixed woodland revealed effects over 16 years following the 1976 drought, where marked changes in the structure and future successional patterns in the wood were recorded (Peterken and Mountford 1996). Soil water shortage modelling undertaken by Granier *et al.,* (2007) indicated a wide spatial distribution of drought stress over Europe, with maximum intensity occurring across a large band extending from Portugal to NE Germany. A higher sensitivity to drought was predicted in beech, and in the broadleaved Mediterranean forests.

FOREST MANAGEMENT

Quality

Broadleaved forestry, particularly when involving valuable hardwoods, is chiefly concerned with *quality* rather than *quantity*. The economic quality sought from the European broadleaved resource will be that which typically enhances the value of timber products, through perhaps timber strength, straightness or decorative figure. For the forest manager, quality may also directly translate to increased economic value if trees are better adapted certain environmental conditions. In the light of climate change, quality may also be expressed through the resilience of the forest resource to environmental threats, and as such their ability to provide robust habitats and cultural values.

Silviculture

Good silvicultural practice can improve forest economic performance through, for example, increasing establishment success, improving growth rates (*e.g.* by improving drainage, and herbicide/fertiliser applications), decreasing knot size, improving stem straightness, reducing compression wood (*i.e.* by thinning), and extending rotations to produce a greater volume of mature wood (Hubert and Lee 2005).

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.

For many broadleaves, especially *Fraxinus excelsior, Juglans regia* and *Prunus avium*, pruning is fundamentally important for the production of quality timber, and becomes increasingly necessary if genetic quality is poor (see below) or plantation design/management unsuitable. Correction of early problems, ‘formative pruning’ can be particularly beneficial for young trees damaged by frost. For example, *Fraxinus* species are especially prone, as damage by frost to the terminal bud during budburst will cause a pair of lateral buds to grow, forming a forked tree of low economic value (Kerr and Boswell 2001).

Kerr and Morgan (2006) experimented on the effects of four levels of formative pruning on pre-canopy 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.

Thinning operations have the potential to provide revenue for the forest owner but more importantly, are 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).

Silvicultural operations undertaken to improve quality are often more efficient in combination with good stand design and the use of quality genetic stock. If the bio-energy market continues to develop as hoped by many in the forestry sector, this may provide great opportunities for the forest owner. However, given widespread recent concern regarding long-term food security and competition for land resources in Europe, it is important to consider that there may be limited opportunities for short-rotation coppice production, given that these systems usually demand fertile land currently under arable production. However, the opportunities for bringing more woodlands into management may be better realised. A large proportion of a broadleaved tree is the branchwood component (20 %; Crockford 1987), therefore this could be better exploited following silvicultural operations such as pruning and thinning. Revenue for wood by-products may encourage more forest owners to manage their stands. In such cases, the production of quality timber and subsequent generation of markets for hardwoods may become a viable proposition.

Genetic improvement

Control of the genetic factor through tree improvement can produce trees that are better adapted to certain environmental conditions (*e.g.* spring flushing phenology and propensity to frost damage, or growth phenology and drought avoidance). Such breeding may also provide higher quality product for markets (*e.g.* low lignin content for paper manufacturing), faster growth rates and calorific value (*e.g.* *Populus* spp. for short rotation coppice), improved timber quality, and enhanced forest economic performance (*e.g.* increased establishment rates, growth rates and improving timber quality with reduced silvicultural inputs). Examples where tree breeding could improve the quality and value of broadleaved tree species have included 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).

Persuading forest owners to utilise improved stock 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.

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.

In recognition of many of these needs, and in particular with a view to co-ordinate the disparate breeding work undertaken in different European countries, the TREEBREEDEX project was launched in September 2006[3]. The four year European Commission funded project (€2.8M) is creating a network of infrastructures related to genetic improvement and variety creation programmes for forest trees. Other recent work at a European scale has included a COST Action (E42) considering the growing of valuable broadleaves, one output of which will be an inventory of reproductive material[4].

Genetic improvement may therefore provide a valuable service in the future, in meeting both the challenges of environmental change and changing socio-economic factors.

