# Impacts of Climate Change on European Forests and Options for Adaptation

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Photos on cover page
Visible impacts of climate change
Top left: Oak seedling in Boreal forest / M. Kolström
Top right: Broken stem / P. Bodea, Fotolia.com
Bottom left: Forest fire / J. Kasulka, Fotolia.com
Bottom right: Xerophytic coniferous forest in the Mediterranean / A. Barbati

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FACT SHEETS



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# EXECUTIVE SUMMARY

## INTRODUCTION

This study compiles and summarizes the existing knowledge about observed and projected impacts of climate change on forests in Europe and reviews options for forests and forestry to adapt to climate change. It has been commissioned by the Directorate General for Agriculture and Rural Development of the European Commission as an initial exploration of this complex issue. Forests are particularly sensitive to climate change, because the long life-span of trees does not allow for rapid adaptation to environmental changes. Adaptation measures for forestry need to be planned well in advance of expected changes in growing conditions because the forests regenerated today will have to cope with the future climate conditions of at least several decades, often even more than 100 years.

Impacts of climate change and adaptation options were reviewed by synthesizing the existing knowledge from scientific literature, complemented with expert assessments. On-going and planned adaptation measures in EU27 Member States were surveyed with a questionnaire. The exposure to climate change was analysed by reviewing latest climate change scenario projections in Chapter 3. The main impact factors affecting forests under climate change were reviewed in Chapter 4.1. Next, the sensitivity to and potential impacts of climate change were analysed (Chapter 4.2). After reviewing different components of the adaptive capacity of forests and forestry (Chapter 5), vulnerability to climate change and related risks and opportunities were highlighted (Chapter 6). Chapters 7 to 9 analyse possible adaptation measures to respond to climate change, assess feasibility and efficiency of prominent measures, and survey their implementation in the 27 EU Member States. The results are presented for four main bioclimatic zones: Boreal, Temperate Oceanic, Temperate Continental, and the Mediterranean. Mountainous regions have been also analysed where appropriate.

## IMPACTS OF CLIMATE CHANGE ON FORESTRY AND FOREST OF IN THE EU

Climatic changes will bring many and complex effects for forests over different EU bio-climatic regions. Rising atmospheric $CO_2$ concentration, higher temperatures, changes in precipitation, flooding, drought duration and frequency will have significant effects on trees growth. These climatic changes will also have associated consequences for biotic (frequency and consequences of pests and diseases outbreaks) and abiotic disturbances (changes in fire occurrence, changes in wind storm frequency and intensity) with strong implications for forests ecosystems.

### Expected climate change exposure in different EU regions

The outcomes of different climate change scenarios showed regional variability of climate change. The changes in average temperatures that forests will have to face over the next 100 years range, according to latest projections, between about 2° C increase in Ireland and the UK, up to about 3° increase in central Europe and 4°C – 5°C increase in northern Boreal and parts of the Mediterranean regions. All models agree that the warming will be greatest over Eastern Europe in winter and over western and southern Europe in summer. In northern Europe the increase in temperature is similar in all seasons. The temperature changes are coupled with increases in mean annual precipitation in northern Europe and decreases further south. The expected change in seasonal precipitation varies substantially from season to season and across regions. The duration of snow cover is expected to decrease by several weeks for each degree of temperature increase in the mountainous regions. Climate is expected to become more variable with grater risk of extreme weather events, such as prolonged drought, storms and floods. Forests will have to adapt to changes in mean climate variables but also to increased variability.

**Main impact factors**

Rising temperatures without increase in precipitation or with decreasing rainfall can lead to drought, especially in the Mediterranean and Continental Temperate conditions. Fire danger is expected to increase throughout Europe, especially in the already fire-prone Mediterranean region. Wind throws and storm damage are most relevant in central Europe, as well as in western and northern Europe. Changes in the seasonal distribution of precipitation will lead to higher amounts of rainfall especially during winter and spring, considerably increasing the risk of flooding in Central and Northern Europe. Climate change affects the temporal and spatial dynamics of pest species, influencing the frequency, intensity and consequences of outbreaks as well as their spatial patterns, size and geographical range. Coevolved relationships between hosts and their pests probably will be disturbed, hosts will come in contact with novel pathogens and herbivores, and changes of species composition of communities are to be expected.

**Sensitivity and potential impacts of climate change in bio-climatic regions**

In the following sections, the most important potential impacts of climate change are summarized for the different bioclimatic regions. The impacts remain uncertain, because of the underlying uncertainties in the climate change projections, but also because of incomplete understanding of tree responses to the changing climatic factors.

***Boreal zone***

The increase in temperature prolongs the growing season and enhances the decomposition of soil organic matter, which increases the supply of nitrogen, all of which enhance forest growth, timber yields and carbon sequestration. Tree species distributions will change and broadleaved deciduous trees are expected to migrate northwards. Improved forest productivity particularly in the North will create opportunities for increased utilisation of forest resources. Forest damage by wind and snow are projected to increase. Some insect species will profit from increasing temperatures, especially at their northern limits. The risk of outbreaks will probably be increased by milder winters that ease the survival of insect and pathogen species during hibernation. On the other hand, increased summer temperatures may benefit predators and parasites and the vitality status of the host trees, thus partly mitigating insect outbreaks. Higher winter temperatures will shorten the period with frozen soils and snow cover, thereby negatively impacting forest management operations.

### *Temperate Oceanic zone*

Temperature is predicted to increase and this will have a positive impact on forest growth and wood production in northern and western parts (i.e. less water limited) and a negative impact on southern and eastern parts (i.e. water limited). In the southern parts of the region droughts are the main constraint of forest growth and productivity. Extreme events such as storms and floods are projected to become more frequent particularly in winter. In large areas of western and central Europe, temperature increase supports the replacement of natural conifers with deciduous trees.
Accelerated development and lowered mortality rates for various pest species will cause more frequent mass propagation, e.g. of bark beetles and forest defoliators. The expansion of highly thermophilic, Mediterranean pathogen species is expected, as well as an increase of pathogenicity of fungal endophytes in drought-stressed trees. Overall, the share of unscheduled felling and salvage cuts after stand replacing disturbances is likely to increase.

### *Temperate Continental zone*

In this area, forest production is constrained by water availability and decreasing annual precipitation or changes in inter- and intra-annual distribution are likely to result in stronger water limitations than today. Production decreases at sites vulnerable to water stress and increases where the increased evaporative demand under the elevated temperature is balanced by an increase in precipitation. Impacts on individual species can be either positive or negative, depending on the site conditions and regional climatic changes. Predisposition of forests to various insect pests and fungal diseases will change. Bark beetle outbreaks in forests dominated by Norway spruce will increase and affect stands even at high elevation. Milder winters may reduce winter hardening in trees, increasing their vulnerability to frost. Fire danger is likely to increase.

### *Mediterranean zone*

Rising temperatures and the projected decrease in rainfall will magnify drought risk. As a consequence, photosynthesis will decrease during hot spells and biomass growth and yield are expected to decline. Prolonged droughts and hot spells will further aggravate forest fire risks. Forest fires will become an even larger threat to Mediterranean forestry and human well-being in rural areas. In dry areas, desertification may accelerate. Forest stands weakened by drought will be subject to increased biotic risks. Distributional shifts of insect populations are highly probable. Highly thermophilic pathogen species are likely to become more virulent. Non-wood products are important in the Mediterranean zone. There is a clear relationship between mushroom production and rainfall. It can be inferred that a decrease in precipitation with increased droughts will likely reduce mushroom production.

### *Mountainous regions*

Mountain forests are especially sensitive to climate change and remarkable shifts are projected in the potential distribution of herbaceous, dwarf shrub alpine plants and even tree species. Warmer temperatures will make mountain forests more susceptible to disturbances from bark beetles. Changing amount of snowfall and duration of snow cover will also affect the severity of fungal diseases. Reduced stability will decrease the protective function against natural hazards like flooding, debris flow, landslide, and rock fall, while hazardous processes itself might be both intensified or alleviated by the expected climatic changes.

## ADAPTIVE CAPACITY AND FOREST VULNERABILITY

### Adaptive capacity

**Adaptive capacity** has two components: the inherent adaptive capacity of trees and forest ecosystems and the socioeconomic factors determining the ability to implement planned adaptation measures. The **inherent adaptive capacity** encompasses the evolutionary mechanisms and processes that permit tree species to adjust to new environmental conditions. We show how evolutionary mechanisms acting at different hierarchical levels, from individuals to communities via populations and species are active in tree species, and may enhance their adaptation capacity to climatic changes. A large body of results stemming from provenance test shows that tree populations differentiated genetically during natural environmental changes that occurred during the Holocene. Examples of individual adaptation via plasticity are suggested by temporal variation of fitness related traits observed during the lifetime of trees, but are very seldom documented at this time. Past seed dispersion data obtained by fossil pollen records suggest that the speed of future natural dispersion may not be able to keep up with the shift of bioclimatic envelopes of trees species. However, maintaining or improving the genetic adaptive capacity of populations and species is important in the long term. The study shows how these mechanisms that were acting in the past under natural climate change will contribute in the future to the adaptation to human-driven climate change.

**Socioeconomic factors** that determine adaptive capacity to climate change include economic development, technology and infrastructure, information, knowledge and skills, institutions, equity and social capital. The socioeconomic adaptation capacity related to the forest sector has rarely been analysed in EU27 up to now. Adaptive capacity is generally higher in regions with active forest management. Forest ownership structures, the availability or shortage of forest sector work force, and the educational level of forest workers are other factors influencing the adaptive capacity in the forest sector.

**The adaptive capacity in the forest sector** is relatively large in the Boreal and the Temperate Oceanic regions. In the Temperate Continental region adaptive capacity in the forest sector is more strongly affected by socio-economic constraints. Adaptive capacity is strongly limited in the Mediterranean region where large forest areas are only extensively managed or unmanaged.

### Vulnerability to climate change in Europe – risks and opportunities

The assessment of regional vulnerability to climate change including quantified risks and opportunities requires more investigation and constitutes a clear research need. So far we can say that improved forest productivity in the Boreal region will create opportunities for increased utilisation of forest resources in the mid- to longer term. However, reduced availability of timber due to inaccessibility of forest resources on wet soils outside the frost period will pose a threat to the industry. Extreme events such as storms, droughts, flooding, and heat waves are probably the most important threats in Temperate Oceanic region. Drought risk is an important threat especially under water limited conditions in Temperate Continental and the Mediterranean regions. The extreme forest fire risk is the largest threat in the Mediterranean region. There are specific threats in mountain regions in relation to the maintenance of the protective function of the forests.

## OPTIONS FOR ACTIVE ADAPTATION TO CLIMATE CHANGE AND THEIR IMPLEMENTATION IN EU27 MEMBER STATES

The adaptation measures considered in the study include responses to both risks and opportunities brought out by climate change and they are classified into eight groups covering all stages of forest resource management at stand level and higher spatial scales: forest regeneration, tending and thinning of stands, harvesting, forest management planning, forest protection, infrastructure and transport, nurseries and forest tree breeding and further adaptation measures in risk management and policy.

### Forest regeneration – important choices to be made in the coming decades

Forest regeneration offers a direct and immediate opportunity to adapt tree species or provenances to the changing climatic conditions. Whether natural or artificial, regeneration is the stage at which the species and genetic composition of the stand gets established, where diversity builds up and can be manipulated.

A highly recommended option to secure the adaptive response of established regeneration is to raise the level of genetic diversity within the seedling population, either by natural or artificial mediated means. In order to maintain high levels of genetic diversity, seedlings coming from different seed stands can be mixed. Enrichment planting in naturally regenerated stands can introduce plants with different genetic characteristics. Introducing new reproductive material should be seen as complementing local seed sources, and never as replacing local material. The enhancement of natural regeneration should also be encouraged in the management of coppice forests through proper silvicultural measures (e.g. regulating standards density and increasing coppice rotation time to trigger natural regeneration).

### Tending and thinning – mixture regulation and stable stands against disturbances

Proposed changes in the frequency and intensity of tending and thinning are mostly aiming at improving stand structure for all regions to reduce susceptibility of stands to disturbances. In Temperate (Oceanic and Continental) regions adaptation measures are often focused on increasing diversity in structure and species mixture regulation via altered tending and thinning practices. An increase in structural diversity is also important for mountainous regions to support the protective functions of forests. Management adjustments, in terms of thinning, will also be required to account for accelerating growth rates due to more favourable growing conditions in a warmer climate particularly in mountain areas and boreal conditions to control average growing stock and subsequently the stability of forests. Increasing management intensity is very feasible, but not so reliable or cost-effective.

### Well organized harvesting at site-specific level

In general, harvesting activities should take place at smaller scales and where possible according to the principles of natural regeneration. Increased attention should be paid to avoid increasing susceptibility to disturbances by harvesting operations such as producing open stand edges exposed to prevailing winds (wind throw) and strong direct sunlight (bark beetles). Development of machinery is one important adaptation measure in Boreal zone and mountain areas.

**Challenging forest management planning**

Forest management and planning is becoming more challenging in the perspective of climate change. New planning and decision support tools are needed to deal with uncertainty and risk in long-term forest planning. Flexible adaptive planning, which takes into account all conceivable scenarios and allows to consider multiple options for future development, may be the best suited alternative. Effective operative and strategic controlling is getting even more important and is a key component of adaptive management Cooperation of scientists, decision makers and stakeholders will lead to a more comprehensive understanding of the complex problems involved in decision making and will provide a more realistic and reliable basis for decision support for management in future forest ecosystems. .

**Forest protection – focus on specific site and stand characteristics**

Norway spruce and pine forests, as well as forest stands of oaks are expected to be most affected by biotic disturbance agents. These tree species are of high socio-economic importance, so that a higher probability of detrimental events might put European forestry at risk. Silvicultural adaptations will be inevitable; however, general recommendations are not possible as comprehensive knowledge on the complex causalities of biotic forest disturbances on a regional scale is demanded. Adaptive measures are to be targeted not only on species composition, but on the full scale of silvicultural options from site selection to harvesting. In general, establishing and sustaining forest ecosystems with highly **diverse tree composition, age and structure** is recommended.

Fire protection will be increasingly important. Conditions leading to forest fires are extremely variable. Adaptation measures include the replacement of highly flammable species, regulation of age-class distributions and widespread management of accumulated fuel. The sensitivity of a stand to wind and snow damages is controlled by tree, stand and site characteristics. Damage risk can be decreased by appropriate species selection, stand treatments and harvest planning. The risk of snow damage can be minimized by avoiding heavy thinning, especially in high risk areas.

**Infrastructure and transport – local solutions**

Potential measures to reduce drought stress include storage lakes and irrigation canals and the restoration of the water regime in floodplain forests by deactivating drainage systems. The development of an appropriate road network is very important especially in mountain forestry to ensure the proposed small scale management activities and to provide accessibility necessary for sanitation felling. In northern regions it is of special importance to reconstruct roads in order to minimize sediment runoff due to increased precipitation and shortened frost periods. The shortened frost periods in boreal forests pose a significant challenge for harvest and transport technology. Suitable infrastructure is also important for round timber storage after large scale wind throws. Improvement of road density and infrastructure is quite feasible, reliable and cost-effective, but these depend on local geomorphology.

**Nursery practices and tree breeding - more knowledge and innovation needed**

We suggest **increasing the diversity of reproductive material** at higher levels than currently in order to increase the adaptation capacity of the regeneration. It is recommended to mix seedlings at the nursery stage coming from different seed stands of the same provenance regions. Seeds from neighbouring provenance regions could be added. Identification of seedlots to be mixed should be based on results of provenance tests. Many provenance tests have been established at a national, local or international level. They need to be analysed in a standardized way in order to recommend directions and range of seed transfer for the mixing.

The degree of genetic diversity can be checked by monitoring genetic fingerprints using molecular markers. This procedure could be implemented at an operational scale to check for levels of diversity prior to plantation. More sophisticated methods based on biotechnologies may shorten significantly these delays, once genes of adaptive significance have been identified. Research efforts are being conducted for searching genes of adaptive significance, but are not at the stage of recommending practical measures. For species where intensive genetic improvements programmes are conducted, it is recommended as well to maintain higher diversity within the varieties.

**Further adaptation options in risk management and policy**

Institutional and policy barriers for responding to climate change should be reduced, for example by adapting forest management guidelines to the changing climate regime.

The development and evaluation of adaptation strategies should be a participative process involving decision-makers, stakeholders, experts, and analysts. Key system vulnerabilities should be identified, and adaptive strategies developed and evaluated in the context of existing decision processes.

For adaptation on an operational level, it is proposed to establish forest reserves for the investigation and monitoring of climate change impacts which can be valuable for science in a general sense and for the development of adaptation strategies in particular. A key approach in risk management is **diversification of tree species mixtures and management** approaches between neighbouring forest stands or within a forestry district to increase adaptive capacity and improve the overall resilience of forests to climate change. At larger geographical scales of management units and forest landscapes, a range of different adaptation strategies can be combined.

**Monitoring** of forest health, pests and diseases is absolutely crucial, (i) to quickly identify new pests (e.g. invasive species) and (ii) because secondary damage agents can in weakened systems quickly turn into large scale threats.

## RECOMMENDATIONS FOR FURTHER ACTION

Many adaptation options have been identified and most of them are either in use or planned to be implemented in different parts of the EU. Measures, to cope with likely greater risk of biotic and abiotic disturbances, are already well established, but they could be further diversified in all bioclimatic zones. As we are still lacking the experience of how tree species and provenances respond to rapidly changing climate conditions, there is a need to develop new strategies for introducing better adapted species and provenances where the present species/genotypes will become unsuitable over the coming decades. Uncertainty about the full extent of climate change impacts and the suitability of adaptation measures creates a **need for monitoring and further research**. We need also to better understand of adaptive capacity, but even more important is that vulnerability assessments are almost completely lacking at national level. Having a good understanding of regional differences in vulnerability to climate change is crucial for targeting adaptation measures.

Potential impacts of climate change on non-wood forest products and other services provided by European forests are less well understood and need special attention. More research is needed to expand the knowledge base related to almost all aspects related to adaptive forest management strategies. The research needs vary between regions depending on the most important climate change risks. Forest research on climate change adaptation needs to be interdisciplinary, covering not only ecological, but also economic and social perspectives.

It is of utmost importance to disseminate the knowledge on suitable adaptation measures to all policy makers at different levels, affected stakeholder groups, particularly to forest owners, forest workers, who need to implement the measures on the ground.

While the majority of climate change impacts are likely to be negative – especially in the long-term – it should not be forgotten that management strategies should also be adapted to utilize opportunities where they arise (e.g. improved tree growth). Such benefits, even if they are only of temporary nature, could increase the adaptive capacity of the sector and support long-term adaptation and innovation to better cope with climate change.

The improvement of regional climate change projections, improving understanding of tree responses and adaptive capacity of the forest sector will result in new information about likely impacts on EU forests. This information should be progressively used in policy development to improve the resilience of forests to future climate.

# 1 INTRODUCTION

## 1.1 Background: climate change and the adaptation challenge

The human influence on the earth's climate is becoming more and more obvious. Climate observations prove the existence of a global warming trend: global average temperature has increased by 0.8°C since 1900 (Hansen *et al.*, 2006) and the 12 hottest years observed globally since 1880 all occurred between 1990 and 2005. The recent European heat wave of 2003 was a drastic demonstration of the extent of impacts we need to expect more often in the future (Schär and Jendritzky, 2004; Ciais *et al.*, 2005) Forests are particularly sensitive to climate change, because the long life-span of trees does not allow for rapid adaptation to environmental changes. Unlike in agriculture, adaptation measures for forestry need to be planned well in advance of expected changes in growing conditions because the forests regenerated today will have to cope with the future climate conditions of at least several decades, often even more than 100 years.

Forest ecosystems play an important role in the global biogeochemical cycles. A recent study demonstrated that mankind is having a significant impact on the carbon balance of temperate and boreal forests, either directly (through forest management) or indirectly (through nitrogen deposition) (Magnani *et al.*, 2007). Forests act both as sources and sinks of greenhouse gases (GHGs), through which they exert significant influence on the earth's climate. Forests can contribute to the mitigation of climate change, but under the existing global climate policy frame this alone will not be enough to halt climate change.

Research on the possible impacts of climate change on forests in Europe and the development of adaptation and mitigation strategies started in the early 1990s, shortly after first concerns were raised about the consequences for Earth's climate of anthropogenic greenhouse gas emissions (e.g. Kanninen and Anttila, 1992; Kräuchi, 1993). Since then, assessments of climate change, its impacts and subsequent consequences to natural resource management have been the focus of continuous research efforts (e.g. Brown *et al.*, 1996; Kellomäki *et al.*, 2000; Lindner, 2000; Lindner and Cramer, 2002; Kellomäki and Leinonen, 2005). Among the known impacts of climate change are changes in tree growth and productivity (Kauppi and Posch, 1988; McGuire *et al.*, 1993; Kellomäki and Kolström, 1994; Bergh *et al.*, 2003; Loustau *et al.*, 2005), changes in forest area and competition between species (Solomon, 1986; Woodward, 1994; Bugmann, 1996; Lindner *et al.*, 1997; Lexer *et al.*, 2002), and changes in damage caused by natural disturbances (Flannigan *et al.*, 2000; Gan, 2004; Gillett *et al.*, 2004; McKenzie *et al.*, 2004; Seidl *et al.*, 2007). It was also recognised that protective functions of forests will be affected by climate change as well (Köchli and Brang, 2005).

Despite the intensive research efforts, planning of adaptation measures for forest management, taking into account the anticipated climatic conditions over the 21$^{st}$ century is a difficult task. This is because: (1) there is still considerable uncertainty about the future climate development and the current climate projections are not yet trustworthy with regard to the projection of future climate variability and extreme events; and (2) the existing impact assessments vary widely, depending on the simulation models applied and climate scenarios investigated. Consequently, decision-making needs to analyse ecosystem vulnerability and risks induced by climate change, and consider the associated uncertainties, while developing adaptation strategies.

## 1.2 Scope of the study

The study synthesise the existing knowledge about observed and projected impacts of climate change on forests in Europe and review options for forestry to adapt to climate change. The study will first analyse the potential impacts on forests in different geographical areas of the European Union based on the expected changes in average climate conditions, climate variability and extreme climatic events and the sensitivity of different forest types to these changes. The adaptive capacities of forests and forestry to the projected changes in climate are analysed, as the projected impacts and the adaptive capacity together determine the vulnerability of forestry to climate change. In the second part of the study, options for encouraging and supporting adaptation in forestry are identified. By presenting a comprehensive and integrated overview of the main research findings in this area, the study aims at helping guiding future strategies for increasing EU forests resilience to the unfolding climatic changes. It highlights robust findings and key uncertainties and provides recommendations for future research needs.

This study has been commissioned by the Directorate General from Agriculture and Rural development and aims to provide the European Commission with an improved understanding of the potential implications of climate change for forests and adaptation options for forestry, covering the EU 27 Member States. It also aims to assist policy makers and forest planners as they take up the adaptation challenge and develop measures to reduce the vulnerability of the sector to climatic changes.

The study will contribute to the objectives of the **EU Forest Action Plan**[1] which proposes to encourage adaptation to the effects of climate change (key action 6), to enhance the protection of forests against, among others, forest fires (key action 10), and to maintain and enhance the protective functions of forests against the increasing threat of extreme weather events as well as erosion and desertification problems (key action 11). Key action 6 of the Plan foresees that the European Commission support measures for adaptation through continued support for research, training, studies on the impacts of and adaptation to climate change, and exchange of experiences regarding carbon conscious forest management practices, which can contribute both to mitigation and adaptation.

## 1.3 Structure of the report

The report is divided into ten chapters. Chapter 1 provides the background knowledge related to climate change and defines the scope of the assessment. Moreover, it provides the objectives of the report and the report structure. Chapter 2 provides the methodology for the whole study. The results of the specific objectives of the study are presented in Chapters 3 to 9 as follows:

- Summary of latest climatic change scenarios for the EU, i.e. exposure to climate change (Chapter 3).
- Assessment of the forest ecosystem sensitivity to climate change and potential impacts on forest and forestry based on current scientific research and knowledge (Chapter 4).

[1] COM(2006) 302 final, Communication from the Commission to the Council and the European Parliament on an EU Forest Action Plan.

- Assessment of the adaptive capacity to climate change, this includes the inherent adaptive capacity of forests and the socio-economic/technical adaptive capacity (Chapter 5).
- Assessment of the vulnerability, risks and opportunities of climate change (Chapter 6).
- Potential adaptation options for increasing resilience of the forest sector in view of the projected impacts of climate change (Chapter 7)
- Evaluation of potential adaptation options in terms of feasibility, reliability and cost-effectiveness (Chapter 8)
- Review of ongoing and planned adaptation strategies in EU 27 member states (Chapter 9).
- Conclusions and recommendations for potential adaptation options for forestry in the EU27 (Chapter 10).

The complete list of scientific and technical studies that provide background information, contribute to the discussion and support the evaluation provided in this report is included in list of references. A glossary of terms and concepts is included in section 2.1.2. Additional information is included in 9 annexes to complement the results provided in the main chapters of the report.

# 2 METHODOLOGICAL FRAMEWORK

## *2.1 Exposure, climate change impacts, adaptive capacity, and vulnerability*

### 2.1.1 Scope of the study and topics addressed

Following the **EU Forest Action Plan** this study summarises existing knowledge about observed and projected impacts of climate change on forests in Europe and reviews options for forestry to adapt to climate change. The study assesses potential impacts, the adaptive capacity of the forests, and the resulting vulnerability and risks of these direct and indirect impacts on the capacity of forests to provide economic, social and ecological services.

The study first analyses the **potential impacts on forests in different geographical areas of the European Union** based on the expected changes in average climate conditions, climate variability and extreme climatic events (exposure to climate change) and the sensitivity of different forest types to these changes. The study covers the effect of impact factors (i.e. atmospheric $CO_2$ increase, changes in temperature and precipitation) on different mechanisms (i.e. growth, mortality, reproduction) having an impact on the capacity of forests to provide economic, social and ecological services. These include goods such as production of timber and non-wood forest products, as well as provisioning services and protective functions such as carbon sequestration, water retention, protection of infrastructure, habitat for wildlife and recreation (cf. Millenium Ecosystem Assessment Reid *et al.*, 2005).

All major direct and indirect impacts of already observed and projected future climate change on EU forests including both **positive and negative impacts** are analysed.

The **adaptive capacity of forestry** to the projected changes in climate will be also analysed, as the projected impacts and the adaptive capacity together determine the vulnerability to climate change.

To achieve the objectives of this project, the approach draws on ***desk research*** and ***scientific and expert assessment***. A thorough literature survey including published (peer reviewed) references as well as research findings from relevant national and EU funded research projects has been carried out. Moreover, other information sources are used, as for example, the fourth Assessment Report of the IPCC (released in November 2007) and other international assessment reports. Where no scientific studies are available, scientific and expert knowledge is used to evaluate the potential impacts based on evidence from other world regions.

### 2.1.2 Concepts used in this report

The IPCC defines climate change as a statistically significant variation in the variables that define the climate of a region (such as temperature or precipitation) or in its variability persistent over an extended period of time (typically decades or longer periods).

The concepts of impacts, vulnerability, risk and adaptation are not defined in the United Nations Framework Convention on Climate Change (UNFCCC) nor in the Kyoto Protocol; the terms are used loosely by many scientific and policy communities and have a meaning in common usage. It has been observed that interpretation of some of these key terms by scientific groups or policy makers can be quite different, which may lead to varied or false expectations and responses (OECD, 2006).

According to the UNFCCC, there is a clear difference between mitigation (reduction of greenhouse gas emissions and carbon sequestration) and adaptation (ways and means of reducing the impacts of, and vulnerability to, climate change). Until recently, UNFCCC negotiations have focused primarily on mitigation; however, it is now clear that objectives of human well-being in the future should be addressed, stressing the importance of adaptation.

For the purposes of this study, the following terms are used:

- **Impact factors** are climatic, physical, and biological variables that are influenced by climate change and cause the impacts in the system.
- **Exposure** specifies the projected change of climate that is affecting the system.
- **Sensitivity** describes the degree to which a system is affected, either adversely or beneficially. The effects of climate change may be direct (e.g., changes in forest growth in response to a change in temperature or precipitation) or indirect (e.g., damages caused by an increase in the frequency of fires or a new biotic pest species).
- **Impacts** are the consequences of climate change that are likely to affect forests and forestry activities, as a function of exposure and sensitivity to changes. For example, a decrease in rainfall during summer is likely to impact forest growth in Mediterranean areas.
- **Adaptation** to climate change refers to adjustments in natural or human systems in response to actual or expected climatic changes or their effects, which can be taken to reduce the impact of a particular risk or exploit its beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory and reactive adaptation, as well as autonomous (i.e., intrinsic to the system under consideration) and planned adaptation (i.e., adaptation measures initiated through human activities).
- **Adaptive capacity** describes the ability of a system to adapt to changes in climate.
- **Inherent adaptive capacity** is the evolutionary mechanisms and processes that permitted to tree species to adjust to new environmental conditions.
- **Socio-economic adaptation capacity** is the ability of human sectors, like forestry, to implement planned adaptation measures.
- **Vulnerability** can be defined as the degree to which a system is susceptible to be affected by adverse effects of climate change. The vulnerability of a given system is a function of the climate variation to which this system is exposed (exposure), its sensitivity, and its adaptive capacity.
- **Risk** is the potential adverse outcome of a particular impact. For example, there is a risk that summer droughts will reduce timber yield.
- **Opportunity** is the potential beneficial outcome of a particular impact. For example there is an opportunity that increased average temperatures will enhance potential growth for certain tree species in northern European regions.

### 2.1.3 Approach to evaluating potential impacts, risks and opportunities

The assessment approach is summarized in Fig. 1. First the expected changes in average climate conditions, climate variability and extreme climatic events are studied, i.e. the **exposure** to climate change (chapter 3). As the potential impacts of climate change differ between bioclimatic zones and forest types in Europe, the study analyses the expected changes in climate and the impacts and adaptation options for different bioclimatic regions/forest types that are described in chapter 2.3.

Once the exposure to climate change is studied, the **sensitivity** of the forests of the different bioclimatic regions to the expected changes in climate is assessed. The rational behind this is that not all the expected changes in climatic conditions will affect forests, which will be sensitive only to some of the expected changes.

Climate change will affect forests through the so called impact factors. The different **impact factors** studied are:

i) atmospheric $CO_2$ increase,
ii) changes in temperature,
iii) changes in precipitation and hydrology,
iv) abiotic disturbances (fire wind storm, flooding, drought),
v) biotic disturbances.

These impact factors are explained with detail in chapter 4.1.

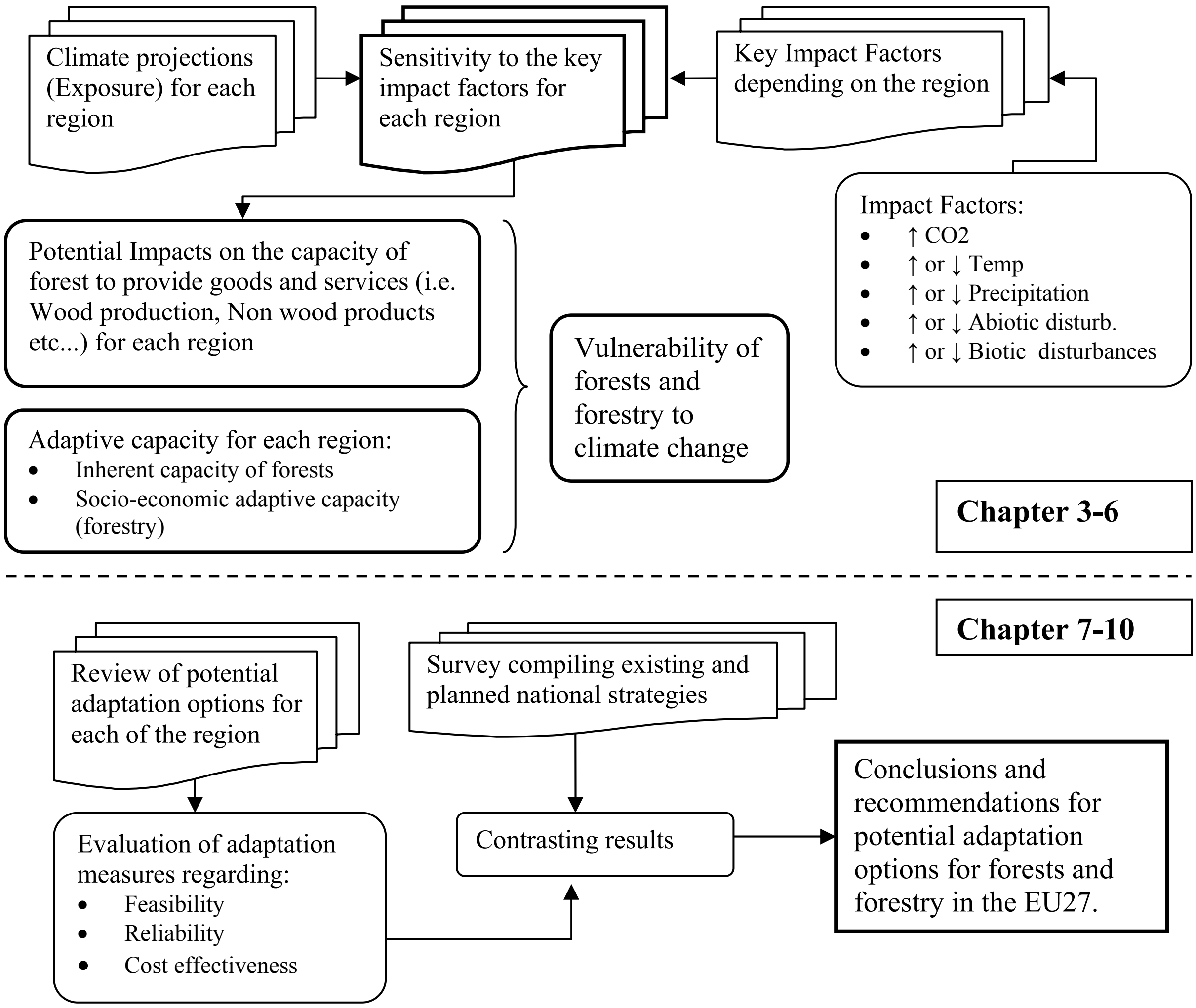


**Figure 1.** Scheme of the approach followed to assess the climate change impacts and vulnerability and adaptation measures in EU forests.