Yield forecasts

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). Any increases in yield with rising CO_2 (Broadmeadow and Randle 2002) may however, be countered by increased incidence of drought, leading to a lower yield in many species.

Nabuurs *et al.,* (2002) modelled large scale forest resource impacts for 28 European countries covering 131.7 Mha of forest under two management scenarios until 2050. Their results indicated that net annual increments in stemwood production of European forests under climate change will 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 was predicted to reduce to 0.79 m^3 $ha^{-1}yr^{-1}$ by 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. Despite uncertainties in the modelling, the results indicate that climate change may lead to extra felling opportunities in European forests of 87 million m^3yr^{-1} (Nabuurs *et al.* 2002). Modellers have also developed regional (*e.g.* Nuutinen *et al.* 2006) and site scale (*e.g.* GroMIT[5]

) analyses and applied them to national models. 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.

Forest policy in Europe

The main forestry policy centres affecting Europe are the

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[3] http://treebreedex.mediasfrance.org/pages/body/homePage.jsp;jsessionid=CEA3EDCF482964A259A456798A326463

[4] http://www.valbro.uni-freiburg.de/

[5] http://www.forestresearch.gov.uk/website/forestresearch.nsf/ByUnique/INFD-626MXH

United Nations Forum on Forests, the European Union, the Ministerial Conference on the Protection of Forests in Europe, the G8, and meetings of the signatories to the Convention on Biological Diversity and the Framework Convention on Climate Change. Within the European Union forest policies are implemented by Member States within a clearly defined framework (EU Forestry Strategy) and recent areas of concern have been the development of sustainable forest management standards, and delivering economic forest management.

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.

Challenges and opportunities

It is clear that there a number of major challenges facing those concerned with forest policy formulation and delivery relating to European forests, as well for those who manage them. There is a need to gather more distribution and abundance data for all European tree species; a European-wide approach would be required to plan and co-ordinate this work. Currently, some nations have comprehensive data for many species but many have ignored valuable broadleaved species with smaller distributions or abundance. New data could be used to underpin predictive work at the European scale, perhaps leading to the development of a pan-European climate change tree atlas, along similar lines to that developed in the USA (Prasad and Iverson 1999-ongoing). This information could be crucial for forest scientists, environmental adaptation strategy development and carbon-energy-timber forecasting.

Another challenge would be to 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.

More encouragement and support should be provided for scientific research programmes. For example, 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 are clearly important areas requiring additional resources, whilst tree breeding work (*e.g.* to develop quality wood for material substitution in shorter rotations, or increased disease resistance) deserves further support.

CONCLUSIONS

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

Projected climate change and impacts on European forests will be wide-ranging, and our responses challenging (Table 3). 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 to European broadleaves. The Mediterranean and Pannonian regions of Europe are likely to most affected, as are forests and individual species at altitudinal limits.

The silvicultural responses to projected climate change should address the development of better understanding of forest growth and yield projections to improve long-term stand management and marketing strategies. Appropriate forest design and management may create a more robust forest resource in response to possible risks and opportunities (Table 3), where possible options could include mixed forests and adopting a close to nature philosophy. Forest owners should embrace true functionality under 'sustainable forest management', addressing ecosystem service provision, economic production, and carbon-lean priorities. They should be encouraged to aim for quality by combining good genetic selection with best silvicultural practice. Forest management strategies must combat long term trends (*e.g.* temperature and CO_2) and be flexible to meet uncertain stochastic events.

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 contexts for European broadleaved forests are likely to 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).

Well designed, well placed, and well managed broadleaved forests may provide one the few likely 'risk-free' options in the face of a very uncertain future. They will provide society with an affordable and flexible insurance policy that will add value to the rural economy.

TABLE 3 *Generalised predictions of impact risk to European broadleaved tree species and possible responses*

risk	impacts	responses
temperature	– higher temperature may increase growth rates but also 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 flood maintenance).
drought	– mortality or stress. – increased susceptibility to pests/pathogens	Account for altitude and aspect. Species selection. Utilise small-scale site features to suit species. Breeding for phenology of growth to avoid drought.
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	Breeding to reduce susceptibility. Genetic variability (provenance) and species mixtures for robustness. Pest control where feasible. Careful control of exotic species.

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