Not all the impact factors will be important for every bioclimatic region studied. Thus, when explaining the sensitivity of forests in different regions, the **key impact factors** affecting the region are addressed. Forest ecosystem **sensitivity** is analyzed focusing on different forests mechanisms (i.e. growth and productivity, mortality, reproduction, biotic disturbance, species competition and species distribution change, changes in number of forest fires and in unplanned fellings etc.), which are serving as indicators for ecosystem responses to past climatic changes.

Thereafter, based on the exposure to expected changes in climate conditions and the sensitivity of different forest types to these changes, the **potential impacts on forests products and services** in different geographical areas of the European Union are analysed. This study covers direct and indirect impacts on the capacity of forests to provide economic, social and ecological services. The following goods and services are studied:

i) wood production,
ii) any non-wood forest products (e.g. berries, mushrooms),
iii) carbon sequestration,
iv) biodiversity, and
    recreation in Boreal zone and protective functions against soil erosion, avalanches, etc., in the mountainous regions.

Vulnerability of forests and forestry to climate change is determined after considering how projected impacts may be modified by the **adaptive capacity** of forests and forestry to the projected changes in climate. The adaptive capacity to respond to the anticipated environmental changes has two components: (i) the inherent adaptive capacity of forests and (ii) the socioeconomic factors in the forestry sector determining the ability to implement planned adaptation measures.

Tree species have capacity to acclimatize (e.g. to increased atmospheric $CO_2$ levels), they may adapt epigenetically to the changing climate and higher temperatures, and through different evolutionary mechanisms support genetic adaptation of populations and species (Kremer, 2007).

The socio-economic adaptive capacity is usually defined as the ability to implement planned adaptation measures, and this ability depends on socio-economic factors such as the GDP per capita, R&D expenditures, access to information, technology, and training.

Thereafter, by linking potential impacts on forest products and services (results of chapter 4.2) and the adaptive capacity (chapter 5) the **vulnerability** to climate change in the different bioclimatic regions and the resulting risks and opportunities is characterised (chapter 6).

**i) Reviewing method**

The desk study aimed to make efficient use of scientific information to generate an assessment that is i) practical and robust, ii) widely applicable and iii) informative on "new thinking and new concepts" in science.

We started our desk research from the scientific understanding and assessment (if available) as formulated in the recent IPCC 4$^{th}$ Assessment Report. Then, we followed by including results from any specific national or supranational relevant assessments not necessarily considered in the IPCC-4AR. Moreover, scientific papers and reports were identified and results assessed in addition to the IPCC results.

The review of scientific papers was conducted with following procedure:

(1) All publications were first screened in order to categorise them according to:
    a. species/forest type
    b. bioclimatic region
    c. impact factor investigated (e.g. increasing temperature or drought)
    d. impact mechanism (e.g. growth response or disturbance frequency)
    e. goods/services addressed
    f. study method
    g. expert judgment on importance
    h. expert judgment on confidence level
(2) The publications were grouped using four of the criteria from the screening (one paper may be included in several groups):
    a. impact factor
    b. impact mechanism
    c. bioclimatic region
    d. species/forest type
(3) Each group of publications was then analysed, beginning with the most important and high-confidence studies. From each study, the main impacts were extracted, the conditions they apply to were recorded, and recognised uncertainties were documented. The applied methods were also characterised. After the more detailed review of the study, the classification of the methodology and the expert judgement regarding the importance and confidence level of the study were revisited and modified when necessary.
(4) The forest ecosystem sensitivity to the projected changes in climate conditions were characterised for the distinguished bioclimatic zones. This step resulted in a number of facts sheets about the main drivers of climate change impacts (both direct and indirect) and how they affect regional forest ecosystems in Europe.
(5) Combining the forest ecosystem sensitivity with the exposure provided the basis for synthesising the most important potential impacts on forests products and services.

As the objective was to cover all categories and regions in a balanced way and to address in each region the main goods and services, the time resources available limited the number of studies that could be analysed in detail for each category.

**ii) Review results**

The review of the scientific literature of the past two decades yielded more than 8000 publications that dealt with climate change and forestry-related topics. About 1000 studies that dealt with European conditions (or were of high general importance) were sampled into a database and around 600 have been further assessed. From the total analysed articles, the vast majority was dealing with boreal forests followed by the Temperate Oceanic region. A significantly smaller part of available articles are addressing the temperate continental and Mediterranean forests. Main reason for this is that forests are economically more important in the north than in the south.

Additionally, other relevant EU funded projects and IPCC reports have been scrutinised. The EU funded projects include SilviStrat (Silvicultural response strategies to climate change in management of European forests), ATEAM (Advanced Terrestrial Ecosystem Analysis and Modelling), ECOCRAFT (Predicted impacts of rising carbon dioxide and temperature in Europe at stand scale), and LTEEF II (Long-term Regional Effects of Climate Change on European forests: Impact assessment and Consequences for carbon budgets).

### 2.1.4 Selection criteria for ranking available studies in order of importance

An important aspect in the evaluation of the potential impacts and the confidence level of the assessments is the critical analysis of the employed methods and scenarios. Many studies are based on modelling exercises. For this purpose, reliable models are required to assess the impacts of climate change on forest ecosystems.

**i) Impact assessment methods**

Several studies have critically analysed model assumptions applied in climate impact assessments and demonstrated that they may strongly influence the projected climate impacts (Loehle, 1996; Loehle and LeBlanc, 1996; Schenk, 1996; Lindner *et al.*, 2002b; Luckai and Larocque, 2002). To understand the effects of different process representations and limitations of alternative model approaches we analysed results of model comparisons (e.g. Tiktak and van Grinsven, 1995; Ryan *et al.*, 1996; Badeck *et al.*, 2001; Kramer *et al.*, 2002; Lindner *et al.*, 2005; Morales *et al.*, 2005). For example, Kramer *et al.* (2002) evaluated six process-based forest growth model models in order to evaluate their suitability to make projections under climate change conditions. They concluded that the generality and realism of these models make them good candidates to make projections under future conditions.

**ii) Criteria used for ranking the available studies**

Considering the large number of published studies on the study subjects, it was necessary to assess the importance and confidence of the assessment studies analysed. For this purpose criteria for expert judgements of the studies were prepared. Studies with a limited data basis were considered as less important than comprehensive assessment studies with multiple species using a range of regional case studies. Studies applying questionable methods or outdated climate scenarios were assigned a low confidence level, whereas state-of-the-art assessments with a plausible range of climate scenarios got a higher confidence level.

**Box 1. Proper models to simulate forest development under the climate change**

The selection of proper model is important. It is necessary to understand the different modelling approaches and their main objectives and characteristics to decide the most convenient tool to be used for further scenario analyses. For example, **empirical growth and yield models** are widely used to support decision-making in forestry. Usually, these models utilise inventory data representing the past growth and development of a forest under specific growing conditions. The applications of such models in simulating the future growth and development assume that the future growing conditions are similar than in the past. Therefore, any changes in the growing conditions may bias the simulated growth and development.

Optionally, one may use **gap or patch models** (Botkin, 1993), which explicitly assess the impacts of temperature, water and nutrients on the growth and development of trees. However, the main goal of these models is to simulate vegetation patterns over time based on the regeneration, growth and death of individual trees and on the interaction between different tree species. The gap models are used, for example, for assessing the potential vegetation patterns and changes in the vegetation distribution under the climate change. Nevertheless, the gap models normally exclude physiological mechanisms linking the growth and development of trees with the climatic and edaphic factors. This may limit their applicability for impact studies compared to mechanistic models or process-based models, which include physiological response mechanisms to changes in environmental conditions (Waring and Running, 1998).

Typically, the structure of **process-based models** is complex; and to initiate calculations a detailed description of the properties of sites and trees is needed. This substantially limits the use of process-based models in day-to-day management. Recently, increased awareness of the influence of changing environmental conditions on forest growth has, however, led to an increased interest in applying process-based models to forest management in order to understand how forests grow and develop under changing environment and management (Mäkelä *et al.*, 2000a; Mäkelä *et al.*, 2000b; Sands *et al.*, 2000). Since there are still great uncertainties about the regional characteristics of the future climate, as well as about the response of our forests to changes in the atmospheric and climatic conditions, the development of adaptive management strategies should be based on sensitivity and risk analyses.

### iii) Structure of result presentations

This study reviews and synthesises a lot of information that needs to be presented in a structured way that is easy to understand and communicate to practitioners, policy makers and various other stakeholders.

Because the potential impacts of climate change differ between bioclimatic zones and forest types in Europe, the results are presented using the different bioclimatic zones and forest types classification developed in this study (see section 2.3). The main body of the report contains the most important scientific findings. Detailed background information are documented in several Annexes.

Facts sheets were developed to present main outputs of the study in a simplified and condensed format. They are targeted especially for the non-scientific audience. Facts sheets present the bioclimatic zonation of forest types, key drivers of change, the main mechanisms of inherent adaptive capacity of forests, sensitivities to climate change and potential impacts in different bioclimatic regions.

## *2.2 Adaptation strategies and survey of ongoing and planned measures in EU Member States*

### 2.2.1 Scope and subtopics

In the second part of the study, options for encouraging and supporting adaptation in European forestry were identified. The scope of the study was the EU 27 Member States. For understanding of important impact mechanisms, also results of climate change impact and adaptation research from comparable climate conditions in other world regions were considered.

A comprehensive **review of potential adaptation options** for forestry in Europe was undertaken. The adaptation measures include responses to both risks and opportunities created by climate change and address all stages of forestry operations. The **general screening of measures** was structured into the following chapters:

- (i) forest regeneration, including selection of species/provenances/genotypes,
- (ii) tending and thinning of stands
- (iii) harvesting
- (iv) forest management planning
- (v) forest protection
- (vi) infrastructure and transport
- (vii) nurseries and forest tree breeding
- (viii) higher level adaptation options in risk management and policy

For each of the eight stages listed above, potential adaptation measures were screened and the most important ones were then described in detail.

### 2.2.2 Feasibility, reliability, and cost-effectiveness of measures

Conclusive targeted research results on adaptation options are scarce in all regions. Therefore, the adaptation options are evaluated and presented at a general level. Regional differences in environmental and/or socio-economic factors are mentioned, where appropriate. The measures are evaluated regarding their feasibility, reliability, and cost-effectiveness. Due to the lack of detailed quantitative analysis, these aspects are assessed by expert judgement using an ordinal scale (low, medium, high). The assessment was made for adaptation approaches, which include a combination of several specific adaptation measures (Chapter 8).

### 2.2.3 Survey of planned adaptation measures in EU 27

A survey has been carried out to compile on-going and planned national strategies for adapting forests and forestry to climate change in the EU 27 Member states. The questionnaire was distributed to EU27 member states via members of the Standing Forestry Committee and through EFI's associate member institutions. The results are contrasted to the results of the review on suitable and cost-efficient adaptation measures for the different the bioclimatic zones/forests types. Based on this, conclusions and recommendations for potential adaptation options for forestry in the EU 27 member states are drawn.

### 2.2.4 Structure of result presentations of adaptation options

An overview of proposed measures to adapt to climate change in all stages of forest operations is given in chapter 7. The evaluation of adaptation measures regarding their feasibility, reliability, and cost-effectiveness is summarized in a table and detailed in the text of chapter 8. On-going and planned adaptation strategies in EU 27 Member States are presented by bioclimatic zones and contrasted with the results of the review on suitable adaptation measures for the different the bioclimatic zones/forests types in chapter 9. The detailed responses from EU 27 Member States are documented in the Annex.

In addition, also in this second part of the study, selected results are presented in fact sheets summarising the main outputs of the study.

## *2.3 Forest Typology*

### 2.3.1 Bioclimatic zonation

Potential impacts of climate change differ between bioclimatic zones and forest types in Europe. The study will analyse climate change impacts and adaptation options for the different bioclimatic regions/forest types.

The reference bioclimatic classification used in this study is the Bioclimatic map of Europe (Rivas-Martínez *et al.*, 2004) (see Fig. 2); the highest units of this bioclimatic classification are four macrobioclimates delimited by means of climatic values and vegetation characteristics; European forests are limited to three macrobioclimates: boreal, temperate and Mediterranean; each of them and their subordinate units or bioclimates is represented by a characteristic group of forest formations.

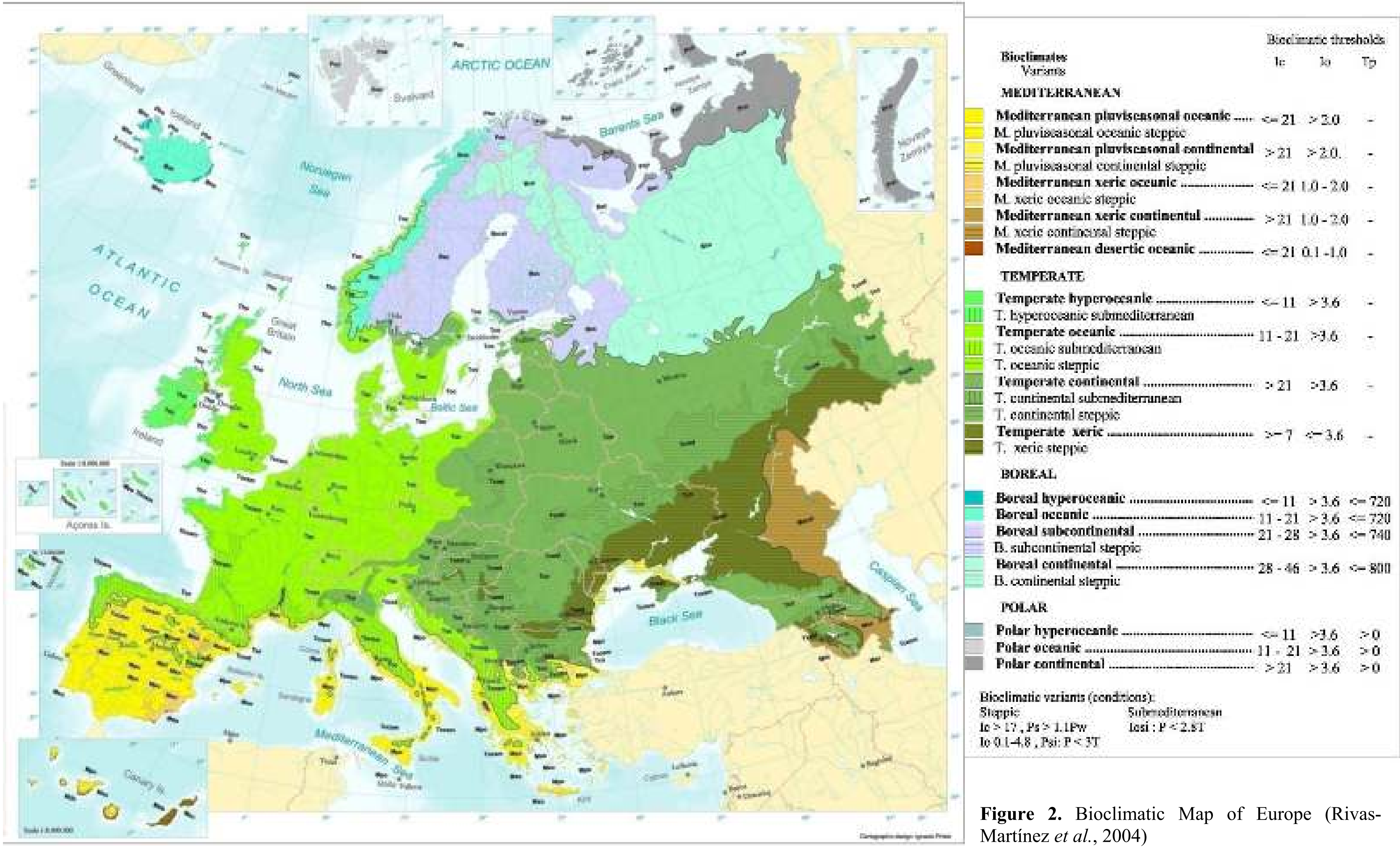


**Figure 2.** Bioclimatic Map of Europe (Rivas-Martínez *et al.*, 2004)

In this study we use four reference bioclimatic zones corresponding to these macro-bioclimates: boreal, temperate oceanic, temperate continental, Mediterranean. Table 1 summarises the main climatic characteristic of each bioclimatic zone and related bioclimates identified with reference to EU27 countries. Even though four bioclimatic regions will be used as a climatic zonation, an additional subchapter considering mountainous regions will be used when presenting the review results of the climate change impacts and adaptation strategies.

Basic assumptions of the classification are:

- the average monthly temperature range between the most extreme months of the year (Continentality Index, Ic see below) has a great influence on vegetation distribution and, as a result, on the boundaries of many bioclimates;
- unlike other climatic classification systems that place high mountains in a single bioclimatic belt type, known as the 'Mountain Climate', the bioclimatic map of Europe consider mountains only as colder, and generally wetter altitudinal variations of the macrobioclimates at the foothill. Every mountain range has a specific vertical zonation of vegetation. Thus, particular bioclimatic altitudinal belts must be recognized for single mountain ranges (cf. Fig. 3).

**Table 1.** Main characteristics of the reference bioclimatic zones used in the study.

| **Bioclimatic zones** | **Bioclimates** | **Bioclimatic thresholds** | | |
|---|---|---|---|---|
| | | **Ic** | **Io** | **Tp** |
| **Boreal** | **Boreal subcontinental - Bsc** | 21-28 | > 3.6 | ≤ 740 |
| **Cool and cold climate**<br>Ic 21-28: T≤4.8°<br>Ic 28-45: T≤ 3.8°<br>Ic >45: T<0 | **Boreal continental - Bco** | 28-46 | > 3.6 | ≤ 800 |
| **Temperate Oceanic** | **Temperate hyperoceanic - Tho** | ≤ 11 | > 3.6 | - |
| **No summer drought**<br>Ic ≤ 21 | **Temperate oceanic - Toc** | 11-21 | > 3.6 | - |
| **Temperate Continental**<br>**No summer drought**<br>Ic > 21 | **Temperate continental - Tco** | > 21 | > 3.6 | - |
| **Mediterranean**<br>**Warm, with a summer drought of at least two consecutive months in which P < 2T.** | **Mediterranean pluviseasonal oceanic - Mpo** | ≤ 21 | > 2.0 | - |
| | **Mediterranean pluviseasonal continental - Mpc** | > 21 | > 2.0 | - |
| | **Mediterranean xeric oceanic - Mxo** | ≤ 21 | 1.0-2.0 | - |

**Ic: Continentality Index** (yearly thermic interval). Ic = Tmax - Tmin. In degrees Celsius, the number expressing the range between the average temperatures of the warmest (Tmax) and coldest (Tmin) months of the year. The simple continentality index-types are: i) hyperperoceanic (Ic 0-11), ii) oceanic (Ic 11-21) and iii) continental (Ic 21-65)

**Io: Ombrothermic Index.**

**Io = (Pp/Tp) 10,** Where: **Pp = Yearly positive precipitation** (mm), total average precipitation of those months whose average temperature is higher than 0°C

**Tp = Yearly Positive Temperature** (in tenths of degrees Celsius), sum of the monthly average temperature of those months whose average temperature is higher than 0ºC.

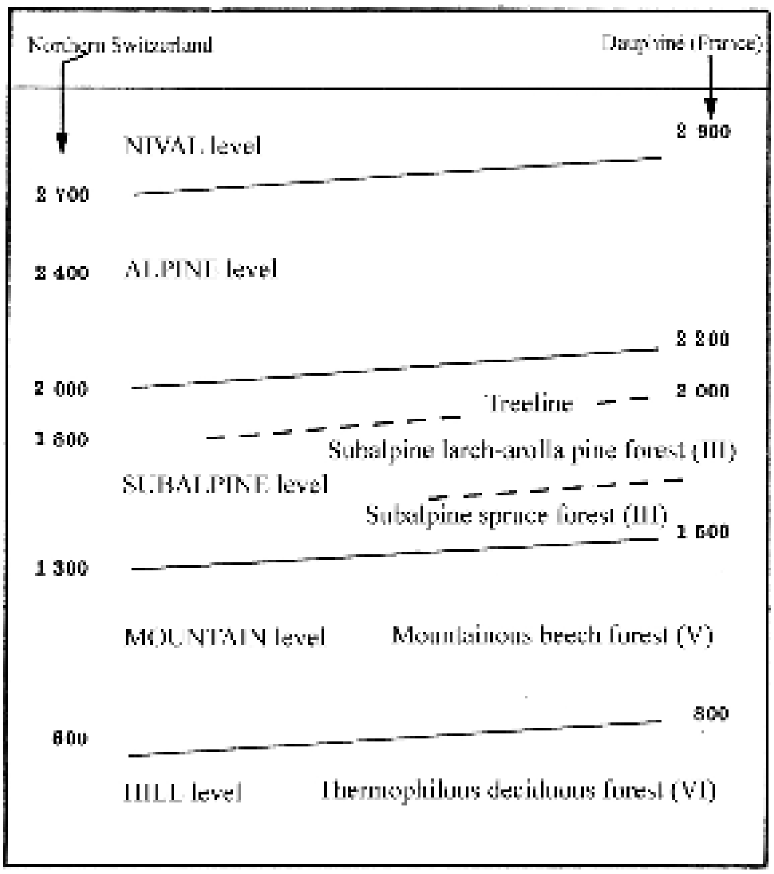


**Figure 3.** Example of vertical zonation of forest vegetation in the north-western Alps (altitude in *m*): in brackets, major forest types (Modified from Ozenda, 1994 ).

## 2.3.2 Forest typology and cross-links with bioclimatic zones

European forests are extremely variable with regard to their ecological and socio-economic conditions. The impacts of climate change on European forests are likely to be unevenly distributed not only across different bioclimatic zones but also among different forest ecosystems of each zone. This is because forest ecological characteristics will affect forest ecosystem sensitivity and the inherent adaptive of capacity of forest ecosystems to respond to climate change.

Accordingly, a forest typology classification reflecting this ecological variability is needed to facilitate the assessment of climate change impacts. To serve this purpose we used as reference the European Forest Type scheme consisting of 14 main categories of European forests recently presented by the EEA (2006). We derived from the original EEA forest typology a simplified classification organized into seven classes, reflecting the major forest types which can be found in the reference bioclimatic zones identified above (Table 2).

**Table 2.** Bioclimatic regions used as a regional classification for this study showing the seven forest types used in this study and the correspondence with the forest typology used in the EEA study (EEA, 2006). Forest type III is related to the mountain region referred to separately in this study.

| Bioclimatic zones | Bio-climates | Major forest type (n.) | Major forest type name | European Forest Types (EEA, 2006) |
|---|---|---|---|---|
| **Boreal** | Bsc | I | Boreal forest | 1, 11, 13 |
| | Bco | VII | Plantations and self sown exotic forest | 14 |
| **Temperate Oceanic** | Tho | II | Hemiboreal forest and nemoral coniferous and mixed broadleaved-coniferous forest | 2 |
| | Toc | III | Alpine coniferous forest | 3 |
| | | IV | Acidophylous oakwoods and mesophytic deciduous forest | 4, 5 |
| | | V | Beech forest | 6, 7 |
| | | VI | Thermophilous deciduous, broadleaved evergreen and xerophytic coniferous forests | 8, 10 |
| | | VII | Plantations and self sown exotic forest | 14 |
| **Temperate Continental** | Tco | II | Hemiboreal forest and nemoral coniferous and mixed broadleaved-coniferous forest | 2 |
| | | III | Alpine coniferous forest | 3 |
| | | IV | Acidophylous oakwoods and mesophytic deciduous forest | 4, 5 |
| | | V | Beech forest | 6,7 |
| | | VI | Thermophilous deciduous, broadleaved evergreen and xerophytic coniferous forests | 8 |
| | | VII | Plantations and self sown exotic forest | 14 |
| **Mediterranean** | Mpo | VI | Thermophilous deciduous, broadleaved evergreen and xerophytic coniferous forests | 8, 9, 10 |
| | Mpc | VII | Plantations and self sown exotic forest | 14 |
| | Mxo | | | |

A brief description of the seven major forest types is reported below.

### I) Boreal forest

The harsh climatic conditions of the boreal bioclimate (temperature and length of the growing season) affect forest composition dominated by two coniferous species (*Picea abies, Pinus sylvestris*) in the late stages of the forest succession; their relative distribution in the Boreal climate zone is driven mainly by edaphic conditions. Deciduous trees including birches (*Betula* spp.), aspen (*Populus tremula*), rowan (*Sorbus aucuparia*) and willows (*Salix* spp.) tend to occur as early colonisers of bare ground or in the early stages of forest succession (see Table 2).

The class also covers the tree-limit (and outer archipelago) belt of (mountain) birch forest in the Fennoscandian region and the wetland forests on peaty soils dominated by *Pinus silvestris, Picea abies* or *Alnus glutinosa.*

**II) Hemiboreal forest and nemoral coniferous and mixed broadleaved-coniferous forest**

The class covers the latitudinal mixed forests located in between the Boreal and Temperate forest zones (*hemiboreal forest*) and anthropogenic coniferous forest in the Temperate (or *nemoral*) zone (see Table 2).

The hemiboreal forest is characterized by the coexistence of boreal coniferous species with temperate broadleaved tree species (*Quercus robur*, *Fraxinus excelsior*, *Ulmus glabra*, *Tilia cordata*); nemoral coniferous forest is dominated by *Pinus sylvestris* ssp. *sylvestris*, *Picea abies* or *Pinus nigra* and may originate both from natural regeneration and from artificial planting. Mixed broadleaved-coniferous forests are represented by mixed forests of Scots pine and birch (mainly found in the highlands of Scotland) and by mixed forest of Scots pine and pedunculate oak (very frequent in western and central Poland and northern Germany).

**III) Alpine coniferous forest**

Coniferous forests of the high elevations of the mountain ranges of Europe scattered within the Temperate bioclimatic zone (Pyrenees, Alps, Appennine, Carphathians). Climatic conditions are similar to the Boreal zone (cold and harsh climate, short growing seasons), except for the light regime and length of the day. Forest tree species composition varies with the vegetation belts (mountainous/subalpine) and site ecological conditions. *Picea abies*, *Pinus sylvestris*, *Abies alba*, *Larix deciduas*, *Pinus cembra*, *P. nigra* and *P. mugo* are the naturally dominant species.

Forest of the Scandinavian Alps are included under class I.

**IV) Acidophylous oakwoods and mesophytic deciduous forest**

Deciduous forests of the Temperate bioclimatic zone including:

- acidophilous oakwoods (*Q. robur*, *Q. petraea*) and mixed oak-birch forest (*Q. robur, Betula pendula*) growing on oligotrophic soils;
- mixed forests on meso- and eutrophic soils made up by a relatively large number of deciduous tree species: *Carpinus betulus*, *Quercus petraea*, *Quercus robur*, *Fraxinus*, *Acer* and *Tilia cordata*.

Radiation, light and temperature regimes, oceanic influences (in the west) and continental influences (in the east) affects forest productivity; the difference between annual precipitation and potential evaporation is, notably, an important factor controlling tree growth. Yields are therefore higher in the western part of the zone, under oceanic influence, than in the south-eastern part where potential evaporation exceeds precipitation.

**V) Beech forest**

Deciduous forests of the Temperate bioclimatic zone dominated by beech; at its northern and eastern boundaries and at high altitudes, beech is limited by low winter temperatures causing either direct damage (extreme winter cold or late frosts in spring) or too short growing season. To the south and at lower altitudes low water availability mainly limit beech distribution.

The class includes:

– lowland to submountainous forests, characterised by the dominance of European beech *Fagus sylvatica* or of *Fagus orientalis* in the eastern and southern parts of the Balkan Peninsula. Locally important additional trees, are *Betula pendula* and mesophytic deciduous species;
– mountainous beech forest, characterised by the presence of conifers (*Abies alba* and/or *Picea abies*) and mesophytic deciduous trees as important forest building trees.

**VI) Thermophilous deciduous, broadleaved evergreen and xerophytic coniferous forests**

The class includes a varied group of broadleaved and coniferous forests ranging from the coast to high mountains of Mediterranean and, to a minor extent, Temperate bioclimatic zones:

– thermophilous deciduous forests mainly occurring in the supra-Mediterranean vegetation belt; thermophilous deciduous forests are limited to the north (or upslope) by temperature and to the south (or downslope) by drought.

The mild climatic conditions of the supra-Mediterranean level determine the predominance of mixed deciduous and semi-deciduous forest of thermophilous species, mainly of *Quercus, Acer*, *Ostrya*, *Fraxinus*, *Carpinus* species are frequent as associated secondary trees. Purely anthropogenic forest of *Castanea sativa* are also included;

– broadleaved evergreen forests mainly growing in the thermo- and meso-Mediterranean vegetation belt and in the warm-temperate humid zones of Madeira (temperate hyperoceanic bioclimate) and Canary islands (Mediterranean pluviseasonal Oceanic bioclimate). Characterised by the dominance of broadleaved sclerophyllous (*Q. suber*, *Q. ilex*, *Q. rotundifolia*, *Q. coccifera*, *Q. alnifolia, Olea europaea* ssp. *sylvestris*, *Ceratonia siliqua*) or lauriphyllous evergreen trees (e.g. *Laurus ocotea*).

Water availability varies considerably between the Macaronesia and thermo- and meso-Mediterranean vegetation belts and it is the main climatic factor limiting tree-growth.

– xerophytic coniferous forests growing from coastal regions to high mountain ranges. Forest physiognomy is mainly dominated by species of *Pinus*, *Abies* and *Juniper*, that are variously distributed according to altitudinal vegetation belts. The association with dry and, often, with poor or poorly developed soils limits tree growth.

**VII) Plantations and self sown exotic forest**

The class covers forest plantations (*sensu* MCPFE, indicator 4.3) and self-sown stands of exotic species.
It includes:

– reforestation with site native conifers, established for the rehabilitation degraded lands within their natural range and forest plantations for timber production, characterised by intensive exploitation for commercial purpose; most frequent species: Pinus species (*P. nigra*, *P. sylvestris*, *P. pinaster*, *P. halepensis*, *Pinus brutia*, *P. pinea*); *Picea abies*; *Abies alba*; *Prunus avium*; *Juglans regia*.
– plantation and woodlands of forest species non-native to Europe or otherwise not locally site-native; some non-native species like *Robinia pseudoacacia*, *Ailanthus altissima*, *Prunus serotina* are able to regenerate and spread naturally competing successfully with native forest species. These almost pure woodlands are increasingly altering the forest composition of natural communities (invasive species). Non-site native species plantations include a number of industrial plantations providing the raw

material for wood processing (timber, pulp). Between the species most commonly used in commercial plantations are: *Eucalyptus* spp.; *Populus* clones*; Picea sitkensis; Pinus radiata; Pinus contorta; Pseudotsuga menziesii, Tsuga heterophylla*.

# 3 CLIMATIC CHANGE SCENARIOS

An important issue when considering adaptation and mitigation responses to climate change is the uncertainty in the predictions of future climate. There are many different models available and big efforts have been made in understanding the inter-model differences in climate sensitivity. In addition to uncertainties derived from the model formulation, there are those derived from future atmospheric emissions. Thus, the range of forecast reflects uncertainty regarding future emissions as well as concerning climate models. As an example, Fig. 4 (extracted from the IPCC Fourth Assessment Report) shows the variability of the global surface warming for the different emissions scenarios used for the assessment (cf. Table 3).

The IPCC fourth assessment report applied different scenarios based on the Special Report on Emission Scenarios (SRES; Nakicenovic *et al.*, 2000). The SRES scenarios are grouped into four scenario families (A1, A2, B1, and B2) that explore alternative development pathways, covering a wide range of demographic, economic, and technological driving forces and resulting GHG emissions. The emission projections are widely used in the assessments of future climate change, and their underlying assumptions with respect to socioeconomic, demographic and technological change serve as inputs to many recent climate change vulnerability and impact assessments (see Table 3).

**Table 3.** Description of the main emission scenarios used in the IPCC special report on emissions scenarios (SRES). The SRES scenarios do not include additional climate initiatives.

| |
|---|
| **A1 storyline Europe** |
| The A1 storyline assumes a world of very rapid economic growth, a global population that peaks in mid-century and rapid introduction of new and more efficient technologies. A1 is divided into three groups that describe alternative directions of technological change: fossil intensive (A1FI), non-fossil energy resources (A1T), and a balance across all sources (A1B). |
| **A2 storyline Europe** |
| A2 describes a very heterogeneous world with high population growth, slow economic development and slow technological change. |
| **B1 storyline Europe** |
| B1 describes a convergent world, with the same global population as A1, but with more rapid changes in economic structures toward a service and information economy with introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social and environmental sustainability. |
| **B2 storyline Europe** |
| B2 describes a world with intermediate population and economic growth, emphasising local solutions to economic, social, and environmental sustainability. It is a world continuously increasing global population, at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. |

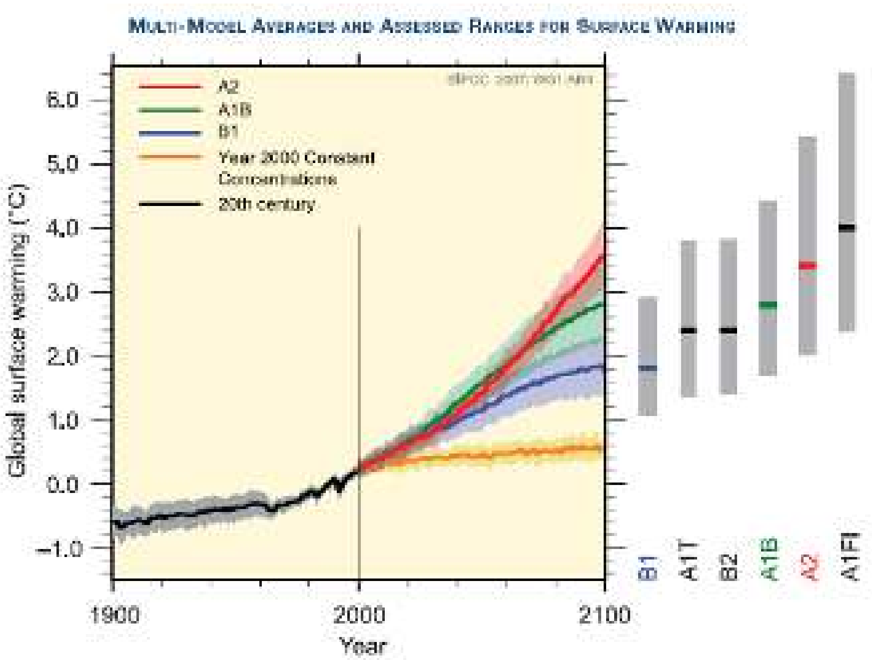


**Figure 4.** Projected temperature increase in different emission scenarios (IPCC Fourth Assessment Report; Solomon *et al.*, 2007). Solid lines are multi-model global averages of surface warming (relative to 1980–1999) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the ±1 standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the **likely** range assessed for the six SRES marker scenarios. The assessment of the best estimate and **likely** ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints.

The advances in climate change modelling now enable best estimates and likely assessed uncertainty ranges to be given for projected warming for different emission scenarios. Best estimates and likely ranges for global average surface air warming for six SRES emissions marker scenarios are shown in Table 4. For example, the best estimate for the low scenario (B1) is 1.8°C (likely range is 1.1°C to 2.9°C), and the best estimate for the high scenario (A1FI) is 4.0°C (likely range is 2.4°C to 6.4°C).

**Table 4.** Projected global average surface warming at the end of the 21st century (Solomon *et al.*, 2007).

| | Temperature change (°C at 2090-2099 relative to 1980-1999) [a, d] | |
|---|---|---|
| Case | Best estimate | *Likely* range |
| Constant year 2000 concentrations [b] | 0.6 | 0.3 – 0.9 |
| B1 scenario | 1.8 | 1.1 – 2.9 |
| A1T scenario | 2.4 | 1.4 – 3.8 |
| B2 scenario | 2.4 | 1.4 – 3.8 |
| A1B scenario | 2.8 | 1.7 – 4.4 |
| A2 scenario | 3.4 | 2.0 – 5.4 |
| A1FI scenario | 4.0 | 2.4 – 6.4 |

Notes: a) These estimates are assessed from a hierarchy of models that encompass a simple climate model, several Earth Models of Intermediate Complexity, and a large number of Atmosphere-Ocean General Circulation Models (AOGCMs) as well as observational constraints. b) Year 2000 constant composition is derived from AOGCMs only. c) All scenarios above are six SRES marker scenarios. Approximate $CO_2$-eq concentrations corresponding to the computed radiative forcing due to anthropogenic GHGs and aerosols in 2100 (see p. 823 of the WGI TAR) for the SRES B1, AIT, B2, A1B, A2 and A1FI illustrative marker scenarios are about 600, 700, 800, 850, 1250 and 1550 ppm, respectively. d) Temperature changes are expressed as the difference from the period 1980-1999. To express the change relative to the period 1850-1899 add 0.5 $^oC$.

According to the 4th Assessment Report of the Intergovernmental Panel on Climate Change (Solomon *et al.*, 2007), without an effective global climate change mitigation policy, best estimates for global warming range from 1.8°C to 4°C increaseby 2100 compared to the 1990 levels. This is much higher than the temperature increase the globe has experienced since pre-industrial times. These changes differ between regions and the emission scenarios used. For example, under the A1B scenario, the projected annual mean warming from 1980/1999 to 2080/2099 varies from 2.3°C to 5.3°C in Northern Europe (NEU) and from 2.2°C to 5.1°C in Southern Europe and Mediterranean (SEM).

Rate and distribution of precipitation strongly depend on a variety of parameters (e.g. topography, vegetation structure, land use). It is, therefore, likely that future changes in precipitation differ strongly in their spatial and temporal distribution (Geßler *et al.*, 2007). A south-north contrast in precipitation changes across Europe is indicated by coupled atmosphere-ocean general circulation models (AOGCMs), with increases in the north and decreases in the south. The annual area-mean change from 1980 to 1999 period to 2080 to 2099 period in the MMD-A1B projections varies from 0 to 16% in Northern Europe (NEU) and from –4 to –27% in Southern Europe and the Mediterranean (SEM; cf. Table 5). The largest increases in northern and central Europe are simulated in winter. In summer, the NEU area mean changes vary in sign between models, although most models simulate increased (decreased) precipitation north (south) of about 55°N. In SEM the most consistent and, in terms of percentage, largest decreases occur in summer, but the area mean precipitation during the other seasons also decreases in most or all models. More detailed statistics are given in Table 5 and Fig.6.

**Table 5.** Regional averages of temperature and precipitation projections from a set of 21 global models in the MMD for the A1B scenario. The mean temperature and precipitation responses are first averaged for each model over all available realisations of the 1980 to 1999 period from the 20th Century Climate in Coupled Models (20C3M) simulations and the 2080 to 2099 period of A1B. Computing the difference between these two periods, the table shows the minimum, maximum, median (50%), and 25% and 75% quartile values among the 21 models, for temperature (°C) and precipitation (%) change. Regions in which the middle half (25–75%) of this distribution is of the same sign in the precipitation response are coloured light brown for decreasing and light blue for increasing precipitation. Signal-to-noise ratios for these 20-year mean responses is indicated by first computing a consensus standard deviation of 20-year means, using those models that have at least three realisations of the 20C3M simulations and using all 20-year periods in the 20th century. The signal is assumed to increase linearly in time, and the time required for the median signal to reach 2.83 ($2 \times \sqrt{2}$) times the standard deviation is displayed as an estimate of when this signal is significant at the 95% level. These estimates of the times for emergence of a clearly discernible signal are only shown for precipitation when the models are in general agreement on the sign of the response, as indicated by the colouring. The frequency (%) of extremely warm, wet and dry seasons, averaged over the models, is also presented. Values are only shown when at least 14 out of the 21 models agree on an increase (bold) or a decrease in the extremes. A value of 5% indicates no change, as this is the nominal value for the control period by construction. The regions are defined by rectangular latitude/longitude boxes and the coordinates of the bottom left-hand and top right-hand corners of these are given in degrees in the first column under the region acronym (see table notes for full names of regions). Source: Christensen et al. (2007).

| | | Temperature Response (°C) | | | | | | Precipitation Response (%) | | | | | | Extreme Seasons (%) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Region* | Season | Min | 25 | 50 | 75 | Max | T yrs | Min | 25 | 50 | 75 | Max | T yrs | Warm | Wet | Dry |
| | | | | | | | | EUROPE | | | | | | | | |
| NEU | DJF | 2.6 | 3.6 | 4.3 | 5.5 | 8.2 | 40 | 9 | 13 | 15 | 22 | 25 | 50 | **82** | **43** | 0 |
| | MAM | 2.1 | 2.4 | 3.1 | 4.3 | 5.3 | 35 | 0 | 8 | 12 | 15 | 21 | 60 | **79** | **28** | 2 |
| 48N,10W | JJA | 1.4 | 1.9 | 2.7 | 3.3 | 5.0 | 25 | -21 | -5 | 2 | 7 | 16 | | **88** | **11** | |
| to | SON | 1.9 | 2.6 | 2.9 | 4.2 | 5.4 | 30 | -5 | 4 | 8 | 11 | 13 | 90 | **87** | **20** | 2 |
| 75N,40E | Annual | 2.3 | 2.7 | 3.2 | 4.5 | 5.3 | 25 | 0 | 6 | 9 | 11 | 16 | 45 | **96** | **48** | 2 |
| SEM | DJF | 1.7 | 2.5 | 2.6 | 3.3 | 4.6 | 25 | -16 | -10 | -6 | -1 | 6 | >100 | **93** | 3 | 12 |
| | MAM | 2.0 | 3.0 | 3.2 | 3.5 | 4.5 | 20 | -24 | -17 | -16 | -8 | -2 | 60 | **98** | 1 | 31 |
| 30N,10W | JJA | 2.7 | 3.7 | 4.1 | 5.0 | 6.5 | 15 | -53 | -35 | -24 | -14 | -3 | 55 | **100** | 1 | 42 |
| to | SON | 2.3 | 2.8 | 3.3 | 4.0 | 5.2 | 15 | -29 | -15 | -12 | -9 | -2 | 90 | **100** | 1 | 21 |
| 48N,40E | Annual | 2.2 | 3.0 | 3.5 | 4.0 | 5.1 | 15 | -27 | -16 | -12 | -9 | -4 | 45 | **100** | 0 | 46 |
| | | | | | | | | SMALL ISLANDS | | | | | | | | |
| MED | DJF | 1.5 | 2.0 | 2.3 | 2.7 | 4.2 | 25 | -25 | -16 | -14 | -10 | -2 | 85 | **96** | 1 | 18 |
| | MAM | 1.5 | 2.1 | 2.4 | 2.7 | 3.7 | 20 | -32 | -23 | -19 | -16 | -6 | 65 | **99** | 0 | 32 |
| 30N,5W | JJA | 2.0 | 2.6 | 3.1 | 3.7 | 4.7 | 15 | -64 | -34 | -29 | -20 | -3 | 60 | **100** | 1 | 36 |
| to | SON | 1.9 | 2.3 | 2.7 | 3.2 | 4.4 | 20 | -33 | -16 | -10 | -5 | 9 | >100 | **99** | 2 | 21 |
| 45N,35E | Annual | 1.7 | 2.2 | 2.7 | 3.0 | 4.2 | 15 | -30 | -16 | -15 | -10 | -6 | 45 | **100** | 0 | 50 |

Notes: Regions are Northern Europe (NEU), Southern Europe and Mediterranean (SEM), Small Islands in the Mediterranean Basin (MED).

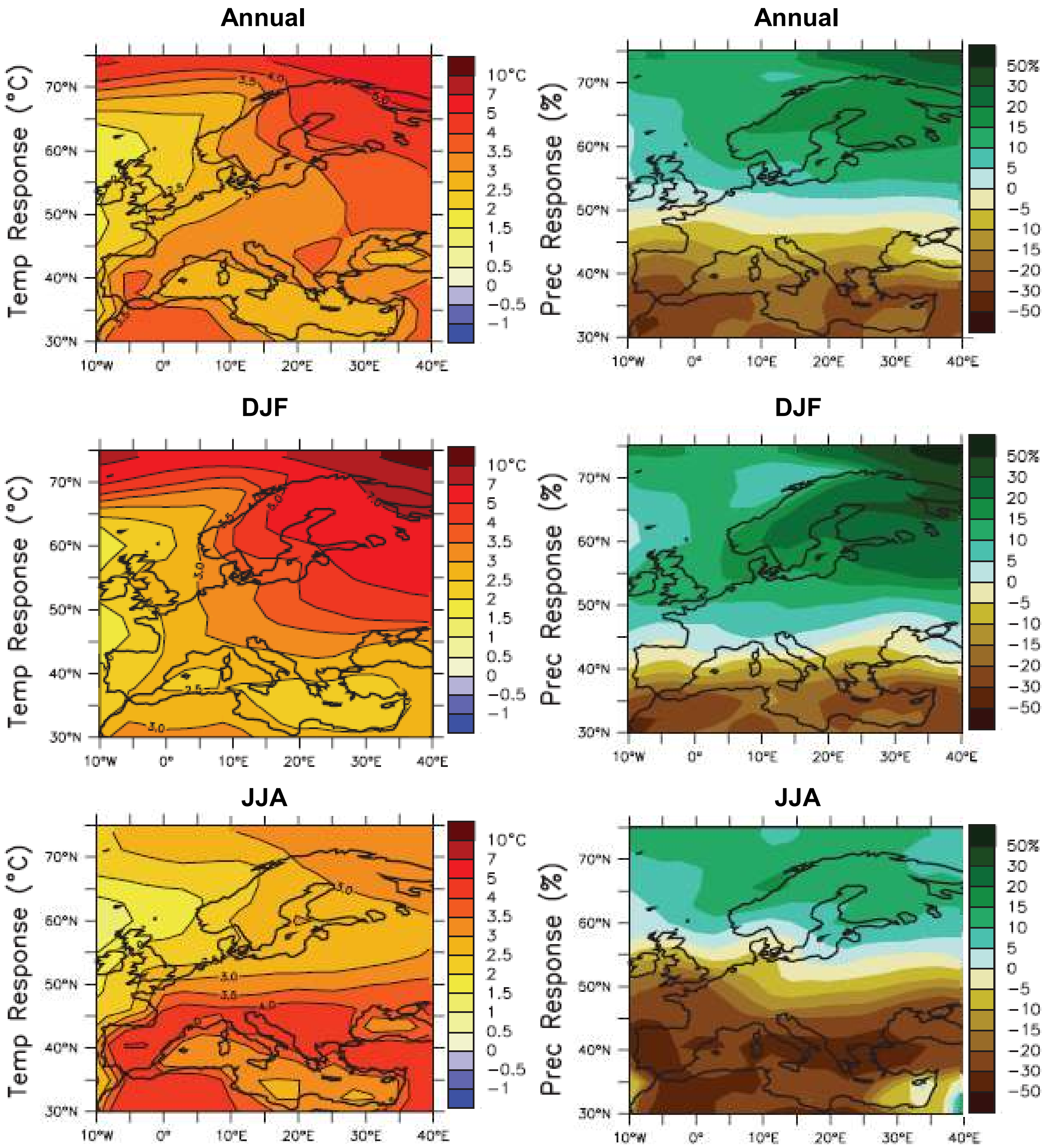


**Figure 6.** Temperature and precipitation changes over Europe from the MMD-A1B simulations (Christensen et al. 2007), Left column Annual mean, DJF (December, January and February) and JJA (June, July and Agugust) temperature change between 1980 to 1999 and 2080 to 2099, averaged over 21 models. Right column: same as top, but for fractional change in precipitation.

In addition, the PRUDENCE project (Christensen and Christensen, 2007) has addressed the uncertainty analysis of regional climate change by producing an ensemble of regional climate model (RCM) simulations for Europe. PRUDENCE has provided an initial evaluation of these uncertainties by running two atmosphere-only general circulation model (AGCM) ensembles and four regional climate model ensembles using two different emissions scenarios to drive its simulations of future climate. The year was divided in four seasons with three months each starting with December, January and February (DJF) and ending with September, October and November (SON). The data for the different seasons and different areas of Europe are presented in Annex 1 (change in temperatures) and Annex 2 (changes in precipitation) for the time window 1961-1990 (control period) and 2071-2100 (future).

Another study within the PRUDENCE project conducted by Kjellström (2004) used a regional model system RCAO for both, control period 1961-1990 and for future 2071-2100 given the emission scenarios IPCC SRES A2 and B2 and using two different global models; HadAM3H and ECHAM4/OPYC3. As a result, all four simulations of climate change resulted in increased temperatures in all seasons. The magnitude of the increase was highest in the RCAO-Echam/A2 with average annual mean increase of 5.3°C over Europe and the lowest in the RCAO-Had/B2 with a mean increase of 2.8°C.

In a similar study, Räisänen *et al.* (2004) used the same models and emission scenarios than Kjellström (2004), the range of change in temperature was 3.2°C for HadAM3H using A2 and 2.3°C for HadAM3H using B2. Predictions for the model ECHAM4/OPYC3 were 3.4 and 2.6°C using A2 and B2 emission scenarios respectively. On the other hand, Giorgi *et al.* (2004) used HadAM3H and RegCM and predicted a range of variation of 2.5 to 5.5°C when using A2 emission scenarios and variation of 1 to 4°C when using the B2 scenarios.

All the studies showed **regional variability of climate change**. For example, the changes in temperature forests will most probably have to face over the next 100 years are between about 2°C increase in Ireland and the UK, up to about 3°C increase in central Europe and 4°C – 5°C increase in northern Boreal and parts of the Mediterranean regions. All models agree that the warming is greatest over Eastern Europe in winter and over western and southern Europe in summer (Giorgi *et al.*, 2004). Moreover, other studies show a very large increase in summer temperatures in the south-western parts of Europe, exceeding 6°C in parts of France and the Iberian Peninsula (Kjellström, 2004; Räisänen *et al.*, 2004; Christensen and Christensen, 2007). Also the maximum daily temperature is expected to increase even more, especially in southern and central Europe. In northern Europe the increase in temperature is of about equal magnitude on all days.

Winter time average daily temperatures are simulated to increase from 3°C to more than 7°C in east Europe. The warming in the cold end of the temperature distribution is even larger. In south-western Europe e.g. Iberian Peninsula and France, the temperature increase is uniform in all parts of the temperature distribution. As a consequence of warmer winters, the duration of snow cover is expected to decrease by several weeks for each °C of temperature increase in the Alps region at middle elevations (Hantel *et al.*, 2000; Wielke *et al.*, 2004; Martin and Etchevers, 2005).

According to the results of the IPCC (Christensen *et al.*, 2007) the temperature changes are coupled with increases in mean annual precipitation in northern Europe and decreases further south. The change in seasonal precipitation varies substantially from season to season and across regions. Summer precipitation decreases substantially in the Mediterranean regions and parts of central Europe (up to 50%). To a smaller degree it also decreases in parts of northern Europe and parts of the Boreal region (Räisänen *et al.*, 2004). On the other hand, winter precipitation is projected to increase in mid and northern latitudes (15-30%), but to change only very little in the Mediterranean and mid-southern latitudes (Giorgi *et al.*, 2004; Räisänen *et al.*, 2004).

Regarding extreme events, the yearly maximum temperature is expected to increase more in south and central Europe than in northern Europe (Räisänen *et al.*, 2004; Kjellström *et al.*, 2007). In central, southern and Eastern Europe, the summer warming will be more closely connected to higher temperatures on warm days than to a general warming while much of the warming in winter is connected to higher temperatures on cold days (Kjellström, 2004). In addition, Christensen and Christensen (2003), Giorgi *et al.* (2004) and Kjellström (2004) all found a substantial increase in the intensity of daily precipitation events even in the areas with a decrease in mean precipitation.

The combined effects of the increase in temperatures and the decrease in summer precipitation would enhance the occurrence of heatwaves and drought (Schär *et al.*, 2004). In this context, Beniston *et al.* (2007) estimated that countries in central Europe would experience the same number of hot days as currently occur in southern Europe and that in Mediterranean areas the drought will start earlier in the year and last longer. Polemio and Casarano (2003) also stated that Mediterranean and even much of the eastern Europe may experience an increase in dry periods by the late 21$^{st}$ century.

Observational records have already documented various impacts in the forest ecosystems. The extreme weather patterns resulted in unprecedented extent and/or frequency of drought, flooding and storm events and these developments are projected to intensify (Meehl and Tebaldi, 2004; Tebaldi *et al.*, 2006).

**Box 2. Expected climate changes in different bioclimatic zones considering mountainous regions as a separate group**

**Boreal** (Sweden and Finland): Temperatures are projected to increase by 3.5-5°C with higher increase during winter (4-7°C) than in summer (3-4°C). Significant increases in yearly precipitation (up to 40%) are predicted. Winters are projected to be wetter.

**Temperate oceanic** (Belgium, Czech Republic, Denmark, France, Germany, Ireland, Luxemburg, the Netherlands and UK): Annual mean temperature increases are projected to be 2.5-3.5°C, except for the UK and Ireland with 2-3°C. Summers are likely to be dryer and hotter (up to 4°C increase). Extreme events such as violent storms and floods are projected to become more frequent due to warmer temperatures and higher volumes and intensities of precipitation, in particular in winter.

**Temperate continental** (Austria, Bulgaria, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia and Slovenia): The annual mean temperature increase is projected to be in the order of 3-4°C except for the more continental regions of Central Europe and the Black Sea Region, like Romania, where temperatures could increase by as much as 4-4.5°C. Annual mean precipitation is expected to increase by up to 10% mainly in winter, while there would be reductions in summer precipitation in several areas (up to -10%).

**Mediterranean** (Cyprus, Greece, Italy, Malta, Portugal and Spain): Annual mean temperature increases throughout Southern Europe and the Black Sea region are projected in the order of 3-4°C (4-5°C in summer and 2-3°C in winter) suffering droughts. Yearly rainfall is expected to drop by up to 20% of current annual precipitation (and up to 50% less in summer). However precipitation is expected to increase in winter. This results in higher intensity precipitation events. Models predict changes in frequency, intensity, and duration of extreme events with more hot days, heat waves, heavy precipitation events, and fewer cold days.

**Specífic changes in mountain regions**:
Alps: Temperature has already increased during the last century twice the global average in the Alps (about +1.5°C). This increase in temperature has been detected at all altitudes with a slight tendency of increasing changes at higher altitudes. By 2050 we can expect an increase of 2° in autumn, winter and spring, and 3° in summer in the Swiss Alps. The run-off will be increased. In addition, the duration of snow cover is expected to decrease by several weeks for each °C of temperature increase in the Alps.

For Mediterranean and Carpathian mountains there is no specific information available that would deviate from the information presented above in the respective bioclimatic zones.

# 4 FOREST ECOSYSTEM SENSITIVITY AND POTENTIAL IMPACTS

## *4.1 Impact Factors – General description*

Based on a thorough literature survey including scientific publications, project reports from relevant national and EU funded research projects, the major direct and indirect impacts of observed and projected climate change on EU forest were analysed. Direct impacts from climate arise from increase in the $CO_2$ concentration and temperature and precipitation changes. Indirect impacts come from the interactions between changes in climatic variables and several abiotic and biotic factors.

Observational records have already documented various changes in climate conditions in Europe. The average temperatures are increasing, and extreme weather patterns resulted in unprecedented extent and/or frequency of drought, flooding and storm events and these developments are projected to intensify (Meehl and Tebaldi, 2004; Tebaldi *et al.*, 2006).

The following direct and indirect impact factors are studied:

- atmospheric $CO_2$ increase
- changes in temperature
- changes in precipitation, flooding, drought duration and frequency
- abiotic disturbances (changes in fire occurrence, changes in wind storm frequency and intensity)
- biotic disturbances (frequency and consequences of pest and disease outbreaks)

Forest ecosystem sensitivity will be analysed by the effect of the different impact factors on the mechanisms affected (i.e. growth, mortality, reproduction, biotic disturbance, species composition change etc.). It should be noted that the presented results are very scenario-dependent.

### 4.1.1 Atmospheric $CO_2$ increase

Atmospheric $CO_2$ is a substrate for plant **photosynthesis**. Therefore, rising concentrations of $CO_2$ in the atmosphere is believed to act as a fertilizer and increase photosynthesis rate (Arp, 1991; Long and Drake, 1992; Curtis, 1996; Koch and Mooney, 1996; Norby *et al.*, 1999; Beedlow *et al.*, 2004). In some experiments stimulation of leaf photosynthesis was evidenced unequivocally in experiments when plants were exposed to enriched $CO_2$ (Norby *et al.*, 1999; Körner, 2006). However, increases in the rates of photosynthesis varied with the duration of the experiment, the plant nitrogen status and the species (Saxe *et al.*, 1998; Medlyn *et al.*, 1999; Norby *et al.*, 1999; Ainsworth and Long, 2005).

Tree growth rate might not increase proportionally with increase in photosynthesis because other factors (such as nutrient availability) may become more important, thus limiting the ability of trees to increase their growth rates, particularly in natural ecosystems (Norby *et al.*, 1999; Hungate *et al.*, 2003; Körner, 2003; Berninger *et al.*, 2004).

**Nitrogen** is required in relatively large quantities in connection with all growth processes in plants (Stitt and Krapp, 1999; Johnson, 2006). When plants are exposed to a $CO_2$-enriched environment, an increase in biomass of plant or soil organic matter will increase the N demand in plants because formation of organic matter requires N and other nutrients in relatively fixed proportions with carbon (Luo *et al.*, 2004; Norby and Iversen, 2006). Over a longer time, N availability will progressively decline unless compensated by additional N supplies or reduced losses. Thus long-term responses of plants to enhanced $CO_2$ concentrations is constrained by N limitation of ecosystem productivity (Comins and McMurtrie, 1993; Luo *et al.*, 2004; Norby and Iversen, 2006).

Increased atmospheric $CO_2$ induces a partial closure of stomata reducing **water** loss by transpiration. This results in an increase in the ratio of carbon gain to water loss, i.e., water use efficiency at the leaf and whole stand level increases (Farquhar *et al.*, 1989; Bowes, 1993; Field *et al.*, 1995; Picon *et al.*, 1996; Drake *et al.*, 1997; Farquhar, 1997; Centritto *et al.*, 1999; Körner, 2000; Wullschleger *et al.*, 2002; Morgan *et al.*, 2004). However, the heat balance of the plant represents a significant complication that interacts with water use efficiency. The evaporation of water off leaf surfaces has a cooling effect. Thus, even if increased atmospheric $CO_2$ could potentially allow a tree to keep the stomata of its leaves closed for longer periods, it might still need to continue to leave the stomata open for the purpose of evaporative cooling to maintain heat balance. As a result, the improvements in water use efficiency could be counteracted by the need to maintain heat balance (Shugart *et al.*, 2003).

In addition, increased allocation of carbon to **root growth** (e.g., increased fine roots, root surface area and volume) and osmotic adjustment in plants exposed to enriched $CO_2$ may enable plants to exploit soil water in a deeper and larger range of soil (Hättenschwiler and Körner, 1998; Wullschleger *et al.*, 2002). Consequently, these responses could increase water uptake and improve water balance in plants, hence ameliorating the negative effects of water stress and better adapting to a water-limited environment (Wullschleger *et al.*, 2002; Morgan *et al.*, 2004). As a result, this effect can stimulate biomass accumulation in seasonally dry ecosystems (Ceulemans and Mousseau, 1994; Saxe *et al.*, 1998), and enhance ecosystem net primary productivity (Amthor, 1995; Loehle, 1995). In a FACE experiment on a closed-canopy, deciduous sweetgum forest, Norby *et al.* (2004) observed the $CO_2$-induced increase in fine-root standing crop (total length of root visible) in summer, which might be an important mechanism for conferring increased resistance to late season drought. Low nutrition and water availability tend to increase the ratio of root to shoot in response to $CO_2$ enhancement (Stulen and den Hertog, 1993; Saxe *et al.*, 1998), allowing plants growing on poor and dry sites to explore a greater soil volume to acquire water and nutrients (Day *et al.*, 1996; Norby *et al.*, 2004; Norby and Iversen, 2006; Phillips *et al.*, 2006). The responses of roots to $CO_2$ are dependent on experimental conditions (Ceulemans and Mousseau, 1994).

Increased $CO_2$ can help trees to overcome **stress from different sources**, e.g. ozone for *Betula pendula* (Riikonen *et al.*, 2004). The increased water use efficiency is particularly important in drier ecosystems (Morgan *et al.*, 2004). On the other hand $CO_2$ increases become less important in northern latitudes where precipitation is normally not limiting. However, Körner (2006) pointed out that reactions of trees to $CO_2$ are variable, might diminish over time, and may be much more influenced by plant-soil interactions than currently known.

A meta-analytical review of free-air $CO_2$ enrichment (FACE) experiments found that **trees** were more responsive to elevated $CO_2$ than other plant functional types (Ainsworth and Long, 2005). In a review of short-term $CO_2$-enriched experiments (less than one season), Ceulemans and Mousseau (1994) found that photosynthesis of deciduous **species** was more sensitive to elevated $CO_2$ than that of conifers. Some species (e.g. mature *Fagus sylvatica* and *Quercus petratea)* respond more than others (e.g. *Carpinus betulus, Prunus avium, Tilia platyphyllos)* (Asshoff *et al.*, 2006). However, evidence from long-term studies (more than one season) suggested that photosynthesis stimulation enhanced by elevated $CO_2$ was similar in unstressed conifers and deciduous trees, ranging from 50–60% (Gunderson and Wullschleger, 1994; Norby *et al.*, 1999).

Most field $CO_2$-enriched experiments showed that elevated $CO_2$ concentration directly enhanced **growth** of young trees or seedlings regardless of growth conditions (e.g. Ceulemans and Mousseau, 1994; Curtis and Wang, 1998; Norby *et al.*, 1999; Norby *et al.*, 2001; Ainsworth and Long, 2005; Körner, 2006), providing strong evidence to support the direct $CO_2$ fertilisation effect. When exposed for longer time periods, photosynthesis and biomass accumulation could be lower than predicted from the initial growth response (Gunderson and Wullschleger, 1994; Sage, 1994; Ellsworth *et al.*, 1995; Vivin *et al.*, 1995; Miglietta *et al.*, 1998; Saurer *et al.*, 2003) because trees might adjust to development under elevated $CO_2$ with time (i.e. acclimation) (Loehle, 1995). The growth response to elevated $CO_2$ of young trees with expanding canopies is often further enhanced by increased leaf production, leading to larger LAI (Ainsworth and Long, 2005). Large, mature forest trees respond physiologically to elevated $CO_2$ in a manner similar to younger trees (Körner *et al.*, 2005).

### 4.1.2 Changes in temperature

The bioclimatic zones in Europe differ in their limitations for forest production. Therefore, increased temperature will have **different effects in different locations**. These effects can be either positive or negative depending on the area and the main limiting factor in this area. Higher temperatures extend the growing season in the northern latitudes. However, in other regions they have a detrimental effect, especially if the precipitation does not increase as in the case of Mediterranean areas (Loustau *et al.*, 2005).

Forest productivity in the northern Boreal region is mainly limited by low temperature, and often by nutrient availability. Under these conditions, higher air temperature prolongs the growing season and thereby increases production. In the southern Boreal and Temperate zones, production is more limited by water, and less by temperature and nutrients. Higher temperatures increase the length of the growing season but the increase in production could be restricted by water availability. Water limitation increases from the Temperate Oceanic to the Temperate Continental and the Mediterranean zone. Therefore, increases in temperature could lead to more droughts, especially in the Mediterranean and Continental Temperate zone.

An increase in temperature alone would be beneficial for boreal (Kellomäki and Wang, 1996; Briceño-Elizondo *et al.*, 2006) and temperate sites (Saxe *et al.*, 2001), but interaction with other features is still under analysis. For example, competitiveness between species can change due to alterations in temperature, $CO_2$ and radiation as has been found for *F. sylvatica* and *Fraxinus excelsior* seedlings (Saxe and Kerstiens, 2005). The reaction to climatic changes can also depend on the competition within a stand. Piutti and Cescatti (1997) found different reactions to temperature and water availability in dominant and suppressed *F. sylvatica*.

In the Alpine zone, production is water limited at low altitudes, but not at higher altitudes where precipitation is significantly higher. Under future climate at higher altitudes production will increase mainly because of a prolonged growing season.

In the Mediterranean areas, where production is limited by low air humidity and soil water because of high evaporative demand, the growth and yield under climate change has been found to decrease (Loustau *et al.*, 2005). In these areas heat is often a stress factor. The optimum temperature for photosynthesis rarely exceeds 30 $^{o}$C. At high temperatures photorespiration is stimulated and photosynthesis is inhibited (Rennenberg *et al.*, 2006).

### 4.1.3 Changes in precipitation

Water is a principal requirement for photosynthesis. There is a linear increase in net primary production with increased water availability in dry regions (Loik *et al.*, 2004). Changes in the rainfall patterns are likely to have large corresponding effects on forest productivity in regions where productivity is water limited (Kirschbaum, 2004). Different climate scenario simulations agree on a general increase in winter precipitation in northern and central Europe and (in some areas very large) decreases in summer precipitation in central and southern Europe (Räisänen *et al.*, 2004).

The site water balance is decisive for future forest growth. Rising temperatures without increase in precipitation or with decreasing rainfall can lead to drought, especially in Mediterranean and continental temperate conditions (Rennenberg *et al.*, 2006). Climate variability is particularly important in connection with the changes in precipitation, because extreme events such as extended droughts and hot spells have much more drastic consequences on tree growth and survival than gradual changes in average climate conditions (Fuhrer *et al.*, 2006). The dry and hot year 2003 caused strongly reduced primary productivity across large areas of Europe (Ciais *et al.*, 2005) and resulted in increased tree mortality in the following two years (Bréda *et al.*, 2006). Growth changes at local scale are superimposed by the hydrological regime. However, extreme events cause growth responses across site conditions (Granier *et al.*, 2007), as trees are obviously adapting to the local site water balance (Kahle, 1994).

Granier *et al.* (2007) summarised effects of heat and drought on trees at the plant level. They document the reduced $CO_2$-uptake and biomass production under drought. The changes induced by drought conditions particularly reduce growth in sensitive species, especially European beech, while sessile oak is more tolerant (Bréda *et al.*, 1993; Backes and Leuschner, 2000; Rennenberg *et al.*, 2004; Czajkowski *et al.*, 2005). Analyses are complicated because of lags in reaction of tree growth to stress, due to conditioned growth behaviour. Granier *et al.* (2007) found the reactions of beech to drought to be more pronounced in 2004 than in 2003, the year of the drought event. An analysis of past responses to drought on long-term research plots in Switzerland documented clear negative responses to drought periods of more than 60 days in the basal area increment of Norway spruce and beech, whereas silver fir (*Abies alba)* showed less and oaks no response (Zingg and Bürgi, 2008).

For Mediterranean conditions, growth reductions are predicted for most species if rainfall does not increase (Rennenberg *et al.*, 2006). These conditions also lead to aggravated competition of seedlings with ground vegetation.

At community level, changed growth of individual trees can influence growth and yield of total stands, and change competition among tree species in a stand (Bugmann and Solomon, 2000). For example, Bonn (2000) found oaks to be less sensitive to water stress than European beech (F. *sylvatica)* and stand composition likely to change if the number of years with water stress increases. Beech dominates natural forests from moderate dry to moist conditions but it replaced by other species like oaks in dry environments. The natural area of distribution of beech to the south is mainly limited by water availability and therefore, beech might face severe problems under drought conditions (Geßler *et al.*, 2007): "Seedlings as well as adult trees may suffer from xylem embolism, restricted nutrient uptake capacity and reduced growth under limited water availability." However, other researchers point out considerable physiological flexibility in the drought response of beech (Czajkowski *et al.*, 2005; Bolte *et al.*, 2007). Growth and development of beech saplings strongly depend not only on soil moisture but also on the prevailing vapour pressure deficit (Lendzion and Leuschner, 2008).

Changes in cloudiness and rainfall can alter the amount of incoming radiation at a site (Niinemets, 1997; Le Duc and Havill, 1998), but these influences are currently not predictable.

The effects on soils are detrimental: under warmer and wetter conditions, nutrient cycling and litter decomposition will speed up (Reichstein *et al.*, 2003; Lensing and Wise, 2007), but under drought conditions increases in litter layers due to hampered decomposition can also be expected, e. g. in pine forests (Kurz-Besson *et al.*, 2006). Heat and drought can negatively influence nutrient availability in soils and lead to enhanced loss in nitrogen via accelerated nitrification (Rennenberg *et al.*, 2006). As climate change effects on soils are reviewed in another study (ClimSoil project commissioned by DG Environment), they were not further analysed here.

### 4.1.4 Resulting changes in tree species composition

In addition to changes in tree growth and productivity changes in species distributions and competition between species are expected (Solomon, 1986; Woodward, 1994; Bugmann, 1996; Lindner, 1997; Lexer *et al.*, 2002). The current distribution of tree species in Europe can be gleaned from maps produced by the EUFORGEN project[2]. Thuiller *et al.* (2006) have modelled changes of tree species distributions under climate change using bioclimatic envelops which describe the potential long-term changes in distribution ranges. They found that "temperate areas (would) 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 their species richness and functional diversity. Atlantic areas provided an intermediate case, with a predicted reduction in the numbers of species and occasional predicted gains in functional diversity. This resulted from a loss in species within the broadleaved deciduous (functional types), but overall maintenance of the group." The range of *P. abies* and *P. sylvestris* might retreat from the south and west while *F. sylvatica* and other temperate hardwoods spread to the north (Sykes and Prentice, 1996). According to the same authors, conifer forest "subject to continuing disturbance show a more rapid shift to dominance by *Fagus* and other temperate hardwoods. Delayed immigration of new species, including *Fagus*, would favour early-successional species such as *Betula pendula* and *Quercus* spp. in a forest with reduced biomass and diversity." For the Mediterranean, socio-

[2] http://www.bioversityinternational.org/networks/euforgen/index.asp, 01.12.2007

economic developments, drought and altered fire regimes may lead to more shrub-dominated landscapes (Mouillot *et al.*, 2002; Resco De Dios *et al.*, 2007). In the Alps, *Picea* might not be suitable as a crop species at lower altitudes (Jankovsky *et al.*, 2004), and deciduous species become competitive towards *Picea* at higher elevations (Lexer *et al.*, 2002). While trees may migrate due to management (planting), forest herbs need migration speeds of 2 – 4 km $y^{-1}$ to make full use of newly suitable regions (Skov and Svenning, 2004; Van der Veken *et al.*, 2004). This puts some species of northern or eastern distribution at risk of losing their range in Europe and can have significant impacts on local and regional biodiversity and conservation efforts. In addition, climatic change can raise the danger of invasive species (Chornesky *et al.*, 2005).

Changes in ecosystem or forest type may be small in the centre of distributions or until some threshold is surpassed (Chapin *et al.*, 2004), and they may take considerable time due to e.g. seed dispersal restraints (Starfield and Chapin, 1996) or habitat fragmentation (Honnay *et al.*, 2002).

### 4.1.5 Abiotic disturbances

Main abiotic disturbances in Europe are caused be fires, wind storms**,** flooding and drought, all of which may be affected by climate change (Flannigan *et al.*, 2000; Gan, 2004; Gillett *et al.*, 2004; Moriondo *et al.*, 2006; Schumacher and Bugmann, 2006; Thonicke and Cramer, 2006; Seidl *et al.*, 2007). In the period 1950-2000, an annual average of 35 million $m^3$ wood was damaged by disturbances (i.e. 8% of total fellings in Europe); storms were responsible for 53% of the total damage and fire for 16% (Schelhaas *et al.*, 2003). Under climate change, the extreme weather patterns, (drought, flooding, wind storms), are projected to intensify. These extreme conditions have several direct and indirect impacts on the forests. As an example, the years 2003 and 2007 demonstrated that forest fires may be substantially more devastating when large scale droughts prevail. Fire in the Mediterranean regions, and wind damage especially in northern and western Europe, may more frequently result in an imbalance in the long-term planning of harvests.

**Fire** danger is expected to increase throughout Europe, especially in the already fire-prone Mediterranean (Mouillot *et al.*, 2002; Mouillot *et al.*, 2003; Moriondo *et al.*, 2006), but also in the Boreal (Stocks *et al.*, 1998) and central European regions (Schumacher and Bugmann, 2006; Thonicke and Cramer, 2006). The impacts of fire on stands are of interest in the fire-prone Mediterranean and Continental regions. Possible effects on a single-stand scale are known. With regard to carbon cycling, impact of fire on soils became of interest in the last years. This has recently been reviewed by Certini (2005): low to moderate fires have little or no negative impacts (they rather eliminate undesired competitor species and increase pH and nutrient availability), but the enhancement of hydrophobicity can render the soil less able to soak up water and more prone to erosion. Severe fires can cause significant removal of organic matter, deterioration of both structure and porosity, considerable loss of nutrients through volatilisation, ash entrapment in smoke columns, leaching and erosion, and marked alteration of both quantity and specific composition of microbial and soil-dwelling invertebrate communities.

**Windthrow and storm** damage are most relevant in central Europe (Thürig *et al.*, 2005; Schutz *et al.*, 2006) as well as in western and northern Europe. Forest damage by wind and **snow** are a continuing cause of economic loss in forestry throughout Europe. In some climate change scenarios windiness increases in northern Europe and decreases in the Mediterranean region. The increase in windiness in northern Europe is largest in winter and early spring (Räisänen *et al.*, 2004). The economic value of the damage corresponds approximately to hundreds of millions of Euros each year (Valinger and Fridman, 1997). For example, in December 1990, approximately 180 million $m^3$ of timber was blown down in Europe during storms. In 1999, storm Lothar resulted in 200 million $m^3$ of damaged timber in central Europe and France. In 2004, there was again 70 million $m^3$ of timber blown down in a winter storm in southern Sweden. In all these events, damage in Norway spruce stands was disproportionately high.

The economic impact of wind damages is particularly severe in managed forests because of the reduction in the yield of recoverable timber, the increased costs of unscheduled thinning and clear-cutting, and resulting problems in forestry planning. Furthermore, broken and uprooted trees left in forest can lead to detrimental insect attacks on the remaining trees because of an increase in the amount of available breeding material (Bakke, 1989; Schroeder and Eidmann, 1993; Peltola *et al.*, 1999).

Extreme **flooding** events are expected to occur more frequently as a consequence of climate change. Global circulation models predict that it is very likely that higher amounts of precipitation will occur in northern Europe, especially during winter and spring, considerably increasing the risk of flooding in Central and Northern Europe. The number of rain days is projected to decrease, but the number of days with heavy rain events is projected to increase. This change is leading to more summer droughts as well as more extreme flooding events during summer (Kramer *et al.*, 2008). Flooding is more harmful if it occurs during the growing season than if it occurs during the dormant season of plants. Plant responses to flooding during the growing season include injury, inhibition of seed germination, changes in plant anatomy and promotion of early senescence and mortality. Trees are most vulnerable to the effects of flooding in late spring, just after the first flush of growth (Glenz *et al.*, 2006).

### 4.1.6 Biotic disturbances

The previously discussed impact factors (atmospheric $CO_2$ increase, changes in temperature, changes in precipitation and changes in abiotic disturbances) seriously influence biotic disturbance agents. **Climate change will affect** herbivores and pathogens **directly** and **indirectly through changes in plant nutritional quality and plant resistance** or through **community interactions** (e.g. natural enemies).

**Table 6.** Impact factors of climate change and their potential effects on herbivores and pathogens

| impact factor | effects (+/-) | impact mechanism |
|---|---|---|
| climate change (in general) | + | new disturbance agents invading forests |
| | + / - | change of frequency and consequences of pest outbreaks |
| | + / - | change of spatial patterns, size and geographical range of pest outbreaks |
| | + / - | changed intensity and extent of damages caused by defoliators due to altered plant resistance and host tissue palatability |
| | + / - | impact on ecology of natural enemies and diseases |
| | + / - | changed sporulation and colonisation success of pathogen species |
| | + / - | impact on the ecology of insect vectors of specific pathogen species |
| reduced irradiance | + | increased risk of catastrophic herbivory |
| temperature increase | + | increased rates of insect development, changes in voltinism, population density and size, and genetic composition |
| | + | increased chances of survival and reproductive potential of insects |
| | + | increased severity of outbreaks concerning certain pest species |
| | + | prolonged duration of outbreaks, increased areas of damage, increased intensity of damage by pest species |
| | + | range expansion northward of certain pest species |
| | + | range shifts (to higher latitudes or altitudes) of certain pest species |
| | + | colonisation of less marginal habitats by relic populations |
| | + | colonisation of new communities by migrant species |
| | + | higher probability of an establishment of exotic species |
| | + | increased intensity of endemic insect damage (background herbivory) |
| | + / - | changed extent of host plant exploitation |
| | + / - | advance of flight phenologies (e.g. butterflies) |
| | - | decreased growth rates, reduced fecundity and survival of species in case of temperatures above optima |
| | - | range contractions (southward) of certain species |
| | - | changes in distribution or population density due to increased asynchrony between host plants and insect herbivores |
| | - | possible population crashes and local extinctions |
| precipitation deficits | + | population increase of certain species in case of moderate water stress of host plants (e.g. aphids) |
| | + | drought-induced outbreaks of bark beetles, increased attacks of healthy trees |
| | + | positive effects of earlier snow melt on insect species benefitting from an extended growing season and early food supply |
| | + | higher probability of secondary pest attacks following early defoliators |
| | + | extension of geographical range by pathogens of mediterranean and tropical origin |
| | + | main trigger of certain complex diseases (e.g. oak decline) |
| | + | trigger for fungal endophytes to shift from latent disease stage to pathogenic stage |
| | + / - | range shifts, extensions and/ or contractions of herbivores and pathogens according to changed patterns of precipitation |
| | - | decrease of overwinter survival of insects hibernating insulated by snow |
| | - | negative effects on pathogens benefitting from insulation by snow (e.g. snow blight) |
| | - | local extinctions |
| | - | negative performance responses in case of severe water stress of host plants (e.g. aphids) |
| | - | decreased outbreaks of defoliators in case of severe drought |
| precipitation increase | + | positive effects on spore production and infection by pathogens (e.g. foliar disease fungi) |
| increased frequency and intensity of storm events | + | possible outbreaks of pest species (e.g. bark beetles) |
| | + | higher probability of infection by pathogens |
| | + / - | altered regional dynamics of insect populations and communities |
| $CO_2$ increase | + / - | complex interactions among temperature, precipitation, nutrient availability, plant quality, insect performance and range expansion make predictions of future pest problems difficult |

**Consequences of climate change – general aspects.** Climate change will have **impact on temporal and spatial dynamics of (potential) pest species**, influencing the frequency and consequences of outbreaks as well as their spatial patterns, size and geographical range. Not only the range of the pest species may be affected, but also (in the long run) the distribution of its host tree species. An important fact is that individual species will respond to climate change not necessarily in the same way. Changes of species composition of communities are to be expected in future and hosts will consequently come in contact with novel pathogens and herbivores. The coevolved relationships between hosts and their pests probably will be disturbed. In areas, where pathogens have been contained at low levels because of unfavourable historic climate conditions, changes in climate may put the associated tree species at great risk (Williams and Liebhold, 1995; Malmström and Raffa, 2000; Roy *et al.*, 2004; Woods *et al.*, 2005).

**Changes in climatic variability may be as important or even have larger effects for both trees and forest organisms** as changes in the average climate. For many species, it is expected that performance and survivorship will not be affected by slight, progressive changes in climatic conditions, but by the likelihood or nature of **catastrophic events**. A clearer understanding of how climatic extremes affect insect populations in the long term is demanded - what are the basic relationships between extreme climatic events and development rate, population growth, phenology or voltinism. Also a specification of the climatic parameters relevant for pathogen development is demanded. Not only indigenous species may be affected but also new disturbance agents may invade European forests, with yet unknown but potentially marked consequences (Ayres and Lombardero, 2000; Malmström and Raffa, 2000; Bale *et al.*, 2002; Rouault *et al.*, 2006).

**Plant nutritional quality and resistance.** Tree physiological condition plays a major role in the pathogenicity and thus the epidemiology of herbivores and pathogens. Especially canker and shoot diseases might become more serious. Due to the lack of physiological models it is difficult to predict how specific climate scenarios will influence tree resistance to pathogens (Ayres and Lombardero, 2000). Likely, the indirect effects of climate through plant resistance (tree secondary metabolism, constitutive and inducible tree resistance) and nutritional suitability of host tissue (palatability) on herbivores are still not clearly understood. Climate change will impact decomposition processes and consequently nutrient supply of plants. Especially the availability of nitrogen may be crucial, as nitrogen-limited host tissue is likely to decline in quality for herbivores, while a good nitrogen supply and the reduction of secondary metabolites at the same time may enhance food quality (Ayres, 1993; Ayres and Lombardero, 2000).

The future seriousness of pest insects will further be affected by impacts of climate change on the ecology of natural enemies and diseases (birds, viruses, entomopathogenic fungi, etc.). Specific **community interactions** may influence population cycles of herbivores. Increases in the frequency of extreme events could disrupt the synchrony between the growth, development and reproduction of biological control agents and their targets (hosts), e.g. destabilising host-parasitoid interactions (Williams and Liebhold, 1995; Cannon, 1998; Ayres and Lombardero, 2000). Diverse pathogen species rely on insect vectors for dispersion (e.g. Dutch elm disease, Pitch cancer, Beech bark disease) and future damage will depend both on the impact of changed climatic parameters on the ecology of the vector and the pathogen. Forest soil community interactions also play an important role concerning the pathogenicity of fungi, as mycorrhizal infection in tree roots competes with saprophytic fungi (Ayres and Lombardero, 2000).

**Influence of changes in irradiance and UVB.** Increased cloud cover (due to an increase in precipitation) leads to reduced radiation, which tends to depress plant carbon budgets and to lower secondary metabolism. Consequently, the risk of catastrophic herbivory might be increasing. Nevertheless, there are only few studies to back up this hypothesis. Likewise, the number of studies on the consequences of changing UVB levels on herbivores is limited and gives conflicting results (see references in Ayres, 1993; Ayres and Lombardero, 2000; Bale *et al.*, 2002).

**Temperature increase – direct effects on herbivores and pathogens. Changes** may be induced **in life-cycle** duration (rate of development), voltinism, population density and size, genetic composition and extent of host plant exploitation of insects. An **increase in temperature towards species optima** will usually accelerate egg and larval development, reducing development times most susceptible to predation and parasitism and thus, increase chances of survival. Accelerated development rates enhance the reproductive potential of insects and other poikilotherms and the earlier completion of life-cycles may allow additional generations within a year for multivoltine species. It is important to note that **high temperatures during heat waves above insects' temperature optima** may also have negative effects on insect populations, leading to decreased growth rates and reduced fecundity and survival (Cannon, 1998; Ayres and Lombardero, 2000; Bale *et al.*, 2002; Parmesan, 2006; Rouault *et al.*, 2006).

**Species at the northern limit of their ranges** will probably profit from an increase in summer sunshine and temperature, populations will become more stable and population densities will increase (Cannon, 1998). Such trend has already been signalled in larger sizes of insect outbreak zones observed in the regions of greatest warming (Volney and Fleming, 2000). Periods of mild winters and particularly warm summers led to a long duration of bark beetle outbreaks and one of the largest area of mortality ever documented in the boreal forest (Malmström and Raffa, 2000). The vast outbreak areas of *Dendroctonus ponderosae*, the Mountain Pine Beetle, in the western United States and Canada are most prominent examples of climate change-induced increase and expansion of bark beetle infestations outside Europe (Carroll, 2007).

**Range shifts, range expansions and/ or contractions.** The size and location of species ranges is influenced by the interaction of available habitats with suitable climate. Range extension of species may be promoted by increases in mean annual, summer and/ or winter temperatures. As geographic distribution of many forest insects is more limited than their host distribution, insect distribution could change very rapidly in response to climatic variations (Cannon, 1998; Bale *et al.*, 2002; Parmesan, 2006; Rouault *et al.*, 2006).

As a response to increased overwinter survival, higher population growth rates due to increased summer temperatures, and extended growing seasons, insect populations may **expand their ranges to higher latitudes and elevations**. In order to evaluate the alteration of spatial dynamics of biotic forest disturbances, the specification of the climatic parameters relevant for development is of crucial interest (Williams and Liebhold, 1995; Ayres and Lombardero, 2000; Bale *et al.*, 2002). According to Bale *et al.* (2002), an extension of distributions to higher latitudes and altitudes will be probable for annual insect species exhibiting a steep growth rate and temperature response curve, respectively. In case of low temperature response, the southern edge of the present geographical distribution may become too warm, which will result in a **northwardly shift** or even **range contraction**.

Most forest insects of Temperate regions overwinter in diapause stage, for the induction and maintenance of which temperature plays an important role. Depending on the species, high winter temperature may affect insect development either positively or negatively and may result in increased or reduced population density (Battisti, 2004). Higher temperatures may promote increased growth rates but can also influence insect diapause. **In many annual insect life cycles, diapause maintenance and timing of its release will mitigate the effects of higher temperatures.** The interaction of day-lenght and temperature during the diapausing stages is not well understood for many common species, especially in the case of pests or potential pest species (Bale *et al.*, 2002).

**Colonisation of new habitats.** Relic populations will be able to expand and colonise less marginal habitats; migrant species may be able to colonise new communities, where the vegetation has not coevolved adequate defense mechanisms (Cannon, 1998). A higher probability of an establishment of exotic species in Europe has already been observed, e.g. in the case of a butterfly species formerly being confined to hot microclimates of northern Africa (Ayres and Lombardero, 2000; Parmesan, 2006).

**Phenological coincidence between herbivores and their hosts.** Host-specific insect herbivores often require close synchrony with host phenology (e.g. timing of larval development and bud burst) in order to successfully complete their life-cycle. Temperature, acting on differential growth rates of an insect and its host plant, might set the upper and lower limits of an insect's distribution range. **Under climate change scenarios, asynchrony between host plants and insect herbivores might become more likely**. On the other hand, degrees of phenological coincidence will probably not be affected in the long term, as selection pressures under gradual warming might be sufficiently intense to bring insect populations back to synchrony. The probable effects on phenological synchrony between host plant and insect are diverse: In case the growth rate of the insect and development of foliage increase to a similar extent and remain synchronised, defoliation levels may be largely unaffected (e.g. spruce budworm). In other cases synchrony (between date of budburst and of larval emergence) may be lost and will lead to high larval mortality rates (e.g. winter moth). (Cannon, 1998; Bale *et al.*, 2002; Rouault *et al.*, 2006).

**Temperature increase – indirect effects through changes in plant nutritional quality and resistance.** Increasing global temperatures can affect the developmental race between poikilotherm herbivores and their host tissue if the temperature sensitivity of the herbivore differs from that of the host. According to Ayres (1993), global warming of 2°-4°C may lead to outbreaks of many insect herbivores in case insects are generally more temperature-sensitive than their host plants. Greenhouse experiments indicated that an increase of 1°C can potentially triple population growth of a herbivore, however, little is known about the relative temperature sensitivity of various insect species and their host plants The performance of defoliators may be enhanced by the temperature increase of foliage or by the feeding on plants with a temperature-induced carbon deficiency. On the other hand, the positive effect of temperature may be modulated by a decrease of foliage quality. There is a need for further studies regarding the effects of temperature changes on plant allocation patterns or resistance to herbivory (Ayres, 1993; Rouault *et al.*, 2006).

**Temperature increase – indirect effects through community interactions.** Population densities of insect herbivores will change not only depending on their own capacity for increase, but on the presence and abundance of predators and parasites. Warmer environmental conditions may increase the effectiveness of certain natural enemy species, such as warmer springs bringing parasitoids more in synchrony with their hosts. Since global change parameters operate in concert, interaction between the different factors needs more investigaton, e.g. how direct effects of temperature interact with natural enemies or host plant condition (Cannon, 1998; Bale *et al.*, 2002; Roy *et al.*, 2004; Parmesan, 2006). Increased temperature could interact synergistically with drought-induced changes in host plant quality and might allow populations to escape natural enemy regulation (Cannon, 1998).

**Changed precipitation patterns – direct effects on herbivores and pathogens. Reduced snowfall or extreme droughts** may lead to **reduced overwinter survival** of insects hibernating in the forest litter (Ayres and Lombardero, 2000) or **lower the risk of damage** by pathogens benefitting from insulation by snow, such as snow blight. Local population extinctions and northward and upward shifts of the mean location of the extant butterfly populations are to be expected (Parmesan, 2006). On the other hand, shorter winter periods due to temperature increase and earlier snow melt **also favour insect development**, as species might benefit from early food supply and an extended growing season (Roy *et al.*, 2004).

**Changes in precipitation patterns and humidity will strongly affect spore production and infection by pathogens**. Most species require free water or high moisture for spore dispersal, germination and infection. An increase in precipitation in areas, where the development of certain species was restricted by humidity conditions, might have serious consequences for the affected tree species (Woods *et al.*, 2005). Prolonged or more frequent periods of drought will, on the other hand, have mainly negative effects for free stages of fungi. Fungal growth within the host will be less compromised, because most pathogens can grow at very low water potentials. This fact may explain the **positive association between drought and fungal diseases revealed by the majority of studies**. There is a **serious threat of pathogens of Mediterranean and tropical origin**, which may extend their geographical range in response to climate change (Roy *et al.*, 2004; Desprez-Loustau *et al.*, 2006).

**Changed precipitation patterns – indirect effects through changes in plant nutritional quality and resistance.** Both the **severity and phenology of water stress plays an important role in the dynamics of herbivores and pathogens**. Certain feeding guilds may be more responsive to water-stressed plants than others because they differentially experience changes in plant nutrition, allelochemistry and growth. Intermittent and continuous water stress will influence insect performance in different ways (Huberty and Denno, 2004). According to the theory of "growth-differentiation balance", moderate water stress would stimulate tree defense, while severe water stress would decrease tree resistance to pest attacks (Rouault *et al.*, 2006).

**Differential reactions of herbivores on moderate water strees of plants.** Moderate water stress of plants tends to retard growth more than it does retard photosynthesis, and carbohydrates are accumulated. Plant allocation to differentiation processes (e.g. secondary metabolism) should increase (Ayres, 1993; Ayres and Lombardero, 2000).

Moderate water stress seems to **increase tree level of resistance to fungi associated with scolytids**. While invasion success of the bark beetles may be promoted on the stressed host trees, the higher insect establishment may be counterbalanced by a lower transfer of the fungi (Desprez-Loustau *et al.*, 2006). In contrast, several successive, short cycles of water stress may **decrease tree resistance to a variety of insect species**, e.g. defoliators. Leaf miners show better performance during periods of drought because they benefit from elevated concentrations of nitrogen and are in the same time able to avoid compartmentalised secondary metabolites. (Huberty and Denno, 2004; Rouault *et al.*, 2006).

**Disease severity of pathogens commonly increases with water stress.** Tree mortality is crucially influenced by the duration and the timing of the stress situation, e.g. whether water stress occurs before or after infection and whether the water deficit does or does not end after a certain time from inoculation. In many cases, water stress of host trees is only a **trigger for already present latent diseases to shift to pathogenic stages** (Desprez-Loustau *et al.*, 2006). Changes in climate, resulting in improved conditions for such endophytes, are going to put forests at risk in many parts of Europe.

**Adverse effects of severe water stress of plants on herbivores except for bark beetles.** Under severe water stress of plants photosynthesis declines and the C:N ratio decreases. According to the carbon/ nutrient balance hypothesis, secondary metabolism should be reduced, however, this prediction seems inconsitent with available data and more empirical studies with ecologically relevant plants, herbivores and treatments might be necessary (Ayres, 1993; Ayres and Lombardero, 2000).

Stress-induced changes in plant water relations have **negative consequences for** survival, density, and overall performance of **chewing insects**. Outbreaks of **defoliators** are likely to be decreased, because the reduced availability of nitrogen in tougher foliage will adversely affect insect performance. Negative performance responses can also be expected of **sap feeders** on continuously water-stressed host plants due to the loss of cell water content and positive turgor pressure, which is required to extract available (and in case of water stress significantly higher levels) of plant nitrogen (Ayres, 1993; Huberty and Denno, 2004; Rouault *et al.*, 2006).

Tree mortality following severe droughts often exhibits species specific patterns. There are likely shifts in species composition regarding both the host trees and the pathogens, for example, *Quercus robur* shows higher sensitivity to water deficits and to root pathogens than *Quercus petraea* (Desprez-Loustau *et al.*, 2006).

Although reduced precipitation would shorten the seasonal period of rapid tree growth when vulnerability to bark beetles is greatest, extreme (severe or long) water stress should **increase vulnerability to beetle attack and decrease tree level of resistance to fungi associated with scolytids** because of limited oleoresin production. Within a region, reduced precipitation could thus lead to increased beetle damage in dry sites, but reduced damage in mesic sites. It is possible that exceptionally dry summers increase tree susceptibility to scolytids, as well as several consecutive years of severe water stress, leading to outbreaks of bark beetle populations and extensive attacks on healthy trees (Ayres, 1993).

**Changed precipitation patterns - indirect effects through community interactions.** Indirect effects on herbivore species may be both negative and positive: drought-increased performance of early defoliators often induces long-lasting plant resistance that will have negative effects on insect species occurring later in the season. On the other hand, severe defoliation due to drought together with defoliator proliferation may also lower tree resistance and facilitate secondary pest attacks the year after the drought. Indirect negative impact on forest pest insect population dynamics via parasitism may be the case if low plant quality reduces development rates of defoliators, thus increasing exposition periods to parasitoid attacks (Rouault *et al.*, 2006).

The colonisation of trees by certain pathogens may be favoured due to lower antagonism by less or non-pathogenic fungi more susceptible to changed patterns of precipitation (Desprez-Loustau *et al.*, 2006).

**Increased frequency and intensity of storm events – direct effects on herbivores and pathogens.** In windthrow gaps or areas, the forest ecosystem is destabilised and abiotic conditions are severely changed. Regional dynamics of insect populations and communities are strongly affected. While some species may have lost their habitats, a wide range of micro-habitats for diverse organisms is still provided. For many significant pests (e.g. the European spruce bark beetle*, Ips typographus)* the amount of suitable breeding material is increased, so that under epidemic conditions, **pest population growth can be dramatic and can contribute significantly to the impact of a disturbance** (Bouget and Duelli, 2004).

Storm events do not only increase the incidence of pest outbreaks but also result in a **higher probability of open tree wounds that allow the entry of pathogen species**. However, there is still lack of knowledge on the specific climatic parameters involved in pathogen development triggered by windthrow (Ayres and Lombardero, 2000).

**Increase of atmospheric $CO_2$ – indirect effects through changes in plant nutritional quality and resistance. Ambiguous reactions of herbivores feeding on plants under the influence of increased levels of $CO_2$.** The direct fertilisation effect of $CO_2$ on plants leads to increased productivity and thus to lower nitrogen concentrations (as C:N ratios rise) of plant tissue. The reduction of nitrogen content in host tissue commonly, but not necessarily leads to an increase of carbohydrate and phenolic-based secondary metabolites, e.g. condensed tannins (Ayres, 1993; Cannon, 1998; Ayres and Lombardero, 2000; Hunter, 2001).

The possible reactions of herbivores to these changes in plant chemistry may be diverse. Lower levels of nitrogen and higher C:N ratios in plants have generally been associated with **compensatory feeding** and subsequent increases in levels of damage or defoliation. However, the ultimative level of damage may be mediated by $CO_2$-induced increases in plant biomass and changes in insect density (Hunter, 2001).

Phytophagous insects may adapt to nutrition of higher C:N ratio, e.g. by a more efficient utilisation of nitrogen (Hunter, 2001). Yet, most insects appear to be unable to compensate fully for reductions in plant quality and may react with (+/-) **higher rates of mortality, poor larval performance and increased development time.** The physiological effects vary according to the particular plant-insect interactions, depending both on the species of plant and the species of insect under study. For example, increase of tannins is found in leaves of birch, poplar and maple under elevated $CO_2$, but not in pine (Cannon, 1998; Hunter, 2001; Battisti, 2004). At the same time, responses of herbivores to $CO_2$- induced changes in leaf chemistry differ significantly among tree species, as was shown for *Lymantria dispar* (Williams *et al.*, 2000; Hättenschwiler and Schafellner, 2004).

**Interactions of increased levels of $CO_2$, temperature and light, and nutrient availability.** Dominant consequence of elevated levels of $CO_2$ is the increase in global temperature; there may be synergistic effects of these factors on plant phenotype, resulting in significantly reduced food quality for insect herbivores. On the other hand, reduced rates of insect growth due to impaired food quality may be compensated by increased growth rates due to rising temperature. **Complex interactions among temperature, precipitation, nutrient availability, plant quality, insect performance, and range expansion make predictions of future pest problems difficult** (Hunter, 2001).

Nutrient availability is likely to affect plant and insect responses to atmospheric change. High nitrogen levels (due to nitrogen deposition) may compensate the effects of $CO_2$ on the concentration of nutrients and defense compounds in the plant tissue and may mitigate the effects of elevated $CO_2$ on insect performance (Cannon, 1998; Hunter, 2001; Battisti, 2004).

Interactive effects of light and $CO_2$ on tree growth and secondary chemistry are to be expected as well. Experiments showed dramatic reductions in the performance of moth larvae in terms of decreases in growth rate and pupal weight, and of increased mortality (Hunter, 2001).

**Increase of atmospheric $CO_2$ – indirect effects through community interactions.** Population densities of herbivores may decrease in case of combined effects of reduced foliar quality and increased rates of attack by natural enemies. The effects upon parasites, predators and pathogens under field conditions are a priority for future research, especially studies on the efficacy of natural enemies under elevated $CO_2$ levels or changes in insect-pathogen interactions (Hunter, 2001).

**Box 3. Example of the effects of climate change on a specific organism:**

***Thaumetopoea pityocampa* – Pine processionary moth (PPM)**
The pine processionary moth is a good example of a Mediterranean pest insect that has the potential of northward range expansion. The moth frequently occurs at outbreak density not only throughout its main distribution area of the Mediterranean basin, but also at the margins of its natural range (e.g. Venosta/ Vinschgau valley in Northern Italy).

**Goods, services addressed**
Defoliation by the PPM may lead to total needle loss of host trees and a severe reduction of tree growth. Production forests are affected as well as forest reserves (e.g. conservation areas of relict *Pinus sylvestris* in the Spanish Sierra Nevada). Outbreaks of the moth not only create economic loss, but also constrain recreational values of forests due to the high density of urticating larval hairs which may cause contact dermatitis and other allergic reactions.

**Potential effects of climate change on PPM**
The main impact factor influencing the spatial patterns of PPM distribution is winter temperature. Day and nighttime temperatures need to reach certain limits in order to allow activation of the larvae and nocturnal feeding (Battisti *et al.*, 2005; Buffo *et al.*, 2007). Milder winters have already been leading to altitudinal range expansions in the *Mediterranean mountains* of Sierra Nevada and Sierra de Baza of southern Spain (Hodar *et al.*, 2003; Hodar and Zamora, 2004) and in the *mountainous regions* of northern Italy (Battisti *et al.*, 2005; Battisti *et al.*, 2006; Buffo *et al.*, 2007). In latter area, PPM finds its northern boundary in Central Europe, because till now, climatic parameters did not allow an occurrence in the Austrian Alps. In the *temperate oceanic* climate zone, however, there seems to be no limit for a further latitudinal range shift of the pest (Robinet *et al.*, 2007). At the end of the last century, the distributional border of the moth in the Paris Basin coincided with a zone unfavourable for feeding activity. With transgression of this zone between the years 2001-2004, the pattern of range expansion is now solely affected by dispersal capability of the pest and host tree distribution.

## Box 4. Table: *Thaumetopoea pityocampa* – literature review on the impact of climate change

| reference | bioclimatic region | forest type | tree species | impact factor | impact mechanism | uncertainties/ knowledge gaps | goods/ services addressed |
|---|---|---|---|---|---|---|---|
| Hodar et al. (2003) | Mediterranean | III, VI | *Pinus sylvestris nevadensis; P. nigra* | temperature increase (winter) | **altitudinal range expansion (uphill)** of a pest limited by winter temperature and change to a new local host: first intrusions of PPM in stands of Scots pine growing at altitudes of 1600-2000m<br>drastic reducton of growth and reproductive capacity of the host tree by defoliation<br>increase of susceptibility of host trees to other impact factors (drought, pathogens)<br>negative effects on forest regeneration and tree survival | | conservation of relict forests; national and natural parks |
| Hodar & Zamora (2004) | Mediterranean | III, VI | *Pinus sylvestris nevadensis; P. nigra* | temperature increase (winter) | the interaction area of PPM and Pinus nigra (actual local host) will shift uphill, but in the upper parts the **new host plant** will be Pinus sylvestris | | |
| Pimentel et al. (2006) | Mediterranean | VI, VII | *Pinus pinaster* | unknown | establishment of a new population exhibiting a **shifted generation cycle**: earlier break of pupal diapause and emergence of adults; larval development during summer when temperature and irradiation reach maxima | factors driving the shift of the population cycle (climatic parameters?) | oldest national forest of Portugal; wood production |
| Battisti (2004) | Mediterranean, Temperate oceanic, Temperate continental | II, III, VI, VII | *Pinus spp.; Cedrus spp.; Pseudotsuga menziesii* | temperature increase (winter) | PPM larvae are oligophagous - thus, climate driven **range expansion** will likely be coupled with **host switching** | | wood production; ornamental trees |
| Battisti et al. (2005) | Temperate oceanic, Temperate continental | II, III, VII | *Pinus sylvestris ; P. nigra* | temperature increase (winter) | **both latitudinal and altitudinal range shifts** have been observed in the last 35 years; the northwards move of range boundaries in the Paris Basin (north-central France) and the upwards move in the northen Italian Alps is likely due to more facilitated winter feeding of the larvae (which is limited by certain temperature thresholds) and thus, increased survival rates | | wood production; recreation / public health (larvae have urticatin hairs, causing allergic reactions) |
| Battisti et al. (2006) | Temperate continental | II, III, VII | *Pinus mugo, P. nigra, P. sylvestris, P. uncinata* | temperature increase (winter and summer) | **altitudinal range expansion** of PPM may be due to both increased flight activity of female moths during the summer emergence (leading to colonisation of trees at high elevations) and reduced mortality rates during winter | | |
| Buffo et al. (2007) | Temperate oceanic, Temperate continental | III, VII | *Pinus mugo, P. nigra, P. sylvestris, P. uncinata* | temperature increase (winter) | the number of feeding hours for PPM larvae during the cold period explains well the survival of a population and may be used as variable in predictive models of range expansion under climate change scenarios | | |
| Robinet et al. (2007) | Temperate oceanic | II, VII | *Pinus sylvestris ; P. nigra* | temperature | the **range shift** in the Paris Basin is now less influenced by possible winter feeding of larvae (temperature conditions are beneficial both inside and outside the actual distribution range), but mainly by the distribution of host trees and female dispersion capability | | |

## 4.2 Sensitivity and potential climate impacts in different bioclimatic zones and forest types

This section is structured as follows. For each of the European bioclimatic zones four different subsections present

- a summary of the **exposure** based on latest climate change scenario projections;
- the **key impact factors**;
- the climate change **sensitivity**, and
- the **potential impacts** on forest products and services.

### 4.2.1 Boreal

- ***Summary exposure***

In the Boreal area, (Sweden, Finland) (Fig. 7), temperatures are projected to increase by 3.5-5°C with higher increase during winter (4-7°C) than in summer (3-4°C). Significant increases in yearly precipitation (up to 40%) are predicted; particularly winters are projected to become wetter.

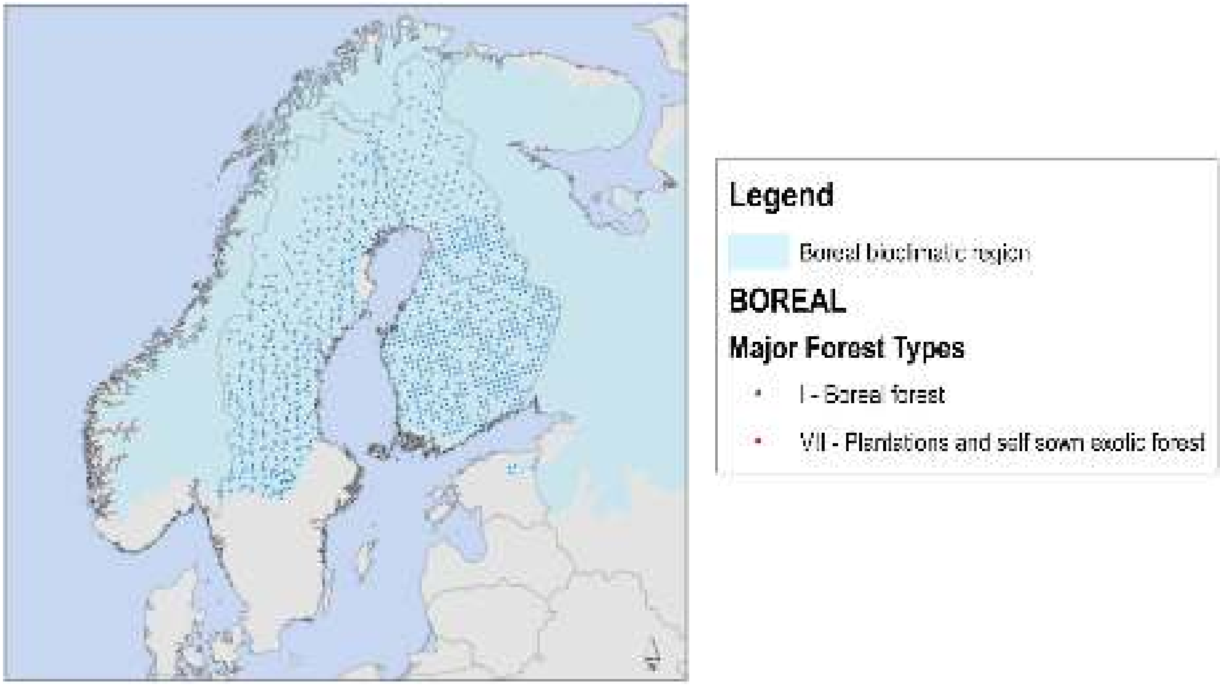


**Figure 7.** Boreal bioclimatic zone and its major forest types in EU Member states

- ***Key impact factors***

The productivity of boreal forests is limited by short growing seasons, low summer temperatures and short supply of nitrogen (Kellomäki *et al.*, 1997; Mäkipää *et al.*, 1998a; Mäkipää *et al.*, 1998b). The main impact factor in the Boreal region is thus the projected change in temperature. The increase in temperature may prolong the growing season and enhance the decomposition of soil organic matter and increase the supply of nitrogen (Raich and Schlesinger, 1992; Melillo *et al.*, 1993; Lloyd and Taylor, 1994; Kirschbaum, 1995). This may further enhance forest growth, consequent timber yield and the accumulation of carbon in the biomass, especially in boreal forests where water is not currently a limiting factor (Kellomäki and Väisänen, 1997). Precipitation is expected to increase which will further benefit growth of forests and may contribute to alter the current forest composition. However, these changes can increase biotic (e.g. insects and pathogens) and abiotic (e.g. windthrows) disturbances with corresponding losses in forest productivity. Moreover, the increase in winter temperatures and precipitation may affect logging operations (especially in swampy areas).

Because of harsh climate, the Boreal zone lies beyond the distribution range of many pest species – a situation which could be drastically changed by increasing winter and summer temperatures. However, pest or pathogen species will not exclusively profit from the climatic changes and organisms especially adapted to severe environmental conditions might also retreat. Tables 7 and 8 list pest and pathogen species that will be positively or negatively affected by climate change in the Boreal region.

**Table 7.** Pest species relevant in the context of climate change in the Boreal zone (see Table 2 for the foret types descriptions)

| Latin name | English name | Relevant impact factors | Major forest type | Affected tree species | Expected effect on species (+/-) |
|---|---|---|---|---|---|
| *Epirrita autumnata* | Autumnal moth | temperature increase | I | *Betula pubescens* | +/- |
| *Ips typographus* | European spruce bark beetle | temperature increase, increase of storm events, drought | I | *Picea abies* | + |
| *Lymantria dispar* | Gypsy moth | temperature increase | I | *Quercus, Carpinus, Betula, Populus, Prunus, Salix, Ulmus, Larix, Picea, et al.* | + |
| *Lymantria monacha* | Nun moth | temperature increase | I | *Quercus, Carpinus, Salix, Tilia, Fagus , Picea, Pinus, Larix et al.* | + |
| *Neodiprion sertifer* | European pine sawfly | temperature increase | I | *Pinus sylvestris* | + |
| *Tomicus piniperda* | Common pine shoot beetle | temperature increase | I | *Pinus sylvestris* | + |

**Table 8.** Pathogen species relevant in the context of climate change in the Boreal zone (see Table 2 for the forest types descriptions)

| Latin name | English name | Relevant impact factors | Major forest type | Affected tree species | Expected effect on species (+/-) |
|---|---|---|---|---|---|
| *Gremmeniella abietina* | Scleroderris cancer | changes in temperature and precipitation | I, VII | *Pinus sylvestris, P.contorta* | +/- |
| *Heterobasidion annosum* | Root and butt rot | temperature increase | I | *Picea abies* | + |

- ***Sensitivity***

In the Nordic countries, **higher air temperature** will lead to earlier and more rapid recovery of photosynthetic capacity in spring and a prolonged photosynthetic active season in autumn for both Norway spruce and Scots pine, resulting in increased carbon sequestration and growth of the cold-temperate and boreal forests (Bergh *et al.*, 2003; Nemani *et al.*, 2003). There is general agreement that the growth increase at single tree level predicted for northern forests leads to higher timber yields in total or allows for shorter rotations (Kellomäki *et al.*, 1997). Different studies at forest level agree with these results (Garcia-Gonzalo *et al.*, 2007b). Some older studies presented an overall increase in forest productivity in Finland, but regionally there was a slight decrease in southern parts of Finland (Talkkari, 1998). However, these older studies did not include direct and indirect effects of $CO_2$ on forest growth and reduced water limitations.

Elevated temperature lead to increased evapo-transpiration and this increases the demand for water. Whereas most of the Boreal zone is currently not water-limited, there are some regions in south-eastern Sweden, where potential evapotranspiration is larger than the actual realised evapotranspiration during the growing season and this could also be the case in southern Finland under climate change (Bergh *et al.*, 2003).

**Precipitation** is expected to increase, but even though water is not the main limiting factor for forest growth in Boreal regions, some studies have indicated that increased water limitation of growth and thus sensitivity to changes in precipitations can be expected when moving from colder high latitudes to warmer southern boreal forests. In areas with reduced precipitation, the potential increase in productivity due to higher temperatures could be reduced or offset because of insufficient water availability (Briceño-Elizondo *et al.*, 2006). In this case, Norway spruce will suffer more than Scots pine and silver birch due to higher retention of water in the crown and less availability of water for the root system (Briceño-Elizondo *et al.*, 2006). Drought stress could partially be mitigated by enhanced water-use efficiency due to enhanced atmospheric $CO_2$ concentrations (Gerten *et al.*, 2005). Milder winters may reduce winter hardening in trees, e.g. in oak stands in the coastal part of south-western Finland, increasing their vulnerability to frost (Hänninen *et al.*, 2001; Hänninen, 2006).

Higher winter temperatures will shorten the period with frozen soils and snow cover, thereby negatively impacting **forest management operations** (Maracchi *et al.*, 2005), e.g. by limiting the accessibility of forest areas with wet soils or decreasing the possibilities to drive with heavy machinery on hill slopes. Increased soil waterlogging and winter floods (Sonesson *et al.*, 2004) could also increase the susceptibility to windthrow, because waterlogged soils give less support to the roots (Peltola *et al.*, 2000; Schelhaas *et al.*, 2003). Forest damage by **wind and snow** are projected to increase under climate change at northern latitudes because of the potential decrease in soil freezing. The economic impact of wind damage is particularly severe in managed forests because of the reduction in the yield of recoverable timber, the increased costs of unscheduled thinning and clear-cutting, and resulting problems in forestry planning. A risk of wind and snow damage is high where there are sudden changes in wind loading to which the trees are not acclimated, as in stands thinned intensively or stands adjacent to recently clear-felled areas. Scots pines and Norway spruces are predicted to be much more susceptible to wind and snow damages than birches (Peltola *et al.*, 1999). Birches have a much smaller crown area for snow attachment than do Scots pines or Norway spruces, and a smaller drag area as far as wind load is concerned. The risk of stem breakage in all the tree species is greater at young stages, as the taper of stems increases with age and the stem becomes more stable. The risk of uprooting increases with tree height, especially in the Norway spruce, because of its shallow root system (Päätalo, 2000).

Changes in the distribution of the **pest species** *Lymantria monacha* and *Lymantria dispar* are likely under climate change (Karolewski *et al.*, 2007). Northward expansions by 500-700 km and thus increased probabilities of outbreaks of both species in the Boreal zone were projected by models of Vanhanen *et al.* (2007). Because of its high tolerance to elevated temperature (Karolewski *et al.*, 2007), the gypsy moth will profit from a high increase in average temperature and will especially benefit in growth at its northern limits (Vanhanen *et al.*, 2007).

Ambivalent effects of climate change were observed for the autumnal moth, *Epirrita autumnata* by Virtanen *et al.* (1998) and Virtanen and Neuvonen (1999). Increased summer temperatures were shown to enhance the activity of predators and parasits and also the vitality status of the host birch trees, and thus might reduce outbreak areas of the insect in the boreal birch forest. On the other hand, given increased egg survival of *E. autumnata* due to a rise in minimum winter temperatures, the authors projected a decrease of birch-growing areas saved from outbreaks to only 1/3 of the present area by 2050 and to only 1/10 by 2100.

Increased outbreak areas of the European pine sawfly, *Neodiprion sertifer* are also expected in pine forests of Fennoscandia due to decreased egg mortality in winter (Virtanen *et al.*, 1996; Lyytikäinen-Saarenmaa *et al.*, 1999; Veteli *et al.*, 2005). Being already one of the major defoliators in boreal forests of Scots pine, the sawfly is likely to expand and broaden its northern limits of distribution and to increase its frequency of mass propagation. The higher probability of forest defoliation will be an advantage for secondary pests, such as the common pine shoot beetle, *Tomicus piniperda*, which depends on subvital host trees (weakened by defoliation, forest fires or snow-breakage) for successful reproduction (Cedervind *et al.*, 2003). More aggressive species of bark beetles are also likely to profit from the changing climatic conditions in the Boreal zone. The European spruce bark beetle, *Ips typographus* has been benefitting by storm events and warm and dry summers in recent years (Worrel, 1983; Okland and Bjornstad, 2003; Wermelinger, 2004). Mild winters and summer temperatures that speed up development may cause a switch from solely univoltine populations to populations that are able to produce more than one generation per year (Wermelinger and Seifert, 1999; Schlyter *et al.*, 2006). Consequently, the risk of (vast) bark beetle outbreaks will rise due to increased population densities and the northward extension of spruce forest prone to attack.

The **pathogenic fungus** *Gremmeniella abietina* is the most common fungal disease in South Finland. Extensive infection by the pathogen (large tree type) has also been reported for plantations of introduced *Pinus contorta* in high elevation areas of northern Sweden (Karlman 2001) and recently also for stands of *P. sylvestris* (Bernhold, 2008). Epidemics are usually initiated by cold and rainy growing seasons and often concentrated on sites of high humidity and cold air (Nevalainen, 1999, 2002). While warm summers with temperatures above the average might slow down the spread of the disease, mild winters combined with summers of high precipitation probably will increase the risk of *G. abietina* outbreaks in northern Sweden (Bernhold, 2008).

Longer growing seasons associated with higher temperatures may increase the incidence of decay in Norway spruce caused by *Heterobasidion parviporum* and *H. annosum*. The border of the “high risk area” regarding root and butt rott is likely going to shift to higher elevations and latitudes of Fennoscandia (Thor *et al.*, 2005; Mattila and Nuutinen, 2007).

- ***Potential impacts on forests products and services***

  - *Wood production*

Gradual increase in temperature and precipitation with a concurrent elevation in $CO_2$ will enhance tree growth and timber yield. Recent regional studies of Garcia-Gonzalo *et al.* (2007b) projected for a forest unit in Central Finland an increase in stand growth by 22–26 % - depending on the climate scenario-, resulting in an increase of 12–13 % in timber yield (8-22 % in Scots pine, 9 % in Norway spruce and 16-18 % in silver birch). Differences between scenarios are due to the water stress caused to the trees, in such a way that scenarios predicting higher increase in temperature and shorter increase in precipitation predict smaller enhancement in productivity.

Briceño-Elizondo *et al.*, (2006) simulated growth in southern and northern Finland and concluded that climate change increased the growth of Scots pine up to 28 % in the south and up to 54 % in the north, whereas the increase for Norway spruce was up to 24 % in the south and 40 % in the north. The response of silver birch was smaller than that of conifers; i.e. growth increased by 21 % in the south and 34 % in the north. The enhanced growth implied an increase in the timber yield regardless of tree species and site. The increase for Scots pine was up to 26 % in the south and 50 % in the north. For Norway spruce, the increase was somewhat smaller, up to 23 % in the south and up to 40 % in the north. For silver birch, the increase was the smallest, up to 20 % in the south and up to 33 % in the north.

Another study for Nordic countries concluded with elevated temperature increased net primary production (NPP) by ca. 5–27 % for coniferous stands, being less for a Scots pine stand growing in a maritime climate like in Norway compared with a continental climate in central Sweden and eastern Finland (Bergh *et al.*, 2003). The increase in NPP could largely be ascribed to the earlier start of the growing season and more rapid recovery of the winter-damaged photosynthetic apparatus, but temperature-driven increases in respiration reduced carbon gain. Simulation results for Scots pine for the three different sites in Finland, Norway and central Sweden, indicate that the response of elevated temperature is less in a milder maritime climate (5–14 % in Norway), where the current mean temperature rises more in February–March than in the colder continental (13–27 % in Finland and central Sweden) (Bergh *et al.*, 2003).

The enhancement will be higher in the north than in the south because growth is more limited in northern latitudes and the positive effect of temperature in the south could be somehow counteracted by limitation of water availability for the trees.

- *Non-wood forest products*

Kauserud *et al.* (2008) reported that over the period from 1940–2006, mushroom fruiting has changed considerably in Norway. The recent autumnal changes in mushroom phenology coincide with the extension of the growing season caused by global climate change and are likely to continue under climate change, with an average delay in fruiting since 1980 of 12.9 days. The changes differ strongly between species and groups of species. Early-fruiting species have experienced a stronger delay than late fruiters, resulting in a more compressed fruiting season. Impacts of climate change on berry-producing vegetation were studied in northern Sweden. Extreme winter warming and increased summer precipitation reduced flowering and berry production in *Vaccinium* species (Phoenix *et al.*, 2001; Bokhorst *et al.*, 2008). However, the relationships between yield of berries and climate variables are not fully understood (Wallenius, 1999). Knowledge gaps remain regarding the quantitative effects of climate change on the production of different non-wood forest products.

- *Carbon sequestration*

The forest carbon balance will be strongly determined by forest management, as most of the additionally sequestered carbon will be removed in intensively managed forest systems. Compared to current climatic conditions, Garcia-Gonzalo *et al.* (2007a) simulated around 1% higher total carbon (C) stock in the forest ecosystem, but the mean increase in total C in timber yield was up to 12 %. However, for some of the scenarios with the highest increases in temperature the studies project a decrease in total C stocks especially due to C release from the soil. A similar pattern in total C sequestration was described by Karjalainen *et al.* (1999), who concluded that a moderate increase in temperature seems to enhance C sequestration in forests, while a more pronounced temperature increase could make forests turn from C sinks into C sources. Mäkipää *et al.* (1999) also found that C in soil could decrease by about 30 % due to the acceleration of soil respiration. Carbon would be lost from the forest floor if only temperature increases and this loss would increase from south to north (Kurz-Besson *et al.*, 2006). In addition to climate effects, the feedback between carbon (C) and nitrogen (N) turnover plays an important role that needs to be more clearly understood to improve estimates of C sequestration in boreal forest ecosystems (Svensson *et al.*, 2008).

- *Biodiversity*

Thuiller *et al.* (2006) have modelled changes of tree species distributions under climate change. They found that broadleaved deciduous trees may expand their potential distribution ranges into the boreal forests. This could increase the tree species diversity and functional diversity. Earlier studies suggested that the range of *P. abies* and *P. sylvestris* may retreat from the south and west (Sykes and Prentice, 1996), but these results should be questioned because of the weak understanding of species replacement at the southern limits of distribution ranges (Lindner *et al.*, 2002a).

Woody boreal vegetation is expected to spread into tundra at higher latitudes and higher elevations (Grace *et al.*, 2002; Kaplan *et al.*, 2003; Gerber *et al.*, 2004). Consequently, species adapted to open conditions without tree cover will have to migrate north and/or to higher elevations. As natural migration rates differ between species, new species compositions may develop and some species may loose their ecological niches (Solomon, 1997; Aitken *et al.*, 2008) and som Artic animal and plant specialists could face extinction (Callaghan *et al.*, 2004).

- *Recreation*

Nature-based tourism is especially vulnerable to climate change and also outdoor recreation is directly affected by changes in climate (Saarinen and Tervo, 2006). In southern Finland, opportunities for snow-related activities are expected to decline, whereas northern Finland could have a competitive advantage compared to winter tourism destinations in central Europe. Summer tourism will be affected by increasing precipitation and extreme events. Tourism entrepreneurs have already experience in struggling with climatic variability and extreme weather events and were confident that they would also be able to handle further gradual changes in climate (Saarinen and Tervo, 2006). Responses received in the second part of this chapter suggest that recreational values of forests will further be affected by climate change as spruce forests will grow denser and become darker (cf. chapter 9.3).

### 4.2.2 Temperate Oceanic

- ***Summary exposure***

The Temperate Oceanic zone includes Belgium, Czech Republic, Denmark, France, Germany, Ireland, Luxembourg, the Netherlands and United Kingdom (Fig. 8). Annual mean temperature increases will be 2.5-3.5°C, except for the UK and Ireland with 2-3°C. Summers are likely to be dryer and hotter (up to 4°C increase). Extreme events such as violent storms and floods are projected to become more frequent due to warmer temperatures and higher volumes and intensities of precipitation, in particular in winter (Fuhrer *et al.*, 2006).

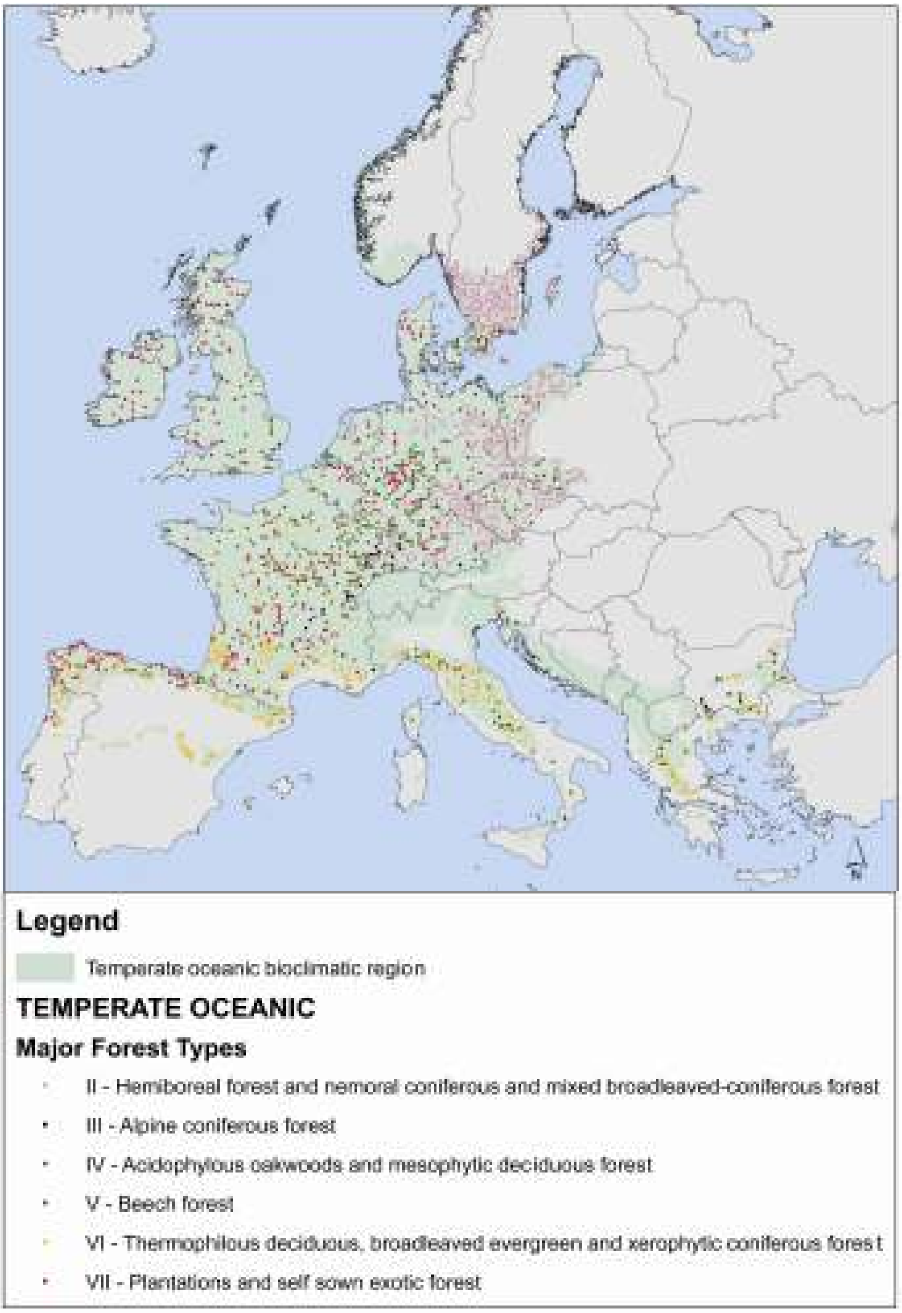


**Figure 8.** Temperate Oceanic bioclimatic zone and its major forest types in EU27 Member States.

- ***Key impact factors***

In the Temperate Oceanic zone production is higher than in the Boreal zone caused by higher air temperature. Temperature is predicted to increase and this will have a positive impact in northern and western parts (i.e. less water limited) and a negative impact on southern and eastern parts (i.e water limited). The potential lack of summer precipitation with consequent droughts is the main constraint factor of forest growth and productivity in the southern parts of the Temperate Oceanic zone (Maracchi *et al.*, 2005).

Diversity of pest and pathogen species in the Temperate Oceanic zone is high and the expected changes in temperature and precipitation may further increase biotic disturbances. Tables 9 and 10 show the pest and pathogen species relevant for the Temperate Oceanic zone in the context of climate change. Abiotic disturbances (fire and wind damages) are also expected to cause losses in forest productivity.

**Table 9.** Pest species relevant in the context of climate change in the Temperate Oceanic zone. See Table 2 for the forest types.

| Latin name | English name | Relevant impact factors | Major forest type | Affected tree species | Expected effect on species (+/-) |
|---|---|---|---|---|---|
| *Agrilus biguttatus* | Oak splendour beetle | temperature increase, drought | IV | *Quercus robur, Q.petraea* | + |
| *Cephalcia arvensis* | Web-spinning sawfly | temperature increase, drought | II, VII | *Picea abies* | + |
| *Dendroctonus micans* | Great spruce bark beetle | temperature increase, drought | II, III, VII | *Picea abies* | + |
| *Elatobium abietinum* | Green spruce aphid | temperature increase | VII | *Picea sitchensis, P.abies, P.pungens, Abies alba* | + |
| *Ips acuminatus* | Pine engraver beetle | temperature increase, increase of storm events, drought | II, III, VII | *Pinus sylvestris* | + |
| *Ips sexdentatus* | Pine stenographer beetle | | II, VII | *Pinus sylvestris, P. pinaster* | + |
| *Ips typographus* | European spruce bark beetle | | II, III, VII | *Picea abies* | + |
| *Lymantria dispar* | Gypsy moth | temperature increase | II, III, IV, V, VI | *Quercus, Carpinus, Fagus, Betula, Populus, Prunus, Salix, Ulmus, Larix, Picea, et al.* | + |
| *Lymantria monacha* | Nun moth | temperature increase | II, III, IV, V | *Quercus, Carpinus, Salix, Tilia, Fagus , Picea, Pinus, Larix et al.* | + |
| *Operophtera brumata* | Winter moth | temperature increase, drought, increase of atmospheric $CO_2$ | IV | *Quercus robur, Q.petraea* | +/(-) |
| *Pityogenes chalcographus* | Small spruce bark beetle | temperature increase, increase of storm events, drought | II, VII | *Picea abies* | + |
| *Pityokteines curvidens* | Bark beetle (Abies) | temperature increase | II, III | *Abies alba* | + |
| *Thaumetopoea pityocampa* | Pine processionary moth | temperature increase (winter) | II, III, VII | *Pinus spp., Cedrus spp., Pseudotsuga menziesii* | + |
| *Thaumetopoea processionea* | Oak processionary moth | temperature increase | IV | *Quercus spp.* | + |
| *Tomicus piniperda* | Common pine shoot beetle | temperature increase, increase of storm events, drought | II | *Pinus sylvestris* | + |
| *Tortrix viridana* | Green oak leaf roller moth | temperature increase, drought, increase of atmospheric CO2 | IV, VI | *Quercus spp.* | +/(-) |

**Table 10.** Pathogen species relevant in the context of climate change in the Temperate Oceanic zone. See Table 2 for the forest types.

| Latin name | English name | Relevant impact factors | Major forest type | Affected tree species | Expected effect on species (+/-) |
|---|---|---|---|---|---|
| *Armillaria spp.* | Root disease | drought | II | *Conifers* | + |
| *Biscogniauxia mediterranea (Hypoxylon mediterraneum)* | Charcoal disease (canker) | temperature increase | VI | *Quercus spp.* | + |
| *Collybia fusipes* | Root rot (Quercus) | temperature increase, drought | IV, VI | *Quercus robur, Q. rubra* | + |
| *Cryphonectria parasitica* | Chestnut blight | temperature increase (summer), drought | VI | *Castanea sativa* | + |
| *Diplodia pinea (Sphaeropsis sapinea)* | Collar rot (shoot blight) | drought | II, VII | *Pinus spp.* | + |
| *Dothistroma septosporum (Mycosphaerella pini)* | Dothistroma needle blight (red-band disease) | changes in precipitation | II | *Pinus spp.* | +/- |
| *Gremmeniella abietina* | Scleroderris cancer | changes in temperature and precipitation | III | *Pinus sylvestris* | - |
| *Heterobasidion spp.* | Root and butt rot | temperature increase | II, VII | *Picea abies* | + |
| *Melampsora pinitorqua* | pine-twisting rust | temperature increase, drought | II, VII | *Pinus sylvestris, P.pinaster* | - |
| *Melampsora spp.* | Rusts on poplars | temperature increase, drought | VII | *Populus spp.* | + |
| *Phytophthora cinnamomi* | Root pathogen (oak decline) | temperature increase, drought | VI, VII | *Castanea sativa, Quercus spp.* | + |

- ***Sensitivity***

**Temperature** increase may have strong impacts on forest productivity and the competitive relationships between different tree species (Lasch *et al.*, 2002b). The impacts of climate warming on forest growth are mainly negative in the Northeast of Germany, because changes in the water balance will lead to increased drought stress. Other simulation studies with a variety of climate change scenarios have indicated that positive growth responses could also occur in temperate forests if increasing precipitation balances the increased evaporative demand under elevated temperatures (Bugmann, 1997; Lindner *et al.*, 1997).

In large areas of western and central Europe, temperature increase supports the replacement of natural conifers with more competitive deciduous trees (Maracchi *et al.*, 2005; Koca *et al.*, 2006). Several studies showed that for example in Switzerland *Picea abies* may be replaced by *Fagus sylvatica* (e.g. Kräuchi, 1995; Bugmann, 1997). Thuiller *et al.* (2006) predicted in the atlantic areas a reduction in the numbers of species and occasional predicted gains in functional diversity. This resulted from a loss in species within the broadleaved deciduous (functional types), but overall maintenance of the group. Bonn (2000) found oaks to be less sensitive to water stress than European beech and **stand composition** likely to change if the number of years with water stress increases.

The most important effects of climate change on temperate forests will probably be mediated through changes in disturbance regimes such as storms, insects and pathogens. Hence, it is useful to consider how climate change will affect these disturbances. Windthrow and storm damage are already relevant in central Europe (Thürig *et al.*, 2005; Schutz *et al.*, 2006).

The projected rise of temperature in the Temperate Oceanic zone will implicate accelerated development and lowered mortality rates for various **pest species**, allowing for mass propagation more frequently, e.g. of forest defoliators. The already significant defoliation of spruce forests in the UK by *Elatobium abietinum* will probably be aggravated because of an earlier starting and prolonged flight period of the green spruce aphid, as a consequence of rising temperatures during autumn and winter (Westgarth-Smith *et al.*, 2007). High temperatures, especially during the summer months combined with a lack of precipitation promoted outbreaks of the web-spinning sawfly, *Cephalcia arvensis*, in the Venetian Pre-Alps already in the 1980's (Marchisio *et al.*, 1994). In general, species that spend parts of their life cycle as nymphs in the ground (e.g. the little spruce sawfly, *Pristiphora abietina,* or the winter moth, *Operophtera brumata*) will benefit from reduced precipitation, as mortality rates will decrease (Netherer and Führer, 1999; Rouault *et al.*, 2006). Population densities of the winter moth and the leaf roller moth, *Tortrix viridana*, have been increasing in France, Switzerland, the Czech Republic and southeastern Sweden, favoured by the warm spring periods of the recent years (Rouault *et al.*, 2006). However, there are also authors who consider a future decreased reproductive capacity of these moth species possible (Dury *et al.*, 1998), as oak leaf digestibility for feeding larvae might be reduced due to a combined increase of atmosperic $CO_2$ and temperature. Together with *O. brumata*, *T. viridana* and *Lymantria dispar*, the borer, *Agrilus biguttatus* is associated with oak decline in northern Germany (Thomas *et al.*, 2002). Extended dry and warm periods and a long-term increase in temperature will probably result in higher frequency and intensity of attacks by this secondary pest, serious in oak forests weakened by diverse biotic or abiotic stress factors. Severe attack, on the other hand, renders trees even more susceptible to drought stress.

Prolonged and warmer vegetation periods will enhance especially the development of several species of bark beetles, allowing the establishment of additional generations and multiplying population densities. Simulations by Jönsson *et al.* (2007) indicated that a second generation of *Ips typographus*, which is commonly univoltine in southern Sweden, will be costumary for this region already at an annual mean temperature increase of 2-3°C. The hot summer of 2003 promoted the mass propagation of the silver fir bark beetle, *Pityokteines curvidens* for the first time in 40 years in Switzerland, and outbreaks of this species have also been recorded for northeastern France (Rouault *et al.*, 2006). The predisposition of European spruce forests to infestations by *I. typographus* and *Pityogenes chalcographus* and of pine forests to *Tomicus piniperda*, *Ips sexdentatus* and *Ips acuminatus* is already high and will still be increasing with more frequent storm damage (Göthlin and Schroeder, 2000; Nageleisen, 2001; Okland and Bjornstad, 2003; Wermelinger, 2004; Jönsson *et al.*, 2007) and the incidence of drought periods (Worrel, 1983; Netherer and Nopp-Mayr, 2005; Rouault *et al.*, 2006). Drought in winter, spring and summer combined with high spring and summer temperatures can also be associated with a higher susceptibility of spruce plantations to the great spruce bark beetle, *Dendroctonus micans* (Rolland and Lemperière, 2004). The scolytid has recently been expanding to southern and north-western France.

Range expansion and range shifts due to changing climatic conditions are to be expected for *L. dispar* and *Lymantria monacha*. The distribution of the gypsy and the nun moth may in future overlap to a larger extent (Karolewski *et al.*, 2007), as the latter already occurs in a more northerly range due to lower tolerance of high temperature and the first will probably expand its range towards the north (Vanhanen *et al.*, 2007). Both, altitudinal and latitudinal (e.g. in the Paris Basin) range shifts have been observed for the pine processionary moth, *Thaumetopoea pityocampa*, in context with rising winter temperatures, the distribution of the host trees and female dispersal capability (Battisti *et al.*, 2005; Rouault *et al.*, 2006; Buffo *et al.*, 2007; Robinet *et al.*, 2007). Since the processionary moth larvae have urticating hair, further population increase and range expansion, which has also been reported for *Thaumetopoea processionaea* in northeastern France (Rouault *et al.*, 2006), may put at risk the future recreational value of affected pine and oak forests.

Due to temperature increase associated with drought, the southern parts of the temperate oceanic forests will have to cope with the expansion of highly termophilic, Mediterranean **pathogen species**, such as the charcoal disease, *Biscogniauxia mediterranea* or the chestnut blight. The northwards shift of the latter, introduced species will further be supported by climate change, as climatic conditions of the most northern parts of the distribution areas is yet less suitable for canker development. The high potential development of fungal diseases present in a latent form in wide areas (e.g. *B. mediterranea*, *Diplodia pinea*) will likely be revealed by the decrease in precipitation, as endophytes may turn to pathogens in drought-stressed trees (Desprez-Loustau *et al.*, 2007). Drought is also a main trigger of infections by root diseases, such as *Armillaria spp.* on conifers (Wargo and Harrington, 1991) and *Collybia fusipes*, a fungus that is reported to locally play a significant role in the complex of oak decline, e.g. in Northeastern France (Thomas *et al.*, 2002; Camy *et al.*, 2003). The relationship between drought, fungus attack, and tree decline and death has also been found for the soil pathogen *Phytophthora cinnamomi* in wide parts of the Mediterranean area, Switzerland, United Kingdom, Slovakia and Romania. The disease will be promoted by an increase in summer temperature; however, in the northern parts of the Temperate Oceanic zone (e.g. north-western Germany) winter survival will still remain limited by low temperatures (Wargo, 1996; Thomas *et al.*, 2002; Desprez-Loustau *et al.*, 2007). Winter temperatures will rise high enough to promote the range expansion of fungal pathogens causing poplar rust. Rising summer temperatures will be beneficial for another subspecies of *Melampsora* and the root rot *Heterobasidion annosum* (Thor *et al.*, 2005; Desprez-Loustau *et al.*, 2007).

Climate change is also assumed to result in a decrease in climatic suitability for the development of certain fungal species throughout the Temperate Oceanic zone. Desprez-Loustau *et al.* (2007) predict an important regression of the potential range of the pine-twisting rust, *Melampsora pinitorqua*. The pathogen, better adapted to a cool and humid subboreal climate, will probably disappear in nearly all southern parts of France. Depending on the changes in precipitation, outbreaks of the *Dothistroma* needle blight on pines might either be intensified in case of moist spring or summer periods or decrease given precipitation deficits (Desprez-Loustau *et al.*, 2007; Kirisits and Cech, 2007).

- ***Potential impacts on forests products and services***

  - *Wood production*

Most of the region is projected to benefit from increased growth rates under average climate conditions and thus also wood production tends to increase. Negative impacts may occur especially in the Southern and Eastern parts of the region where climate has a noticeable Mediterranean or continental influence. Potentially devastating negative impacts may occur due to extreme climatic events and enhanced disturbances (both biotic and abiotic). However, these events cannot yet be forecasted and it is impossible to quantify likely impacts. But the share of unscheduled fellings and salvage cuts after stand replacing disturbances is likely to increase.

In Germany Lasch *et al.* (2002a) presented a study where productivity of the four main species in Germany under climate change was studied. They used two different climate change scenarios (ECHAM4 and HadCM2); the difference between the scenarios was the simulated increase in precipitation, being higher in HadCM2 scenario. For the HadCM2 scenario they predicted an increase of around 7% for Norway spruce and Scots pine, smaller increase for beech (2%) and even a decrease in oak production (7%). Whereas with the drier scenario they predicted a decrease in production for all the species (Norway spruce -4%, pine -7%, oak -12% and beech -16%).

In northern France, forest productivity is expected to be enhanced by climate change, increasingly from west to east, whereas in the southwestern Atlantic region, productivity will be reduced by climate change to an increasing degree from west to east (Loustau *et al.*, 2005).

- *Non-wood forest products*

Gange *et al.* (2007) analysed autumnal fruiting patterns of macrofungi over 56 years and found that average first fruiting date of 315 species was advanced, while last fruiting date was delayed. Fruiting of mycorrhizal species that associate with both deciduous and coniferous trees was delayed in deciduous, but not in coniferous, forests. Resent research activities in United Kingdom have stimulated renewed interest in common walnut (*Juglans regia* ) and some other species. Common walnut can be used for timber production and highly marketable fruit crop. These walnut species are likely to be more suitable than many native tree speices to the climatic conditions predicted for the UK within a single generation (Hemery and Russell, 2006).However, there is a gap of knowledge about impacts of climate change on productivity of mushrooms and other non-wood forest products in this region.

- *Carbon sequestration*

Most of the Temperate Oceanic region is benefiting from increased tree growth and productivity and consequently carbon sequestration rates are increasing as well. For example, in Belgium the biomass organic carbon (C) increased in coniferous forests as well as in broadleaf and mixed forests between years 1984 and 2000 (Lettens *et al.*, 2008). In coniferous forest in Germany environmental changes induced also increase in biomass C accumulation for all age classes during years 1982-2001 (Vetter *et al.*, 2005). Central European forests have a significant potential to sequester atmospheric carbon and nitrogen not only in stand biomass, but also in the soil (Prietzel *et al.*, 2006). However, there are many factors which have impact on carbon sequestration and these factors should be taken account as well as possible when C sequestration is estimated. For example, European deciduous tree species differ in C and N sequestration rates within forest floor and mineral soil (Vesterdal *et al.*, 2008) and distribution of carbon over the different ecosystem compartments are related to species composition and site characteristics (Vande Walle *et al.*, 2001; Bert and Danjon, 2006). In addition, reduction of rainfall or changes in rainfall distribution due to climate change will affect soil $CO_2$ emissions and possibly C storage in temperate forest ecosystem (Borken *et al.*, 1999). Impacts on carbon sequestration are strongly affected by management interactions. Knohl *et al.* (2003) found unmanaged deciduous forest at a comparatively late stage of successional development can still act as significant carbon sinks. However, the carbon balance may be negatively impacted by more frequent disturbances.

- *Biodiversity*

Projected impacts on biodiversity are very sensitive to the model assumptions. Most existing studies rely on environmental envelop approaches which suggest that there will be a shift in the natural species composition from coniferous dominated forests towards broadleaved species. It is still less understood how fast growing species will retrieve from areas that are no longer matching their natural ecological niche. As the majority of European forests are intensively managed, management effects will strongly influence the transition by either maintaining economically important species outside their natural range (cf. Norway spruce example) or by supporting the regeneration of new target species. Changes in tree species composition will be followed by changes in flora and fauna. The likely increase in disturbance frequency and intensity will benefit species that are adapted to disturbed and open forest ecosystems, whereas species depending on mature and closed forests may be negatively affected. For example, the frequency and intensity of wild and prescribed fires can have significant effects on biodiversity and ecosystem function (Davies *et al.*, 2008). Different species groups might respond differently to changing conditions. As a result of climate change, epiphytic species appear to be increasing, but in contrast, many terricolus species are declining (Aptroot and van Herk, 2007). In the Netherlands, thermophilic plant species have become more common compared with 30 years ago, and cold-tolerant species have declined (Reid, 2006).

### 4.2.3 Temperate Continental

- ***Summary exposure***

The Temperate Continental region includes Austria, Bulgaria, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia and Slovenia (Fig. 9) The annual mean temperature increase is projected to be in the order of 3-4°C except for the more Continental regions of Central Europe and the Black Sea Region, like Romania, where temperatures could increase by 4-4.5°C. Annual mean precipitation is expected to increase by up to 10% mainly in winter, while there would be reductions in summer precipitation in several areas (up to -10%).

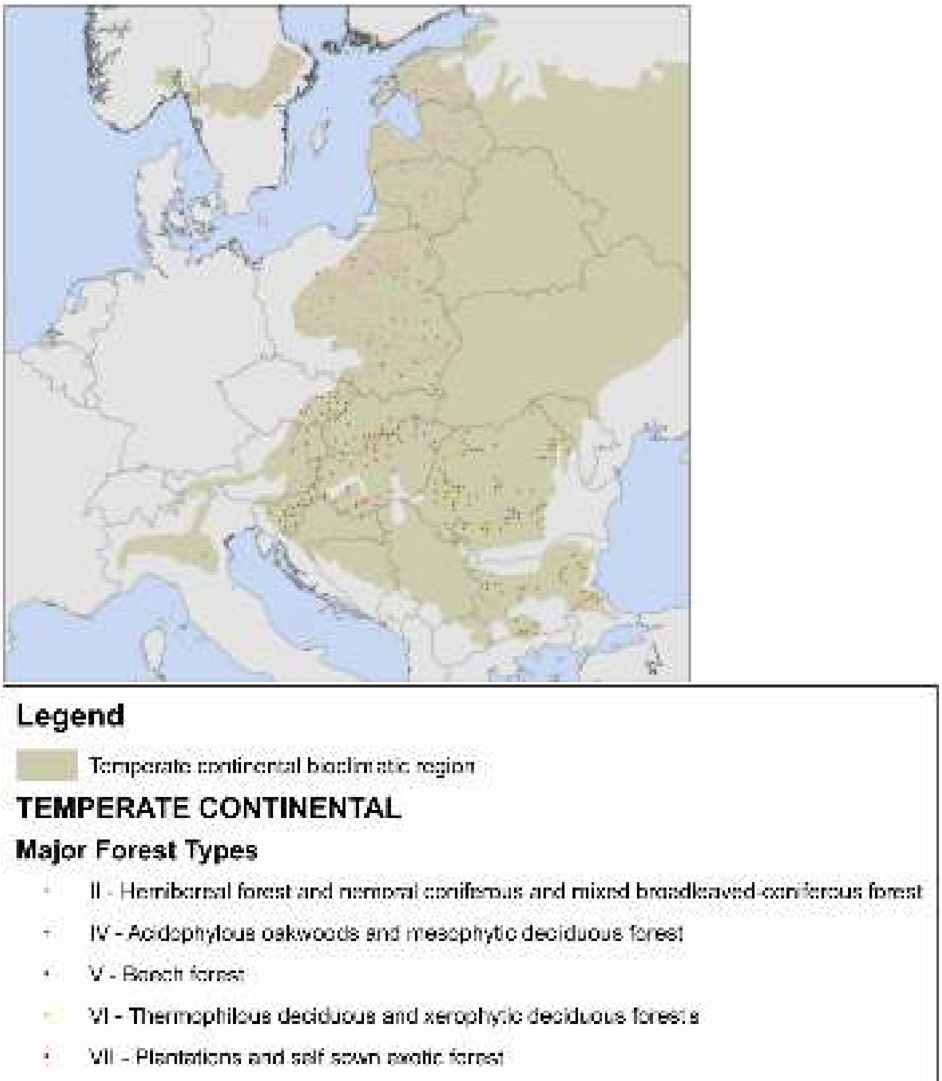


**Figure 9.** Temperate Continental bioclimatic zone and its major forest types in EU27 Member States.

- ***Key impact factors***

In the continental forests the potential lack of summer precipitation with consequent droughts is the main constraint factor of forest growth and productivity (Maracchi *et al.*, 2005). Temperature increase and changes in precipitation are the main factors predisposing forests to various insect pests and fungal diseases. Tables 11 and 12 show the pest and pathogen species relevant for the Temperate Continental zone in the context of climate change.

**Table 11.** Pest species relevant in the context of climate change in the Temperate Continental zone. See Table 2 for the forest types.

| Latin name | English name | Relevant impact factors | Major forest type | Affected tree species | Expected effect on species (+/-) |
|---|---|---|---|---|---|
| *Ips typographus* | European spruce bark beetle | temperature increase, increase of storm events, drought | II, III, VII | *Picea abies* | + |
| *Lymantria dispar* | Gypsy moth | temperature increase, drought | II, III, IV, V, VI | *Quercus, Carpinus, Fagus, Betula, Populus, Prunus, Salix, Ulmus, Larix, Picea, et al.* | + |
| *Lymantria monacha* | Nun moth | temperature increase | II, III, IV, V | *Quercus, Carpinus, Salix, Tilia, Fagus , Picea, Pinus, Larix et al.* | +/(-) |
| *Pityogenes chalcographus* | Small spruce bark beetle | temperature increase, increase of storm events, drought | II, III, VII | *Picea abies* | + |
| *Tortrix viridana* | Green oak leaf roller moth | drought | IV, VI | *Quercus spp.* | + |

**Table 12.** Pathogen species relevant in the context of climate change in the Temperate Continental zone. See Table 2 for the forest types.

| Latin name | English name | Relevant impact factors | Major forest type | Affected tree species | Expected effect on species (+/-) |
|---|---|---|---|---|---|
| *Armillaria spp.* | Root disease | drought | II | *Conifers* | + |
| *Heterobasidion annosum* | Root and butt rot | temperature increase, changes in precipitation | II, VII | *Picea abies* | +/- |
| *Dothistroma septosporum (Mycosphaerella pini)* | Dothistroma needle blight (red-band disease) | changes in precipitation | II | *Pinus spp.* | +/- |
| *Phytophthora spp.* | Root pathogen (oak decline) | drought | VI, VII | *Quercus spp.* | + |

- ***Sensitivity***

In general, in the Temperate Continental zone production is more constrained by water than in the Temperate Oceanic zone.

By the end of the century (2071 to 2100) in continental and central Europe, **net primary production** (NPP) of conifers is likely to decrease due to water limitations (Lexer *et al.*, 2002; Martínez-Vilalta and Piñol, 2004; Körner *et al.*, 2005). This is because the demand of water increases with elevated temperatures and increased evapo-transpiration. The demand of water during the growing season is normally larger than the amount of rainfall. This indicates that if temperature increase is not coinciding with increased rainfall, water could limit growth to larger extent than today. Therefore, production decreases at sites vulnerable to water stress and increases at sites where the increased evaporative demand under the elevated temperature is balanced by an increase in precipitation.

The effect of climate change on **individual species** can be either positive or negative, depending on the site conditions and regional climate changes. Responses simulated with different models vary considerably, which is adding considerable uncertainty (Kellomäki and Leinonen, 2005). *F. sylvatica* is projected to face severe problems when temperatures increase (Geßler *et al.*, 2007): Bonn (2000) found oaks to be less sensitive to water stress than European beech and stand composition likely to change if the number of years with water stress increases.

In temperate forests, milder winters may reduce winter hardening in trees, increasing their vulnerability to **frost** (Hänninen, 1991, 2006).Fire danger is likely to also increase (Moriondo *et al.*, 2006). This, however, does not translate directly into increased fire occurrence or changes in vegetation (Thonicke and Cramer, 2006).

The projected increase of summer temperature will especially be beneficial for **outbreaks** of *Lymantria dispar* in the Temperate Continental zone (Karolewski *et al.*, 2007). While the nun moth, *Lymantria monacha*, is likely to suffer from heat stress by climate warming beyond 3.6°C, even a high increase in average temperature (up to 5.8°C) will have positive effects for the gypsy moth (Vanhanen *et al.*, 2007). Hlásny and Turcány (in press) found indications for altitudinal shifts of gypsy moth outbreaks in Slovakia in warm years, and expect a doubling of outbreak areas by 2015 compared to the period 1951-1980. An increase in areas of defoliated oak forest will also raise the probability of attack by secondary pathogens and pest insects (Pernek *et al.*, 2008). In Austria, defoliation by gypsy moth is mentioned by Balci and Halmschlager (2003) as one of the factors involved in the "complex disease" oak decline, together with other insect pests (*Agrilus spp., Scolytus spp., Tortrix viridana*) and drought stress of the trees. Climate change may however induce a shift from the main host species *Quercus spp.* to alternative tree species, such as *Fagus sylvatica* in Slovakia, in case *Quercus cerris* is limited in the expansion areas (Hlásny and Turcány, in press). A host switch of the polyphagous insect may also be influenced by elevated levels of $CO_2$ in the atmosphere. Hättenschwiler and Schafellner (2004) observed that changing leaf chemistry affected larvae feeding on oaks negatively, but those feeding on hornbeam were affected positively.

Wherever forests are dominated by *Picea abies*, outbreaks of the spruce bark beetles *Ips typographus* and *Pityogenes chalcographus* will be brought forward by disturbing events, such as wind throw or extreme weather conditions (Wermelinger, 2004). Generally, areas providing suitable climatic conditions for the termination of more than one bark beetle generation will increase with rising average temperatures. For Slovakia, Hlásny and Turcány (in press) prognose a doubling of areas where *I. typographus* can fully develop a second generation by 2075 and expect the possibility of a completed third generation in certain regions of the country by 2045.

Reductions in summer precipitation resulting in drought-stress of forests will predispose host trees to root diseases such as *Armillaria spp.* (Wargo and Harrington, 1991). Tree dieback due to the honey fungus is also reported in association with oak decline, together with an assortment of **fungal pathogens** (e.g. *Phytophthora quercina*), during periods of soil water deficits and climatic conditions unfavourable for tree vitality (Balci and Halmschlager, 2003). High temperatures and xeric conditions seem to favour the incidence of decay by *Heterobasidion spp*., however, the risk of infection by the root rot is reported to be very low under extremely dry climatic conditions (Woodward *et al.*, 1998).

Given an increase of precipitation in spring, the future risk of severe outbreaks of fungal pathogens best sporulating and germinating during warm and moist periods might be high. For instance, extended periods of precipitation combined with intermediate temperature (15°-20°C) are optimal for infections of pines by *Dothistroma* needle blight (Woods *et al.*, 2005).

Recent outbreaks in Austria (and throughout Europe) could potentially be linked with climate change (Kirisits and Cech, 2007).

- ***Potential impacts on forests products and services***

  - *Wood production*

Few studies are available for the continental region as defined in this review. However, results from a continental region in the north-eastern German lowlands suggested that wood production could decline in the order of 10% (Lasch *et al.*, 2002a). In addition, results from Austria suggest that beyond a temperature increase of approximately 1 $^{o}$C (with no changes in precipitation) impacts may become widespread and severe (Lexer *et al.*, 2002). The study also suggests that at low-elevation sites *Picea abies* would become unsuitable as a crop species.

  - *Non-wood forest products*

Only one example of impacts of climate change on non-wood forest products was found. In Slovenia, olive trees are at their northern climatic limit, such that they are periodically endangered by severe frosts. The average recurrent period of frosts has increased from 18$^{th}$ century to current situation. Expansion beyond the borders of the traditional area of the species, however, could be questionable despite a predicted climatic warming, since the same prognoses also forecast a greater possibility of weather disasters and extremes, including frosts (Ogrin, 2007).

  - *Carbon sequestration*

Forests in Temperate Continental zone may respond to predicted climate change with increased carbon sequestration, especially in the northern parts of the region. In the short term, however, it was argued that these forests may be a source rather than a sink for atmospheric carbon as the relative distribution of carbon among ecosystem components adjusts in response to changing climate conditions (Vucetich *et al.*, 2000; Reed and Nagel, 2003). There are many differences how different kinds of forests capture carbon. For example, according to a simulation study, slowly growing oak forests in Central Europe captured more carbon than the more vividly growing spruce and pine forests due to larger soil carbon sequestration (Pérez *et al.*, 2007). Disturbances might reduce and proper management might increase carbon sequestration under climate change (Seidl *et al.*, 2008a; Seidl *et al.*, 2008b).

  - *Biodiversity*

Tree species composition in the temperate forests in Europe has been historically subject to drastic changes. Conifers have been introduced on sites naturally dominated by broadleaved species. There is evidence of disadvantages associated with pure coniferous forest under climate change conditions: the risk of increased mortality under drought conditions, relatively high susceptibility to storm, snow and ice, as well as higher susceptibility to fungi and insects. A shift of tree species composition closer to that determined by the current climatic and edaphic conditions is expected to increase the capacity of forest to adapt to changing climatic conditions (Spiecker, 2003). Species richness tends to decrease during drought periods. The magnitude of responses to warming and drought depends on the difference between sites, years, and species and these multiple plant responses could have consequences at ecosystem and community level in terms of decreasing biodiversity (Peñuelas *et al.*, 2007b).

### 4.2.4 Mediterranean

- ***Summary exposure***

In the Mediterranean area, i.e. Cyprus, Greece, Italy, Malta, Portugal and Spain (Fig. 10), yearly rainfall is expected to drop by up to 20% of current annual precipitation (with up to 50% reduction in summer). However precipitation is expected to increase in winter. This results in higher intensity precipitation events. Annual mean temperature increases throughout southern Europe and the Black Sea region would be in the order of 3-4°C (4-5°C in summer and 2-3°C in winter). Models predict changes in frequency, intensity, and duration of extreme events with more hot days, heat waves, heavy precipitation events, and fewer cold days.


**Figure 10.** Mediterranean bioclimatic zone and its major forest types in EU27 Member States.

- ***Key impact factors***

In the Mediterranean region, rising temperatures and decreasing rainfall will lead to increased occurrence of drought periods. This leads to an increase in the most important abiotic risk in the Mediterranean region, the fire risk. In addition, forest stands will be weakened by the unfavourable environment which will increase biotic risks. In this context, drought will probably be a main factor driving pest outbreaks in the Mediterranean zone. Especially in plantations, water supply already is and will increasingly become in future a key factor of tree survival. Tables 13 and 14 show the pest and pathogen species relevant for the Mediterranean zone in the context of climate change.

**Table 13.**Pest species relevant in the context of climate change in the Mediterranean zone. See Table 2 for the forest types.

| Latin name | English name | Relevant impact factors | Major forest type | Affected tree species | Expected effect on species (+/-) |
|---|---|---|---|---|---|
| *Lymantria dispar* | Gypsy moth | Temperature increase | VI, VII | *Quercus, Carpinus, Fagus, Betula, Populus, Prunus, Salix, Ulmus, Larix, Picea, et al.* | - |
| *Lymantria monacha* | Nun moth | Temperature increase | VI, VII | *Quercus, Carpinus, Salix, Tilia, Fagus , Picea, Pinus, Larix et al.* | - |
| *Matsucoccus feytaudi* | Maritime pine bast scale | | VI | *Pinus pinaster* | + |
| *Phoracantha sp.* | Longicorn borer | Drought | VII | *Eucalyptus spp.* | + |
| *Thaumetopoea pityocampa* | Pine processionary moth | Temperature increase (winter) | VI, VII | *Pinus spp.* | + |

**Table 14.** Pathogen species relevant in the context of climate change in the Mediterranean zone. See Table 2 for the forest types.

| Latin name | English name | Relevant impact factors | Major forest type | Affected tree species | Expected effect on species (+/-) |
|---|---|---|---|---|---|
| *Armillaria spp.* | Root disease | drought | VI | *Pinus, Picea, Abies, Quercus* | + |
| *Biscogniauxia mediterranea (Hypoxylon mediterraneum)* | Charcoal disease (canker) | temperature increase, drought | VI | *Quercus spp.* | + |
| *Ophiostoma ulmi* | Dutch elm disease | temperature increase, drought | VI | *Ulmus spp.* | + |
| *Cryphonectria parasitica* | Chestnut blight | temperature increase (summer), drought | VI | *Castanea sativa* | + |
| *Diplodia pinea (Sphaeropsis sapinea)* | Collar rot (shoot blight) | temperature increase, drought, nitrogen | VII | *Pinus nigra, P.sylvestris, P.halepensis, P.pinaster, P.pinea* | + |
| *Heterobasidion abietinum* | root and butt rott | summer drought | VI | *Abies alba* | + |
| *Melampsora spp.* | Rusts on poplars | temperature increase, drought | VII | *Populus spp.* | + |
| *Phytophthora cinnamomi* | Root pathogen (oak and chestnut decline) | temperature increase, changes in precipitation | VI | *Quercus ilex, Q. suber, Castanea* | + |

- ***Sensitivity***

Rising **temperatures** with stable or decreasing precipitation increases drought stress (Granier *et al.*, 2007). During the drought year 2003 ecosystem production decreased with increasing water stress at all investigated sites. Even drought-adapted ecosystems are influenced by drought, as shown for coniferous (Goldstein *et al.*, 2000) and evergreen species (Reichstein *et al.*, 2002; Rambal *et al.*, 2003). Other studies show that *Quercus ilex* and *Pinus* species spent more carbon in maintaining and producing leaves to replace those lost in more rapid turnover. Such a replacement of leaves increases growth and maintenance respiration (Sabaté *et al.*, 2002). In general, many authors agree that increased drought is likely to lead to reduced plant growth and primary productivity (Ogaya *et al.*, 2003; Llorens *et al.*, 2004), reduced nutrient turnover and nutrient availability (Sardans and Peñuelas, 2005, 2007; Sardans *et al.*, 2008), and altered plant recruitment (Lloret *et al.*, 2004; Quintana *et al.*, 2004).

Elevated **$CO_2$ increases** water use efficiency of trees (cf. chapter 4.1.1) and this can counteract or offset potential negative effects of changes in climate. However, there is a limit on this effect and growth reductions are predicted for most species if rainfall does not increase (Sabaté *et al.*, 2002).

**Precipitation**, the changes in the pattern of rainfall distribution may have a stronger effect on forest growth than the decreased precipitation because trees are adapted to grow within the constraints of a given climate and water regime (Resco De Dios *et al.*, 2007). Although forest stands show some plasticity, growth and vitality are expected to suffer with changes in timing and duration of water stress.

Dendrochronological records showed that growing season **drought** has a great impact on beech from low hills to mountains (1000-1400 m) in Spain (Piovesan *et al.*, 2005). This is in concordance with the results shown by Peñuelas and Boada (2003) who have documented a **biome shift** in Mediterranean mountains. They compared historical data (inventories and ortophotos) and correlated them with climate data. The climate data showed a temperature increase of 1.4 $^{o}$C and no change in the total precipitation over the last 50 years. They found that heather (*Calluna vulgaris*) and European beech (*Fagus sylvatica*) in the higher elevations were progressively replaced by Holm oak (*Quercus ilex*). The main causes were a reduction of recruitment of beech by 41% and an increase in defoliation (31%). Holm oak shifted upwards replacing beech forest and beech forests shifted upwards becoming confined at medium altitude peaks. Local replacement of beech at medium altitudes of 880 – 1200 m starts with a progressive stand “isolation” due to decreasing beech regeneration. As a result, in Monseny (Catalonia) beech forest has decrease 17% and Holm oak has increased its area ca. 20%. Moreover, other studies show that long-term drought stress has reduced the productivity of beech forests in the central Apennines, in agreement with similar trends identified in other Mediterranean mountains (see Jump *et al.*, 2006), but opposite to growth trends reported for many forests in central Europe (Boisvenue and Running, 2006).

Other field studies indicated serious damages in terms of weakened trees, increased susceptibility to pathogens, increased fire hazard and death of many populations due to drought (Ogaya and Penuelas, 2003; Ogaya *et al.*, 2003). These damages were more serious in hardwood than in softwood species, except for *Quercus coccifera* (Kermes oak) and *Pinus halepensis* (Aleppo pine) where outcomes still appear uncertain. Moreover, drought decreased *Q. ilex* populations. *Erica spp* (Heather) and *Phyllirea latifolia* L (Mock privet), two shrubby plants, less affected by drought, are likely to increase in the *Quercus ilex* habitat with consequent loss of oak cover. Mean stem diameter increment declined when water availability was experimentally reduced by about 15%, with great variation between species (Ogaya *et al.*, 2003). *Arbutus unedo*, with initially faster growth rates than *Quercus ilex* and *Phillyrea latifolia*, experienced the largest growth reduction in the drought plots (77%), suggesting a higher drought sensitivity than *Q. ilex* (55%) and *P. latifolia* (no drought effect). Therefore, a species gradient of growth responses to drought can be established from the most sensitive *Q. ilex* (smaller growth and greater mortality in the drought treatments) to the less sensitive *P. latifolia*. In the drier conditions predicted in the Mediterranean area in the frame of climate change, an important reduction of growth rates can hence be expected, accompanied by a gain of dominance of drought-tolerant species such as *P. latifolia* in detriment of more mesic species such as *Q. ilex* (Ogaya and Penuelas, 2003).

The most important **abiotic disturbance** in the Mediterranean region is fire. **Fire** risk is expected to increase significantly (Mouillot *et al.*, 2002; Mouillot *et al.*, 2003; Moriondo *et al.*, 2006). Total burned area in Spain has increased six-fold between 1960 and 1990 (Prieto, 1993) and fire-return frequency has decreased during the same period (De Luís *et al.*, 2001). Climate warming is thought to have contributed greatly, because daytime temperatures increased and relative moisture decreased, affecting vegetation growth, fuel structure and combustibility (Resco De Dios *et al.*, 2007).

Moriondo *et al*. (2006) studied the effects of climate change on fire risk in the Mediterranean countries using different parameters related to the risk of fire: (i) the length of the season with fire risk, (ii) the number of seasons with fire risk and (iii) the mean seasonal Forest Fire Weather Index (FWI), which is a daily meteorological-based index designed in Canada and used worldwide to estimate fire danger in a generalized fuel type. The results show that under climate change there is an increase in the number of years with fire risk, especially in the northern parts of the Mediterranean region (North Spain, North Italy and Southern France) where the number of years at risk increases by up to 50%. Moreover, an increase in the length of the season with fire risk is also predicted, this means that on average for the whole Mediterranean region, the beginning of the fire season is predicted to be 27 days earlier under the A2 scenario and 22 days earlier in the B2 scenario compared to present day. The largest changes were observed in the belt between 600 and 1200 m a.s.l. Additionally, the end of the fire season was delayed by 10-12 days. Another result was the increase of extreme events (e.g. total number of days with Fire Weather Index FWI >45 and episodes with FWI >45 for 7 consecutive days) during the fire season. As expected, the A2 scenario showed a greater increase in risk than B2 scenario. These general increases in fire risk may have a very strong impact in areas where forest land cover is high (e.g. the Alps region in Italy, the Pyrenees in Spain and mountains of the Balkan region).

The impact of fire on soils has important secondary effects on carbon cycling and water relations. Fires with low to moderate intensity have little impacts on soils (they rather eliminate undesired competitor species and increase pH and nutrient availability). But the enhancement of hydrophobicity can make the soil more prone to **erosion** (Certini, 2005). Furthermore, increased torrentiality (Giorgi *et al.*, 2004) is likely to lead to increased erosion risk (De Luís *et al.*, 2003) due to reduced plant regeneration after frequent fires (Delitti *et al.*, 2005).

Severe fires can cause significant removal of organic matter, deterioration of both structure and porosity, considerable **loss of nutrients** through volatilisation, ash entrapment in smoke columns, leaching and erosion, and marked alteration of both quantity and specific composition of microbial and soil-dwelling invertebrate communities. The synergy created by increasing fire frequency and high intensity storms could, in turn, increase soil erosion. De Luís *et al.* (2001) showed that high intensity rainfalls after fire could adversely affect establishment of new plants, because of soil and nitrogen losses.

In addition, drought and altered fire regimes may lead to more shrub-dominated landscapes (Mouillot *et al.*, 2002; Resco De Dios *et al.*, 2007). On the other hand, Thuiller *et al.* (2005) analysed the invasion risk of alien plant invasion from South Africa using bioclimatic niche modelling. They found that most of the south-western part of Europe is potentially suitable for invasion by South African species. The high intensity of tourism between Europe and South Africa as well as massive imports of plant material to the former continent make Europe potentially vulnerable to invasions by more South African plants in the future.

The higher incidence of extreme weather events, increasing temperatures and severe droughts will strongly affect **biotic disturbances**. Especially in plantations, water supply already is and will increasingly become in future a key factor of tree survival. As an example, water stress of eucalypt trees plays a crucial role in the colonisation success, larval survival and growth of the phloem-boring beetle *Phoracantha semipunctata* (Hanks *et al.*, 1999; Caldeira *et al.*, 2002). It is highly probable that temperature increase will lead to distributional shifts of insect populations. Pest species are likely to profit from climate change in case of altitudinal expansion or dislocation of the distribution range, especially when coupled with host switching as in the case of *Thaumetopoea pityocampa* (Hodar *et al.*, 2003; Battisti, 2004; Hodar and Zamora, 2004). On the other hand, in case temperatures raise above optimal development conditions, certain species, such as *Lymantria dispar* and *Lymantria monacha,* may also face southern restrictions of distribution. While heat stress during summer will likely be responsible for a northward move of the nun moth, gypsy moth reacts sensitively on rising winter temperatures, as diapause requirements might not be satisfied any more (Gray, 2004; Karolewski *et al.*, 2007; Vanhanen *et al.*, 2007).

Highly termophilic **pathogen species**, already typical components of the microflora of Mediterranean tree species, are likely to become more serious in South Europe. Typical components of the endophytic microflora inhabiting Mediterranean tree species, such as *Biscogniauxia mediterranea* on *Quercus spp*. and *Diplodia pinea* on *Pinus spp*., may develop rapidly in case of water stressed host trees and cause sudden dieback. As the organisms in their latent form may be present in wide areas for a long period, such shifts from latency to pathogenic stage in case of fitting environmental conditions (drought) may pose a considerable threat to southern forests under a changing climate (Stanosz *et al.*, 2001; Vettraino *et al.*, 2002; Desprez-Loustau *et al.*, 2006; Capretti and Battisti, 2007; Desprez-Loustau *et al.*, 2007; Maresi *et al.*, 2007; Resco De Dios *et al.*, 2007). Temperature increase and summer droughts will promote outbreaks of various pathogenic fungi, such as the Dutch elm disease, *Ophiostoma ulmi* (Resco De Dios *et al.*, 2007), poplar rusts, or the chestnut blight (Desprez-Loustau *et al.*, 2007). Summer drought was also observed to be the main factor governing the spread of *Heterobasidion abietinum* in South Italian stands of silver-fir, together with the root disease *Armillaria spp*. (Puddu *et al.*, 2003; Desprez-Loustau *et al.*, 2006). Changing patterns of precipitation have been leading to an increasing incidence of oak decline in the Iberian Peninsula. Although the causal agent of the disease still remains unclear, decline and death of oaks recently could be associated with *Phytophthora cinnamomi*. The highly pathogenic fungus is especially active under warm climate and requires wet soil conditions to infect roots. Long periods of high temperature interspersing with short intervals of heavy precipitation, which have become more common recently and are to be expected even more frequently in future, highly predispose *Quercus* species to attack (Robin *et al.*, 1998; Gallego *et al.*, 1999; Sanchez *et al.*, 2002; Desprez-Loustau *et al.*, 2006; Desprez-Loustau *et al.*, 2007; Resco De Dios *et al.*, 2007).

- ***Potential impacts on forests products and services***

  - *Wood production*

Due to recurrent severe droughts, the Mediterranean vegetation show adaptations, but even drought adapted ecosystems are influenced by drought. Scots pine (Pinus *sylvestris*) has increased stem growth during the 20$^{th}$ century in Catalonia, but increasing temperatures had already negative impacts on drier sites (Martínez-Vilalta *et al.*, 2008). The negative effect of the increase in temperature may become stronger and not compensated by the positive effects promoted by increasing atmospheric $CO_2$ concentration. Therefore, wood production is expected to decline. The increased fire risk will further reduce wood production and decrease timber values in burned areas.

  - *Non-wood forest products*

No specific studies are available on climate change impacts on cork production or on mushroom production. Both are important non-wood forest products in the Mediterranean region. However, it has been shown that there is a clear relationship between mushroom production and rainfall (Martínez de Aragón *et al.*, 2007). Total production was positively correlated to mean annual rainfall as well as with rainfall from the months just before and during the autumn fruiting period. In a study from the Central Pyrenees, Bonet *et al.* (2008) also found that the annual variation in mushroom production correlated with rainfall in the months September–November. From these studies it can be inferred that a decrease in precipitation with increased droughts will likely reduce mushroom production.

  - *Carbon sequestration*

Negative impacts of drought on forest growth and productivity will also affect carbon sequestration rates and the net carbon balance will be strongly affected by disturbances, especially by projected increases in frequency and intensity of forest fires. Management changes in pine forests (increasing the rotation age and site quality and decreasing thinning intensity) may be able to increase the total aboveground and stem wood biomass carbon pools (Balboa-Murias *et al.*, 2006).

  - *Biodiversity*

The distribution range of a number of typical tree species is likely to decrease in the Mediterranean (Schröter *et al.*, 2005). Drought periods will shift also species composition: in more moist localities the proportion of drought-sensitive species would increase, due to a higher likelihood of co-occurrence of species that share moist climatic requirements (Lloret *et al.*, 2007). The forecasted global warming and fire increase may trigger irrecoverable biodiversity losses and shifts in vegetational composition within a few decades or centuries at most. Fire and drought-sensitive vegetation types seem particularly threatened by large-scale displacement (Colombaroli *et al.*, 2007).

### 4.2.5 Mountainous regions

The scope of this section is to summarize forest ecosystem sensitivity to climate change and the potential impacts on forest goods and services in mountainous regions of Europe (Alps, Carpathian Mountains and Pyrenees). The assessment of the effects of climatic changes on mountain forests subsequently allows the evaluation of potential impacts on goods and services. One important forest service in mountainous and Mediterranean regions (is the protective functions (e.g. protection of infrastructure as well as protection against erosion and of water resources in the two regions respectively).

We focus on the three major mountain ranges in Europe, the European Alps, the Carpathian Mountains and the Pyrenees (Fig. 11). The conducted literature review bases mainly on scientific literature but extends to project reports and conference proceedings where available. Over 100 literature sources have been identified, with the vast majority addressing the Alps. Available literature concerning the Pyrenees and the Carpathian Mountains is very scarce.

- ***Summary exposure***

Temperature increase during the last century is already twice the global average in the **Alps** (about +1.5°C). This increase in temperature has been detected at all altitudes with a slight tendency of increasing changes at higher altitudes. By 2050 we can expect an increase of 2° in autumn, winter and spring, and 3° in summer in the Swiss Alps. The run-off will be increased. In addition, the duration of snow cover is expected to decrease by several weeks for each °C of temperature increase in the Alps.

The mean annual temperature increase is projected to be in the order of 3-4°C except for the more continental regions of Central Europe and the Black Sea Region, like Romania, where temperatures could increase by as much as 4-4.5°C. Annual mean precipitation is expected to increase by up to 10% mainly in winter, while there will be reductions in summer precipitation in several areas (up to -10%). For the **Carpathian Mountains** values of at least similar magnitude can be expected.

Lacking detailed information for the **Pyrenees** values of the Mediterranean (Portugal, Spain, S. France, Italy, Slovenia, Greece, Malta and Cyprus) might be used to describe the general climatic trend. Annual rainfall is expected to drop by up to 20% of current precipitation (up to 50% in summer). However precipitation is expected to increase in winter. This results in higher intensity precipitation events. Annual mean temperature increases will be in the order of 3-4°C (4-5°C in summer and 2-3°C in winter). Climate models predict changes in frequency, intensity, and duration of extreme events with more hot days, heat waves, heavy precipitation events, and fewer cold days.

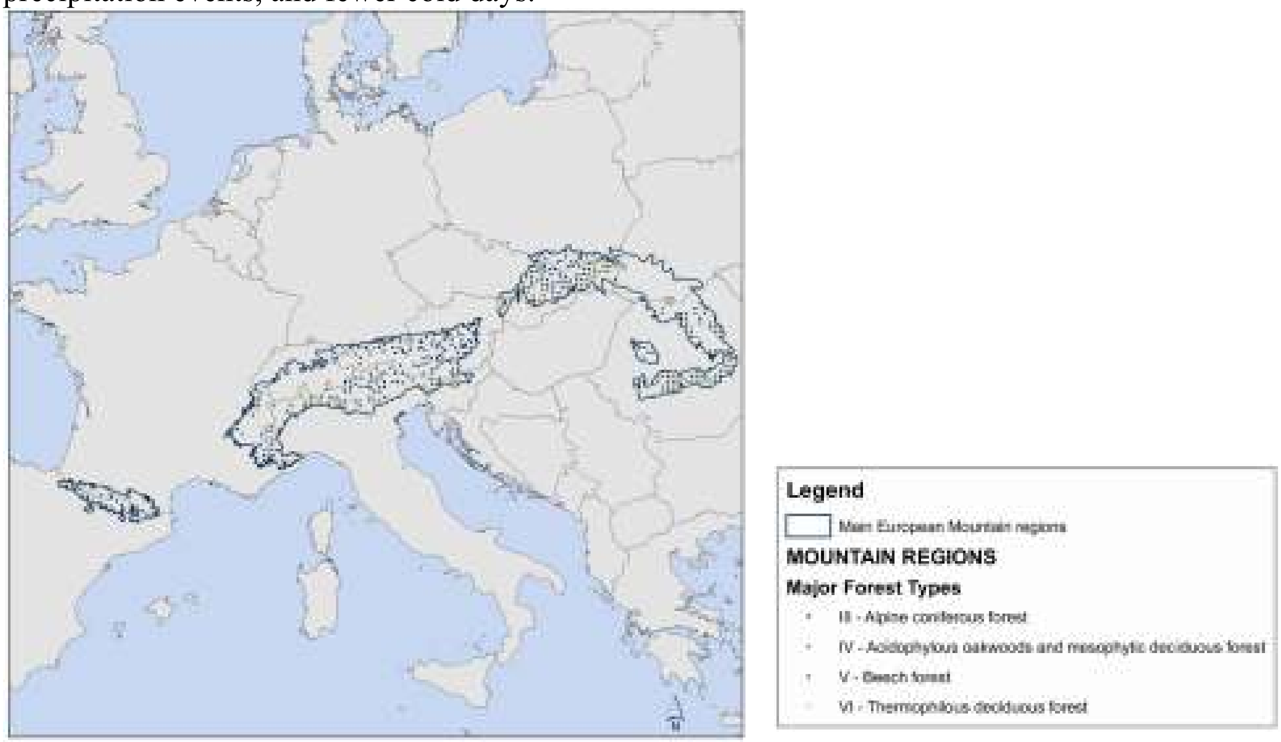


**Figure 11.** Mountain regions and their major forest types in EU27 Member States.

- ***Key impact factors***

Tree and stand level ecological processes in mountain regions may be limited by a variety of environmental factors. Limiting factors as well as their interactions vary along steep environmental gradients. In general processes at high altitudes (subalpine, alpine and nival vegetation zones) are limited by temperature. An increase in temperature has thus the potential to mitigate this limitation and enhance tree growth in high elevation areas. However, the local response of subalpine and alpine vegetation to warming will strongly depend on small scale processes and interactions with micro-relief, soil formation processes and geology.

At low elevations, in the foothills of mountain ranges as well as in inner basins, precipitation and subsequently drought is frequently limiting forest productivity. Changes in the precipitation regime (amount, intra-annual distribution) in combination with increasing temperatures may thus constitute the main impact factor for these areas. Because of varying interactions of these climatic factors with soil nutrient status, which varies at small scales due to complex geology and soil formation processes, the causality of impact factors and ecosystem sensitivities is highly complex. In addition, changes in climatic factors could increase the susceptibility of mountain forests to disturbances such as bark beetles. Tables 15 and 16 show the pest and pathogen species relevant for the mountainous zones in the context of climate change.

**Table 15.** Pest species relevant in the context of climate change in mountainous regions. See Table 2 for the forest types.

| Latin name | English name | Relevant impact factors | Major forest type | Affected tree species | Expected effect on species (+/-) |
|---|---|---|---|---|---|
| *Cephalcia arvensis* | Web-spinning sawfly | temperature increase, drought | III | *Picea abies* | + |
| *Ips acuminatus* | Pine engraver beetle | temperature increase, drought | II, III, VII | *Pinus sylvestris* | + |
| *Ips sexdentatus* | Pine stenographer beetle | temperature increase, drought | II, III, VII | *Pinus sylvestris* | + |
| *Ips typographus* | European spruce bark beetle | temperature increase, increase of storm events, drought | II, III, VII | *Picea abies* | + |
| *Pityogenes chalcographus* | Small spruce bark beetle | | III | *Picea abies* | + |
| *Thaumetopoea pityocampa* | Pine processionary moth | temperature increase (winter) | II, III, VII | *Pinus sylvestris, P.nigra, P.mugo, P.uncinata* | + |
| *Tomicus piniperda* | Common pine shoot beetle | temperature increase, drought | II, III, VII | *Pinus spp.* | + |
| *Tomicus minor* | Lesser pine shoot beetle | | II, III, VII | *Pinus spp.* | + |
| *Zeiraphera diniana* | Larch budmoth | temperature increase | III | *Larix decidua* | (+)/- |

**Table 16.** Pathogen species relevant in the context of climate change in mountainous regions. See Table 2 for the forest types.

| Latin name | English name | Relevant impact factors | Major forest type | Affected tree species | Expected effect on species (+/-) |
|---|---|---|---|---|---|
| *Diplodia pinea (Sphaeropsis sapinea)* | Collar rot (shoot blight) | temperature increase, drought | III | *Pinus nigra, P.halepensis* | + |
| *Dothistroma septosporum (Mycosphaerella pini)* | Dothistroma needle blight (red-band disease) | precipitation increase | II, III | *Pinus nigra, P.sylvestris, P.cembra, P.mugo, P.uncinata* | + |
| *Gremmeniella abietina* | Scleroderris cancer | changes in temperature and snow cover | III | *Pinus cembra, P. mugo* | - |
| *Heropotrichia juniperi* | black snow mould | reduced snowfall and duration of snow cover | III | *Picea abies, Pinus cembra, P.mugo, Abies alba, Juniperus communis* | - |
| *Phacidium infestans* | common snow mould / snow blight | reduced snowfall and duration of snow cover | III | *Pinus cembra* | - |

Generally, the main impact factors described for the European Alps can also be expected to affect the **Carpathian Mountains**. Climate change is likely to relax temperature-induced stress in the high elevation zones. Drought due to changes in precipitation regimes alongside an increasing temperature is likely to be the main factor in valleys and foothills. Interactions between impact factors, local environmental conditions (e.g., microclimate, soil conditions) as well as changes in the disturbance regime are, however, strongly influencing ecosystem sensitivity.

Drought is the main limiting factor to tree growth in the **Pyrenees** (cf. chapter on the Mediterranean region). Thus impact factors modifying the water regime are of paramount relevance for the region. Besides temperature, precipitation and local soil water holding properties, increasing atmospheric $CO_2$ content and its influence on water use efficiency have to be mentioned. Moreover, changes in the fire regime, the main disturbance factor in the region, have to be expected in relation to climatic changes.

- ***Sensitivity***

Rising **temperatures** will affect forest ecosystems in European mountain regions in multiple ways. Large changes due to increasing temperatures and vegetation period lengths are reported and expected for the subalpine regions of the European Alps. Growth in those regions is usually temperature limited, therefore **increasing growth rates** can be expected, which has been already observed in empirical studies all over Europe's mountainous regions. For *Picea abies* increasing growth trends have been reported by Bolli *et al.* (2007) and Rolland *et al.* (1998), conducting case studies in subalpine regions of the Alps. Also for *Pinus cembra* growing at the tree line a distinct radial growth response to global warming has been observed in the Alps (Paulsen *et al.*, 2000; Vittoz *et al.*, 2008). For the French Alps Keller *et al.* (2000) report, that a doubling of $CO_2$ would induce a growth increase for conifers at high altitudes (1600-2200 m a.s.l.), as a result of an extended growing season due to warming.

Available literature for the **Carpathians** conforms to these findings for the Alps. At high elevations temperature is the currently limiting environmental factor. In a warmer climate productivity at high altitude sites will therefore increase as long as sufficient water supply is provided (e.g. Skvarenina *et al.*, 2004; Savva *et al.*, 2006; Büntgen *et al.*, 2007).

Not only high altitude regions are subject to changing growth trends. For Austria a general positive **growth** response of Norway spruce is reported from the Austrian Forest Inventory. In a simulation study based on data of the Austrian Forest Inventory temperature increases and longer growing season conditions were reported to be the main causes for this effect (Hasenauer *et al.*, 1999; Hasenauer, 2000). For Switzerland similar patterns are projected by Kienast (2000) in an expert assessment. The authors is expecting an increased growth of *Pinus sylvestris, Fagus sylvatica* and *Quercus sp.* by 10% and for *Picea abies* by 5% by the year 2020 assuming an increase in temperature of 2°C and an increase in precipitation of 10-20%. This is in line with a simulation study by Schelhaas *et al.* (2002).

However, especially for *Picea abies*, often cultivated outside its natural range, **decreasing productivity** can be expected in low lying regions. In a simulation study for an inner alpine basin in Carinthia, Austria, Lexer *et al.* (2006) found growth increases for *Fagus sylvatica* and *Quercus robur* under all investigated climate scenarios whereas productivity of *Picea abies* declined slightly under conditions of combined temperature increases and decreased precipitation. Consistent with these results Keller *et al.* (2000) conclude that in many cases the growth reactions (positive or negative) may be more pronounced the closer the observed species is to its natural range limits.

Theurillat and Guisan (2001) state, that the European Alps appear to have a natural inertia and thus to tolerate an increase of 1–2° C of mean air temperature as far as plant species and ecosystems are concerned in general. However, the impact of land-use is very likely to offset this buffer in many areas. For a change of the order of 3° C or more, profound changes may be expected (Theurillat and Guisan, 2001). Similarly, Lexer *et al.* (2002) conclude from a large-scale simulation study that temperature increases of more than 1°C may trigger substantial **changes in natural species composition**. The set of suitable tree species will increase at higher elevations due to increased competitivity of broadleaved species under warmer conditions. Therefore also the **silvicultural decision space** concerning species and regeneration systems will increase. Lexer *et al.* (2002) emphasize that *Picea abies* will become unsuitable as a crop species at low-elevation sites under a set of analyzed climate change scenarios.

Climate change will also affect the **distribution of forest types**. The results of a simulation study conducted for Switzerland indicate that the overall ‘winners’ of projected climate change in terms of area occupied are colline oak-hornbeam forest types and even thermophilic forest types that are not observed in today’s landscape. Major ‘losses’ are projected to occur in today’s higher montane and the subalpine vegetation belt where the invasion of deciduous tree species such as beech or maple reduce the potential range of forest types typically dominated by conifers (Kienast *et al.*, 1996). These results are in accordance with the findings of Kienast (1991), Lexer (2001), and Zebisch *et al.* (2005). The changes in the ecological potential might eventually result in a changed abundance of dominating tree species (Brzeziecki *et al.*, 1995; Kienast *et al.*, 1996). Theurillat *et al.* (1998) show similar patterns for Switzerland too, by using a static modelling approach. According to their results, changes in forest types might occur in 30-55 % of the forested area for an increase of 1-1.4° C, and up to 55-89% for a 2-2.8° C increase.

For the Low Tatra Mountains (**Carpathian Mountains**, Slovakia), Balaz and Mindas (2004) estimated the effects of climate change on different tree species by means of a static life zone approach. They found that the area with unfavourable conditions for *Picea abies* will double under projected climate change (+2.7°C in 2075). For *Abies alba* they expect the share of unfavourable area to rise to more than 90%. Therefore they conclude *Picea abies* and *Abies* *alba* will be partially substituted by *Acer pseudoplatanus* and *Larix decidua* on northern and southern slopes respectively (Balaz and Mindas, 2004). The current mountain pine zone (*Pinus mugo*) will probably disappear and will be occupied by *Picea abies*.

These changes in forest type distribution will also lead to **changes in species richness**. Kienast *et al.* (1998) carried out a simulation study on species richness in mountain forests in Switzerland using a potential natural vegetation approach. Their scenario assuming warmer temperatures and no precipitation changes results in a shift from communities with relatively low species richness to communities with high species richness. This trend is primarily caused by the expansion of forest types like oak and oak-hornbeam as well as beech-dominated forest types. Furthermore, species-rich submontane and montane forest types (e.g. *Abieti-Fagion*) gain in area at the cost of high montane and subalpine types which are, on average, rather poor in species. Contrasting results were found for a scenario with simultaneous temperature and precipitation increases, where no significant changes in species richness could be found (Kienast *et al.*, 1998).

For alpine coniferous forests increases in air temperature and vapour pressure deficit could lead to **changed interspecific competition** regimes. Projected changes could favour *Larix decidua* over *Pinus cembra* and *Picea abies* in interspecific competition because the regulation mechanism of stomatal conductance allows longer periods of photosynthesis for larch (Anfodillo *et al.*, 1998). This is supported by the study of Büntgen *et al.* (2006) concluding on advantages in competition of *Larix decidua* over *Picea abies* under increasing summer temperatures and reduced soil water availability (D'Arrigo *et al.*, 2004; Wilmking *et al.*, 2004). The results of Bugmann *et al.* (2005) underline these projected trends for *Pinus cembra* forests on south facing slopes, which are replaced by mixed forests dominated by *Picea abies* in a simulation study. Major changes for alpine coniferous forests are also reported by Badeck *et al.* (2001) who compare different simulation models in pristine forests in Switzerland.

Temperature increases might also increase the **mortality** in forest ecosystems. Dobbertin *et al.* (2005) postulate that drought stress may incite the already observed *Pinus sylvestris* decline. As a consequence pure pine forests at low elevations will no longer be supported under a warming climate. This is underlined by an earlier study where the authors relate recently observed mortality in Swiss inner alpine *Pinus sylvestris* stands to the strong climatic warming of the last decades (Rebetez and Dobbertin, 2004). If the climate is changing towards longer summer drought periods, higher mean temperatures and shifted seasonality of moisture availability, conditions will be too harsh for *Pinus sylvestris* to the benefit of *Quercus pubescens* (Weber *et al.*, 2007).

A particularly complex aspect with regard to the response to increasing temperatures in mountainous ecosystems is tree line dynamics. As naturally temperature limited ecosystems subalpine forest communities might be particularly temperature sensitive resulting in **tree line shifts**. Bolli *et al.* (2007) found the **availability of suitable microsites** the main limiting factor controlling tree invasion. Tree-line increase due to higher temperatures may thus have considerable time lags where suitable microsites in the alpine zone are absent. In contrast to this findings are the results of Tinner and Kaltenrieder (2005) based on paleoecological proxies. The authors postulate rapid upslope movements of the tree line of up to 800 m within a few decades or centuries at most as a response to the projected warming.

For the period between the first half of the $19^{th}$ century and present conditions Nicolussi *et al.* (2005) recorded a **tree line** shift from 2180 m a.s.l. to 2245 m a.s.l. for *Pinus cembra* in the

Kauner valley in Tyrol, Austria. Additionally they observed saplings up to 2370 m a.s.l., indicating an ongoing rise of the tree line as a result of warmer summer temperatures after 1980. Bugmann *et al.* (2005) conducted a simulation study showing a strong increase of tree line elevation (up to ca. 2500 m a.s.l.) with a concomitant upward shift of the respective forest types. Theurillat *et al.* (1998), conclude for the Swiss Alps that for an increase of 1-2° C in mean annual temperature, the present upper subalpine forest limit is not likely to shift upward much more than 100-200 m due to temperature related inertia. The kampfzone, however, might move into the low alpine belt in favourable places. For a stronger temperature increase of 3-4° C, the kampfzone would be very likely to invade the current alpine belt, causing an upward shift of the forest limit into the low alpine belt (Theurillat *et al.*, 1998).

Gehrig-Fasel *et al.* (2007) additionally address the fact that **land use has a large influence on the tree line**. From a study on tree line shifts in Switzerland they conclude that land abandonment is the most dominant driver for the establishment of new forested areas at the tree line ecotone. In their study only a small fraction (4%) of observed upward shifts can be attributed to recent climate warming. However, this fraction is likely to increase if climate continues to warm. This is supported by Vittoz *et al.* (2008) who observed tree line dynamics in Swiss *Pinus cembra* stands. Similarly Dullinger *et al.* (2003) state that if climate warming relaxes the environmental constraints that currently limit *Pinus mugo*'s altitudinal distribution, a consecutive range expansion into former alpine grasslands may take place quite rapidly (Dirnböck *et al.*, 2003; Dullinger *et al.*, 2003, 2004). Such an accelerated upward movement of *Pinus mugo* shrub-lands may pose a major **threat to many herbaceous alpine species** if they are unable to migrate as well (Grabherr *et al.*, 1994; Theurillat and Guisan, 2001; Thomas *et al.*, 2001). For all conducted simulation studies investigating tree line shifts relatively low climate change drivers have been used compared to the expected exposure. This is especially true for Dullinger *et al.* (2004) who use temperature increases in a range from 0.65 to 2° C until the year 2150.

Camerero and Gutierrez (2007) investigated **regeneration responses** on climatic change and changes in grazing pressure for *Pinus uncinata* in north eastern Spain. They observed recent regeneration pulses which can not be explained by the decrease in grazing pressure since the middle of the 20$^{th}$ century. Climate is expected to be the main driving force of the recent pine expansion at the local scale. The authors conclude that the presence of a relatively "invasible" understory and the grazing decline may be prerequisites for further expansion of *Pinus uncinata* populations.

Peñuelas and Boada (2003) investigated a global change induced biome shift in the Montseny Mountains in north eastern Spain. They observed an upward expansion for 70 m of *Fagus sylvatica* at the tree line and conclude warming and decrease of anthropogenic pressure favouring this upward shift. The ca. 1.2-1.4° C increase in annual temperature seems to be a strong driver. Moreover, this change facilitates the replacement of *Fagus sylvatica* by *Quercus ilex* at lower elevations, a species better adapted to warmer and drier conditions. They conclude that warming seems to play a stronger role than land use changes at the extensively managed lower altitude ecotonic borders of the *Fagus sylvatica* forests (Peñuelas and Boada, 2003; Peñuelas *et al.*, 2007a). Camarero and Gutierrez (2004) conducted a study on *Pinus uncinata* dominated tree line dynamics and their results are somewhat contrasting those reported previously. They find that the period from 1950 to 1999 was characterized by greater interannual temperature variability and higher fall-winter temperatures (Bücher and Dessens, 1991; Agustí-Panareda *et al.*, 2000). These factors allowed the tree line to remain static while tree density increased within the ecotone. Therefore, they conclude higher temperature not to be the only climatic factor stimulating an upward shift in the studied tree lines. They predict that the recent global warming is unlikely to cause an altitudinal ascent of tree lines in the studied ecosystems, if the warming is accompanied by an increase in temperature variability (Camarero and Gutierrez, 2004).

Due to shifted seasonality of **precipitation**, particularly inner alpine environments will encounter increasing **drought stress** which will lead to decreasing growth. This has been reported for *Pinus sylvestris* and *Quercus pubescens* in an inner alpine valley in Valais, Switzerland (Eilmann *et al.*, 2006), and for *Picea abies* and *Pinus sylvestris*. The heat wave of 2003 has shown the huge sensitivity of *Picea abies* to drought in inner alpine valleys (Pichler and Oberhuber, 2007).

Drought stress might be even more important in the Pyrenees. Andreu *et al.* (2007) conducted a study on tree growth variability in Iberian pine forests via tree ring chronologies. Changing tree-growth patterns were detected since the middle of the 20$^{th}$ century as a response to an increase in water stress. Regarding broad leaved tree species, studies on *Fagus sylvatica* in the Montseny Mountains by Peñuelas and Boada (2003) provide evidence that this species may be in decline at lower altitudes. Growth at the lower limit (~1000 m a.s.l.) of *Fagus sylvatica* in this region decreased by 49% between 1975 and 2003 linked to recent climatic warming. Evidence suggests that increasing temperatures are exacerbating drought stress. These results are indicating that only a small increase in aridity may decrease growth of *Fagus sylvatica* over large areas (Jump *et al.*, 2006).

Even in subalpine regions of the Alps water can become a **limiting factor for tree growth**. Büntgen *et al.* (2006) find that numerous subalpine spruce chronologies confirm increased late-summer drought stress. An idealized temperature response of subalpine tree growth can be inflicted by increasing drought stress. This is confirmed by Oberhuber and Kofler (Oberhuber and Kofler, 2003) pointing at the strong effects of slope and orientation in mountainous landscapes.

These results for the Alps are in line with results for the Carpathians. Modrzynski and Eriksson (2002) conducted a phytotron experiment to simulate drought stress responses of *Picea abies*. Low-altitude populations of *Picea abies* showed a strong negative reaction to drought stress, whereas high-altitude populations were more tolerant. The authors concluded that "[…] if global warming would be accompanied by soil drought, the low-altitude populations would reduce their growth much more than the high-altitude ones. But if global warming would be combined with an adequate increase of precipitation, then low-altitude populations would profit from this climate change more than high-altitude ones" (Modrzyński and Eriksson, 2002). Changing water availability will **alter the distribution of forest types** as exemplified for the Carpathian region by Skvarenina *et al.* (2004), who analysed the climatic water balance under climate change (+2.7°C temperature increase in 2075) for entire Slovakia. Both mid- and low-elevation vegetation stages will experience a trend towards increased aridity (-50 to -400 mm/a). Future bioclimatic conditions will favour broadleaved tree species such as *Fagus sylvatica, Acer sp.* and *Fraxinus excelsior*, whereas a decline of *Picea abies* is expected. The climatic water balance of the supramontane - alpine (*Picea-Abies-Fagus*) vegetation stages will, however, not worsen significantly (Skvarenina *et al.*, 2004).

Effects of an **increased atmospheric $CO_2$ level** on forest growth in mountainous regions are not fully understood to date. Handa *et al.* (2005, 2006) show that *Larix decidua* is responding with increased growth to elevated $CO_2$ while *Pinus uncinata* did not. Based on an in situ $CO_2$ enrichment experiment at the alpine tree line in Switzerland they conclude that "[…] the expected changes in growth of these tree line trees with improving carbon availability as atmospheric $CO_2$ continues to increase will thus depend on both the interplay between biotic and abiotic processes, and the species or tree functional types involved […]" (Handa *et al.*, 2005).

Earlier initiation of root or shoot growth, due to a warming related relaxation of environmental harshness in high mountains, could make trees more vulnerable to **temperature drops** in early summer. This has been observed for instance by Oberhuber (2004) for *Pinus cembra* in Tyrol (Austria).

Mortality due to **forest fires** could gain importance in the European Alps under future climate conditions. Reinhard *et al.* (2005) for instance show that fire proneness related to climatic drought increased over the period 1971–2003 in Ticino, southern Switzerland. In particular the months January to April, the period where forest fires historically have been most frequent, are reported to have become drier in the second half of the 20th century. The results of Reinhard *et al.* (2005) show an increasing trend in all climatic variables indicating drought and subsequently fire risk. The increasing importance of forest fires in a warmer and drier climate is also emphasized by Schumacher and Bugmann (2006) and Fuhrer *et al.* (2006). As a result of indirect effects of increasing temperatures (e.g. forest fire) Hättenschwiler and Körner (1995) expect an increase in sites favourable to *Pinus sylvestris* regeneration, based on empirical observations. Nevertheless, forest fires will be far more important in the Pyrenees than in the Alps or Carpathians under warmer and drier conditions.

Mountain forests are particularly sensitive to changes in disturbance regimes as mediated by poikilotherm **insects** due to steep temperature gradients (see section 2.2.1 Impact Factors - General description). In Norway spruce forests the European spruce bark beetle *Ips typographus* (L.) (Col. Scol.) and the small spruce bark beetle, *Pityogenes chalcographus* are major disturbance agents (Christiansen and Bakke, 1988; Forster *et al.*, 1999; Jurc *et al.*, 2006). Breeding habitat of the beetle are stressed Norway spruce trees (e.g. Christiansen and Bakke, 1988; Zemek *et al.*, 2003), however, during an outbreak also vital trees may be attacked by the beetle (Schroeder and Lindelöw, 2002). In the foothills of the Alps the cultivation of Norway spruce mainly due to economic reasons and ease of management has led to large areas of coniferous forests on sites naturally supporting mixed deciduous forests (Spiecker, 2000; Spiecker *et al.*, 2004). Such secondary spruce forests are often not well adapted to the site conditions and are particularly susceptible to bark beetle damage. Moreover, windstorms create large quantities of favourable breeding material for the reproduction of *I. typographus* (Göthlin and Schroeder, 2000; Schroeder, 2001; Wermelinger, 2004; Eriksson *et al.*, 2005) and weaken surrounding stands (e.g., root damage) which frequently results in vast beetle gradations.

The observed increase in **bark beetle damages** in Swiss and Austrian mountain forests over the last 15 years (Krehan and Steyrer, 2004; Engesser *et al.*, 2005) have been partly triggered by storm damage events (e.g., Viviane in 1990, Wiebke in 1992) and favoured by the warm climatic conditions of the recent decade. This adds to the growing concern that climate change may strongly affect the disturbance regimes in European Norway spruce forests due to the greater likelihood of additional generations of *I. typographus* per year (e.g. Volney and Fleming, 2000; Bale *et al.*, 2002; Baier *et al.*, 2007; Hlásny and Turcány, in press), and furthermore, by increased frequency of drought stress for Norway spruce which may also increase the susceptibility of spruce trees to infestation by *I. typographus* (Christiansen and Bakke, 1988; Dutilleul *et al.*, 2000). Due to the wide latitudinal and altitudinal distribution of the main European tree species the spatial distribution of important insect herbivores is in many cases limited by harsh environmental conditions rather than host availability. For instance, for the Norway spruce bark beetle *Ips typographus* the current spatial distribution of the host species strongly exceeds the thermally feasible area of insect development. A shift in climatic conditions could thus trigger dramatically increased damages in coniferous forests at higher elevations (Seidl *et al.*, 2008c).

Results from scenario based impact assessments by Seidl *et al.* (2006) and Seidl *et al.* (2008a) show that ***Picea abies´* susceptibility** to bark beetle infestations is strongly increasing under climate change, which is also supported by other authors (e.g. Pichler and Oberhuber, 2007).

Under a climate change scenario, Norway spruce stands will also become more predisposed to defoliation, as shown by recent outbreaks of the spruce webspinning sawfly, *Cephalcia arvensis* in the Southern Alps. Abnormally high temperature in June and July during consecutive years was identified as major factor promoting exponential **population growth** of the sawfly, repeated defoliation and final dieback of the affected spruce stands (Battisti, 2004).

A **variety of bark beetle species** are part of the biocoenosis of alpine *Pinus spp.* forests and mostly occur secondarily on trees of low vitality. Yet, epidemics may become more likely given weather extremes such as precipitation deficits and long periods of high temperature (Nierhaus-Wunderwald and Forster, 2000). By now, pine stands at lower altitudes of dry inner alpine valleys in Switzerland are prone to attacks by the pine stenographer beetle, *Ips sexdentatus* and the pine engraver beetle, *Ips acuminatus*. Given increased summer temperatures, mass outbreaks of the latter may become more probable due to the possible termination of a second beetle generation. Rising temperatures may also trigger high population densities of the pine shoot beetles, *Tomicus piniperda* and *Tomicus minor*, and enhance the susceptibility of alpine pine forests of all age classes to infestation.

In the Southern Alps, **altitudinal range** expansion of the pine processionary moth, *Thaumetopoea pityocampa* is to be expected due to rising summer temperatures. Battisti *et al.* (2006) expect the colonisation of *Pinus spp*. (e.g. *Pinus nigra* in Valle Venosta of Alto Adige) at increasingly higher elevations, promoted by enhanced flight activity of the female moths, and as a result of reduced mortality rates during warmer winter periods.

Although development of many poikilotherm organisms is influenced in a positive way by rising temperatures, a striking example for an also possible **negative feedback** is the collapsed outbreak of the larch budmoth, *Zeiraphera diniana* in the Upper Engandine Valley in 1989 (Battisti, 2004). Mass propagation was probably stopped by abnormally high temperatures in winter and spring that caused high egg mortality and prevented a good synchronisation between bud burst of *Larix decidua* and hatching of the larvae. The larch budmoth exhibits a cyclic population development, which leads to high numbers of individuals and defoliation of inner alpine larch stands every 8-10 years. However, coinciding with the trend of climatic warming since the 1980s, population dynamics have been changing and the oscillation amplitudes have been diminishing, showing only sub-defoliating peak densities (Esper *et al.*, 2007). According to Baltensweiler (1993), the cyclic occurrence of the pest insect will not be much affected as long as the winters remain cold and the summers dry. In this case a continuing warming trend might simply lead to a shift of the optimum zone upwards. However, population dynamics of the recent years let assume that population cycles are already strongly affected by an increase of temperature in winter combined with rising temperatures and amounts of precipitation in summer. Such absence of disturbance must not necessarily be beneficial for alpine ecosystems. Esper *et al.* (2007) state that epidemics of the larch budmoth play an important role in ecosystem functioning and missing forest defoliation may have drastic consequences for nutrient cycling and other ecosystem processes.

The severity of **fungal diseases** in mountainous regions is strongly affected by changes in temperature and precipitation, especially the amount of snowfall and duration of snow cover. Snow blight, *Phacidium infestans* and the serious disease *Herpotrichia juniperi* (black snow mould) both need deep snow cover for development and infection of the host trees (Nierhaus-Wunderwald, 1996). The occurrence and pathogenicity of Scleroderris canker, *Gremmeniella abietina* is also closely related to the persistence of snow cover in spring. The longer snow cover stays, the longer the fungus is able to develop under beneficial moisture conditions. Tree mortality due to the canker is particularly high after cold and wet summers that provide optimal conditions for spore production, spreading and infection (Senn, 1999), whereas high summer temperatures are lethal for the fungus (Nierhaus-Wunderwald, 1996). Temperature increase and reduced winter and summer precipitation might consequently reduce the future risk of canker attack and snow mould and thus decrease stress of trees growing in areas of high altitude or close to timberline. On the other hand, the combination of higher temperatures and decreased humidity can also favour fungal development, as in the case of *Diplodia pinea* on *Pinus nigra* (Maresi *et al.*, 2007) and a regional increase of (summer) rainfall might have positive effects on certain species, such as *Dothistroma septosporum* on *Pinus spp*. (Kirisits and Cech, 2007).

Schelhaas *et al.* (2002) investigated the **combined effects** of climatic changes (+1.5°C increase in temperature, slight increase in precipitation) and related disturbance regimes for Switzerland with a large-scale scenario model and found growth increases of about 2 m³/ha per year until the year 2048. However, interacting disturbance agents under changing environmental conditions and their effects on forest dynamics have not been addressed holistically to date and thus remain uncertain. Furthermore, our review revealed a general lack of information on direct impacts of climate change on regeneration processes in mountain forest ecosystems. Although they are, partly implicitly, included in analyses on tree line shifts and species composition changes an explicit focus on these complex processes could help to understand ecosystem responses to climatic changes.

In summary, the conclusions of Lischke *et al.* (1998) that **no uniform, simple response of mountain forests to climate change can be expected** is also emphasized by this study.

- ***Potential impacts on forests products and services***

Not surprisingly, timber production is the most often addressed service in the literature, concerning climate change impacts, followed by biodiversity, carbon sequestration, protection and water retention and provision, whereas non-wood forest products and recreational use have never been addressed directly. Several studies investigated multiple impacts, but not in the sense of an integrated assessment regarding multiple-purpose forestry.

  - *Wood production*

The projected climatic changes will lead to changes in productivity. In higher elevations net primary production (NPP) of current forests will be increasing as long as the sites are not limited in water availability. Interactions with nutrient availability may affect the impacts on production. Secondary Norway spruce forests at low elevation sites in drought prone areas will encounter decreased productivity. At low elevation sites *Picea abies* will become unsuitable as a crop species while at higher elevations under warmer climates the set of suitable tree species and therefore the silvicultural decision space will increase due to increased competitivity of broadleaved species. Sites with sufficient precipitation in the present montane vegetation zone were identified as having increased productivity under the projected climatic changes.

Changes in species composition in course of large scale disturbances in current conifer stands may lead to reduced stem wood production and subsequently to economic losses from timber production.

Realized production will be strongly affected by the future disturbance regime, particularly at low elevation sites. With high confidence damages by bark beetle infestations will increase. Future storminess and related damages are subject to high uncertainty.

- *Non-wood forest products*

No specific studies are available on climate change impacts on **mushroom production** which is important in the **Pyrenees**. However, a study has been presented where the individual climate variables show a clear relationship between mushroom production and rainfall. They concluded that total production is positively correlated to mean annual rainfall specially when considering the rainfall data from the months just before and during the autumn fruiting period. Even though in this article was not studied the effect of droughts in mushroom production, it s clear that a decrease in precipitation with increased droughts will lead to a decrease in mushroom production (Bonet *et al.*, 2008). For the impact of climate change on non-wood forest products little or no information is currently available, thus clearly indicating knowledge gaps.

- *Carbon sequestration*

Due to enhanced productivity the forests in the **European Alps** are expected to maintain their potential function as a carbon sink at least for the first half of the 21st century. For the second half increasing respiration rates and frequent disturbances at low elevation sites are projected and therefore the sink function will decrease and forests may become a C source (Karjalainen *et al.*, 2002; Thürig *et al.*, 2005; Zierl and Bugmann, 2007; Seidl *et al.*, 2008a; Seidl *et al.*, 2008b). Ultimately, socio-economic conditions (demand for forest biomass, market prices) will determine whether mountain forests will remain a sink for carbon.

- *Water retention and provision of clear drinking water*

Regarding water retention and the provision of clear drinking water under climate change targeted research results are sparse. Frequent and large-scale disturbances in mountain forests may negatively impact the functioning of water protection forests by reduced ability to dampen run-off peaks. Rapid decomposition of litter and humus layers due to intensified disturbances and increased temperatures may lead to leaching of nitrate (e.g. Jandl *et al.*, 2008). Regarding the interaction of N deposition, climatic changes and forest composition substantial knowledge gaps exist.

In the Pyrenees changes in precipitation, temperature, and snow accumulation, together with an increase in vegetation density in headwater regions, has led to a marked reduction in water availability in the region. Water resource managers have introduced major changes to dam operations to meet increasing water demand for irrigation purposes in lowland areas. Climatic and land-cover scenarios for the next century indicate that the sustainability of the equilibrium between available resources and water demand will be seriously threatened (López-Moreno *et al.*, 2008).

- *Biodiversity*

Impacts of projected climatic changes on biodiversity are not yet studied sufficiently but some conclusions can be drawn on the basis of scientific literature.

Species rich broadleaved forest communities **in Alps** will increase their potential area (Kienast *et al.*, 1998). Actual species and habitat diversity will be strongly determined by management activities. Plant species diversity in the alpine and nival vegetation zones will be adversely affected in a warmer climate due to upwards shifts of subalpine forest communities (e.g. Grabherr *et al.*, 1994; Theurillat and Guisan, 2001; Dullinger *et al.*, 2003).

Referring to plant diversity, species suitability shifts as reported by Balaz and Mindas (2004) from **Carpathian Mountains** are surely affecting biodiversity, but it is unclear to which extent and in which direction. For herbaceous plants of the alpine vegetation zone, biodiversity losses might occur. This would be the case if, as it is denoted by Balaz and Mindas (2004), *Pinus mugo* and *Sorbus aucuparia* would invade the current alpine vegetation zone and the herbaceous plants would not be able to change their ranges at the same pace (Theurillat and Guisan, 2001).

- *Protective function against natural hazards*

Forests providing protection against natural hazards for human infrastructure require specific structural and compositional properties in order to fulfil their tasks. Regarding the different natural hazards occurring in alpine environments different properties are needed to provide the protective function. Both, forest structure as well as the hazardous processes themselves are potentially sensitive to climatic change, adding to the complexity of assessing potential interactions. The natural hazards and respective protective functions of forest ecosystems presented here are a selection of natural hazards occurring in European mountain ranges. The discussed hazards are:

- flooding
- debris flow
- landslide
- rock fall
- avalanche

Natural hazards which can not be significantly influenced by protective forests have been disregarded. Such hazards are earthquakes, volcanism, rock slides and in general hazardous processes whose magnitudes (i.e. energy) are beyond the dissipative capacity of forests.

For a thorough analysis of the impact of climatic changes on the protective function we distinguish two elements. On the one hand it is important to know how the forests are influenced by climate change and on the other hand it is necessary to gain insight into potential climate sensitivities of hazardous processes. Whereas the former is extensively discussed in the previous section (cf. forest ecosystem sensitivities) we briefly describe climate change impacts on the hazardous processes here and subsequently venture for an integrated view of both elements. Fig. 12 is illustrating this concept for easier understanding. Forests and natural hazards tend to react on different time scales to climate change due to the inertia inherent to the different processes, resulting in uncertainties for an assessment of the future development of protective functions.

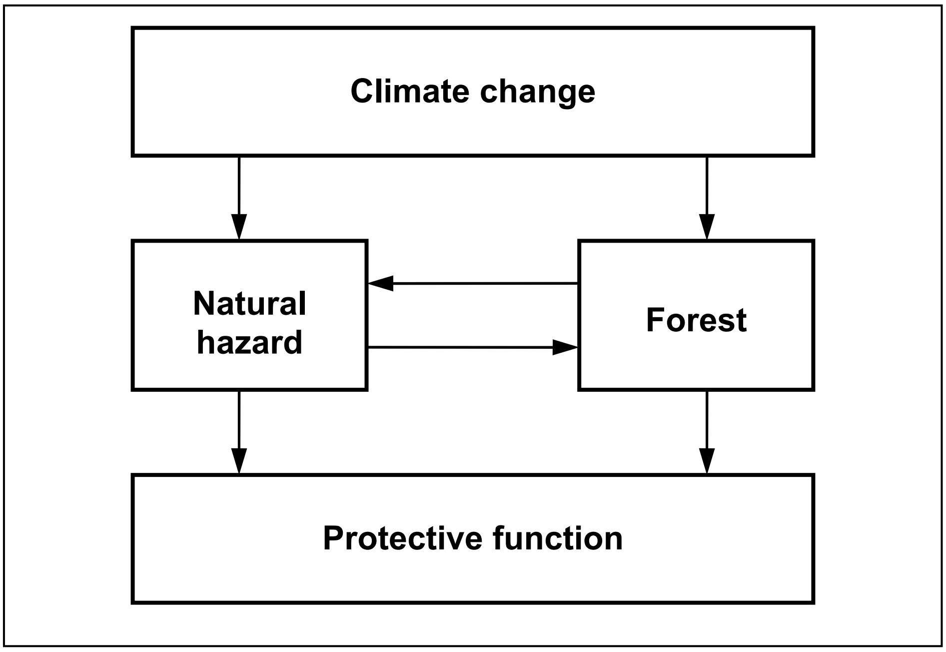


**Figure 12**: Illustration of climate change impacts on the protective function of forests.

It has to be noted that literature on climate change impacts on natural hazards in forested landscapes is sparse. Substantial research has been conducted for regions above the timberline, focusing on glacial and permafrost retreat and the related hazards like glacial lake outbursts, debris flows, rock slides, rock falls, moraine dam failures and ice avalanches. Due to the enormous involved energies and low frequencies of these events, however, the protective function of forests plays a minor role with regard to these hazards.

*Flooding*

Shifts in snow cover duration and amount will significantly influence runoff and water availability (Beniston, 2003). Glacier retreat will add to this development. Nowadays glaciers in the European Alps are balancing the discharge of torrents and mountain rivers during heat waves with little precipitation due to increased ablation rates (melt water). The shrinking glaciers will lose volume and therefore also balancing capacity. Consequently a greater variability in river discharge, for torrents and mountain rivers, has to be expected (Zappa and Kan, 2007). Climate change will also alter seasonal patterns of river discharge. Graham (2005 in Beniston, 2005), for instance, expect enhanced flood risk in the late winter in alpine catchment areas at the end of the 21st century, compared to today due to changed precipitation patterns. Concurrently drought will be intensified in late summer and early autumn. Ultimately, the hydrological conditions projected by regional climate models for the European Alps correspond to current conditions in the Mediterranean mountain regions (Beniston, 2005). Furthermore, Beniston (2005) concludes that increases in extreme precipitation events in combination with snowmelt could increase the frequency and severity of floods. Such extreme events would affect erosion, discharge and sedimentation rates in alpine catchments, and have the potential to damage hydro-power infrastructure. Furthermore, sediments deposited in large quantities on agricultural lands, irrigation canals and streams would lead to reductions in agricultural production. Climate change will affect seasonality and variability of runoff and discharge. Furthermore, increased and more severe extreme precipitation events will enhance frequency and magnitude of floods (Beniston, 2005).

In general, an increase in forest cover in subalpine and alpine zones enhances flood protection, due to runoff dampening. – Tree line shifts are reported to occur in a range from slow shifts (Bolli *et al.*, 2007) to several hundred meters within a relatively short time (Tinner and Kaltenrieder, 2005). Whereas effective in small catchments at continental scales the ability of forests to prevent flooding is limited. This is shown in a study by Bendix (1997) investigating human impact on flood discharge in the river Rhine catchment. According to Bendix (1997) the sensitivity of the flood regime to large-area land use changes is low. The results of a GIS-based water-balance model show, that a conversion of 25% farmland to coniferous forests in the Rhine catchment would only yield a water-level reduction of 6 cm at the Cologne (Germany) gauging station during a flood event (comparable to the flood in 1993) (Bendix, 1997). In general it can be said, that the smaller the catchment, the larger the possibilities to enhance flood protection by natural or artificial reforestation. – In smaller catchments, however, also the impact of large scale disturbances, like wind throw or fire, on the protective function is more pronounced than in larger ones. Summarizing, the protective function of forests against flooding may be particularly important in headwater catchments in the mountains protecting smaller settlements and infrastructure.

*Debris flow*

In studying climate change impacts on debris flow a lot of attention has been paid to the periglacial regions and less to regions at lower altitudes. The principal triggering mechanisms for debris flows are abundant rain, snow-melt and runoff or a combination of them. Rebetez *et al.* (1997) report, for Switzerland, that during the 20$^{th}$ century the number of extreme rainfall events, capable to trigger debris flows, has increased. Additionally, glacial and permafrost retreat, as increasingly observed over the last decades and expected to continue in the future, releases a huge amount of easily erodible debris mass (Zimmermann and Haeberli, 1992; Haeberli and Beniston, 1998; Watson and Haeberli, 2004). Studies from the Italian Alps document increasing debris flow frequencies at the margins of glaciers (Chiarle *et al.*, 2007). Revegetation of terrain after deglaciation is slow and therefore leaves deglaciated morainic deposits unprotected against erosion for decades to centuries (Haeberli and Beniston, 1998; Watson and Haeberli, 2004).

For the protective function against debris flows it is important to distinguish between debris flows triggered below and above the timber line. For debris flows with their starting zone in the periglacial region, often characterized by large magnitudes, the protective influence of underlying forests is limited. In general forests have the potential to reduce debris flow hazard by covering erodible debris, dampening of water infiltration into the soil and by reducing soil moisture in the starting zone. In the transit and run out zone the influence of forest is less distinct due to the high energy of these often channelled flows. Woody debris can even worsen the situation by clogging the channel.

Concerning debris flows starting within potentially forested land, increased forest cover due to climate change (cf. tree line shift) may influence future debris flow activity by dampening runoff peaks and reducing erodible masses. At this point considerable uncertainties with regard to the protective function of forests against debris flow under changing climatic conditions remain.

*Landslide*

Melting of permafrost and changes in hydrology at high altitudes will change the pedological conditions in steep mountain slopes, making them more unstable, and potentially increasing the frequency and intensity of landslides (Beniston, 2005).

However, the spatial pattern of landslide (re)activation is likely to be complex, as different areas in Europe will experience variable changes in the magnitude and frequency of precipitation (cf. Chapter 3). Moreover, landslides are influenced by both meteorological changes in the long term (monthly or yearly rainfall) and short term (daily or weekly rainfall) (Asch, 1996; Buma and Dehn, 1998; Buma and Dehn, 2000).

Detailed information on climate change impacts is provided by first studies harnessing computer models. Dehn (1999) carried out a simulation study on landslide activity under climate change for a mudslide in the Dolomites, Italy (1320-1520 m a.s.l.). He finds a significant reduction of landslide activity in spring for the simulated period from 2070 to 2099. This is due to the rise of winter temperature which impedes storage of winter precipitation as snow. As a consequence, less melt water is available in spring with subsequent lower run-off peaks, causing a decrease in landslide activity. Results on impacts found in various simulation approaches, such as a decrease in landslide activity in spring, can be considered of high confidence. For the other seasons no clear signal could be detected (Dehn, 1999).

Similar to debris flows, landslide protection by forests is most efficient in the starting zone by dampening run off and water infiltration, lowering of the soil water table and stabilizing the soil by rooting. Therefore, an essential issue for the protection against landslides is the maintenance of vegetation cover to prevent erosion (Beniston, 2003). In the transit and run out zone vegetation effects are less important. Tree line upward shift, as projected by different authors as a result of changing climate, may lead to extended areas benefiting from the positive effect of tree cover. This is at least important for shallow landslides where rooting in the upper soil layers is a crucial stabilizing factor. As for debris flow a lot of attention has been paid to regions of glacier retreat and permafrost degradation also with regard to landslides. For areas below the timberline information on future landslide activity is still sparse.

*Rock fall*

Rock fall studies have been implemented evaluating the impact of past climate change, however literature on projected future climate change impacts is scarce. As stated before (cf. debris flow), much more research efforts have been made in researching the periglacial region. One exception is a study by Gruner (2004), who evaluated 800 rock fall events in the northern Swiss Alps. No correlation has been found between humid and warm periods and an increase of rock fall events between 1500 and 1900. For the 20$^{th}$ century the study reports an increase of rock fall events in winter during the cold period between 1950 and 1980, due to rock mass contraction and joint expansion. Rock fall frequency was higher than in the periods from 1900 to 1950 and from 1980 onwards despite increasing intensive precipitation events in the last decades of the 20$^{th}$ century. A general increase in rock fall events due to warmer climate was not discernible and is not expected within the next 50 years. Gruner (2004) expects the warmer climate to cause a further decrease in rock fall events in winter and a moderate increase in summer due to a higher frequency in extreme precipitation events (Gruner, 2004).

For protection against rock fall a continuous (over time and space) forest cover with certain structural specifications is important throughout the full rock fall trajectory. In the starting zone the protective function is most efficient by stopping the rock before it gains speed and thus energy, or by simply preventing detachment from bedrock. In the transit and run out zone high stand densities and/ or trees of certain dimension (i.e. dbh) are beneficial to reduce energy of jumping and rolling rocks. Disturbances like fire, wind throw and bark beetle infestations have the potential to negatively influence the protective function of forest stands against rock fall at project level (Schumacher and Bugmann, 2006). As there is no clear projection for storm intensity and frequency (cf. exposure) currently no impact of climate change related wind throw on rock fall protection can be projected. Increased fire occurrence is expected to impose adverse impact especially in the drier regions of the Alps, e.g. Ticino, Switzerland (Reinhard *et al.*, 2005; Fuhrer *et al.*, 2006; Schumacher and Bugmann, 2006). Disturbances in general change the stand structure and therefore can heavily influence protective functionality and furthermore hamper controlled management.

*Avalanche*

Avalanche activity is controlled by snow cover, terrain and weather. Consequently the relationship between climate and avalanches is less direct than between climate and snow cover (Föhn, 1992). Laternser and Schneebeli (2002) analyzed a 50-year time series (second half of the 20th century) of avalanche activity data of 84 Swiss avalanche observation stations. Using different statistical descriptors, they were unable to detect a long-term change in avalanche activity, which stands in contrast to a significant increase of winter precipitation (Laternser and Schneebeli, 2002).

Projected climate change trends are likely to cause reduced snow loads at lower altitudes due to rain replacing snowfall, but increased snow masses at high levels due to more abundant (solid) precipitation. It has been estimated that the snowline will rise by about 100-150 m for every degree of warming (Watson and Haeberli, 2004).

Glazovskaya (1998), conducting a broad simulation study for a $CO_2$ doubled atmosphere covering the northern hemisphere, calculated an up to 50% decrease of days with intensive snow fall (> 10mm $d^{-1}$) for the Alps. The consequence would be a reduction of the avalanche season in the Alps (Glazovskaya, 1998). But due to this large-scale approach these results have to be seen as tentative and therefore they only show a possible trend of future avalanche development. Martin *et al.* (2001) conducted a simulation study over the 21st century for the French Alps. As a result they find the avalanche hazard to decrease slightly in winter (November-January) and a more pronounced reduction in February and May-June (because of decreasing snow cover duration). The relative importance of new-snow avalanches is expected to diminish (Martin *et al.*, 2001).

Overall, the combination of processes such as a rising snowline and changing precipitation patterns with local geomorphological conditions renders a conclusive overall statement on climate-induced changes of avalanche risks in European mountainous areas unfeasible.

Climate change impacts influencing the protective function of forests against avalanches include the rise of the tree line which reduces possible avalanche starting zones. As stated before, literature sources are not consistent how fast these rise will happen, but there is clear evidence supporting the general trend of an increasing timberline, provided that suitable microsites are available (Bolli *et al.*, 2007).

Furthermore, increased disturbance frequency and severity very likely will affect the functionality. A loss of snow cover stabilizing trees is especially crucial for avalanche protection forests. These structural elements not only affect avalanche development they are of significant importance with regard to regeneration where snow gliding is prohibiting the establishment of saplings. In particular, fires might increase in drier regions of the Alps in the future (Reinhard *et al.*, 2005; Fuhrer *et al.*, 2006; Schumacher and Bugmann, 2006) and bark beetle outbreaks are to be expected also in higher elevations. However, little information is available on direct climate change effects on avalanche activity and potential interactions with forest structure and functioning.

With respect to the different avalanche types no research has been conducted investigating in which way the occurrence and characteristics of avalanches will be influenced by climate change. Nevertheless this information would be beneficial with regard to the protective function, because according to the avalanche type protective forests have to have different properties.

So far we could not identify any reports on a scenario-based analysis of climate change impacts for **the Pyrenees**. Particular protective functions may be at risk in a warmer and drier climate which favours forest **fires**. Moreover, increased torrentiality (Giorgi *et al.*, 2004) is likely to lead to increased erosion risk (De Luís *et al.*, 2003) due to reduced plant regeneration after frequent fires (Delitti *et al.*, 2005).

In general, the impact of climate change on the protective functions of forests is not yet thoroughly understood. Therefore research is needed to enhance knowledge and foster climate change adaptation in this crucial field for societies in mountainous areas.

# 5 ASSESSING ADAPTIVE CAPACITY OF EU FORESTS

This chapter assesses the adaptive capacity of forest ecosystems and the forest sector to respond to the anticipated environmental changes. The two components of adaptive capacity will be analysed:

(i) the **inherent adaptive capacity** of trees and forest ecosystems, and

(ii) the **socio-economic factors** determining the ability to implement planned adaptation measures.

## 5.1 Inherent adaptive capacity

Tree species have been exposed during their evolutionary history to long term "natural" environmental change, and have shown capability to respond and adapt to these changes. This historical evidence suggests that they have demonstrated evolutionary potential to cope with climatic changes. By "inherent adaptive capacity", we refer to the evolutionary mechanisms and processes that permitted tree species to adjust to new environmental conditions. Rather little is know on the pace of the evolutionary processes, whereas a large body of results obtained mostly in provenance tests demonstrate that tree populations were substantially differentiated during the Holocene. Learning from these records, we will review in this section how these mechanisms may be acting during the ongoing and future climatic changes. Translated in genetic terms, climate change represents a gradual directional environmental shift that is sporadically shaken by stochastic events (so called extreme events). Evolutionary response of population can most easily be predicted in the case of directional selection pressures, and theory may be appealing in this frame. However, occurrence of extreme events raises a major challenge that has not been addressed theoretically.

We review the different mechanisms and how they are acting at different hierarchical levels, from individuals to communities via populations and species. Additionally we focus our attention at the time scales at which these mechanisms are acting. These are:

- Evolutionary  mechanisms at the individual level
  - Individual heterozygosity
  - Acclimation
  - Epigenetic response
- Evolutionary mechanisms at the population level
  - Natural selection
- Evolutionary mechanisms at the species level
  - Enhancement of local adaptation by gene flow
  - Colonization of new sites
- Evolutionary mechanisms at the community level
  - Facilitation versus competition among tree species
  - Interspecific hybridization

### 5.1.1 Evolutionary mechanisms at the individual level

Adaptive mechanisms of individual trees have been gathered under the generic term *plasticity.* Strictly speaking, phenotypic plasticity is the ability of a tree to exhibit different phenotypes under different environmental conditions (Fig 13). Furthermore if different tree genotypes express different phenotypic plasticity, then phenotypic plasticity has a genetic background, and can be of evolutionary significance.

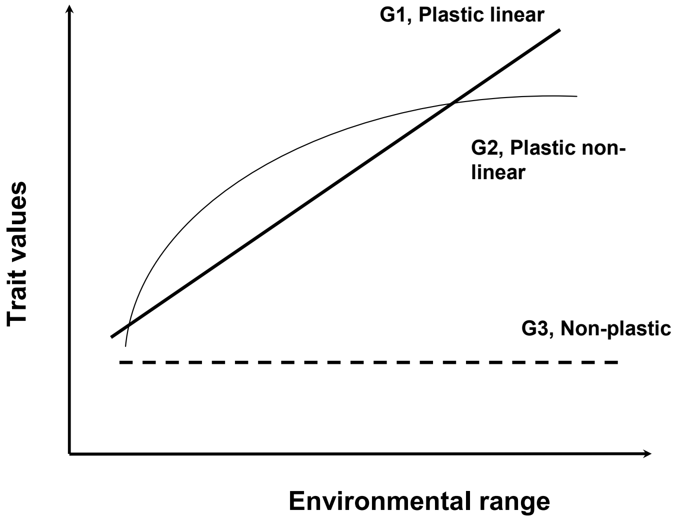


**Figure 13**. An example of genotypic reaction norms illustrating the concept of phenotypic plasticity. In the simple case, the lines represent the norms of reaction of each genotype, while the slope is a measure of the degree and pattern of phenotypic plasticity. For example, genotypes 1 and 2 are both plastic, but display different patterns in response to the same environments; genotype 3, on the other hand, shows no plasticity for this trait in this environmental set.

- ***Individual heterozygosity***

In diploid organisms, there are two alleles coming from each parent at a given locus. A heterozygote locus bears two different alleles, and individual heterozygosity is the proportion of heterozygote loci within a given organism. Hence individual heterozygosity accounts for genetic diversity at a single tree level. There has been considerable debate on the evolutionary significance of heterozygosity, some authors claiming that heterozygous individuals exhibit greater buffering capacity towards environmental change (Mitton, 1997). Whatever the evolutionary significance of heterozygosity might be, there are examples where individual heterozygosity has been correlated (surrogate or cause?) to adaptation to strong environmental changes. This is illustrated by the comparative analysis of heterozygosity in sensitive versus tolerant beech populations in heavily polluted areas during the late 1970s in Germany (Müller-Starck, 1988). In this example (Table 16), the observed heterozygosity of each tolerant beech population was larger than the heterozygosity of sensitive populations wherever the comparison was made, and the difference was larger at higher altitudes where pollution was stronger.

**Table 16.** Observed heterozygosity (Ho) in pollution sensitive and tolerant stands of beech. Pairs of beech stand were sampled at different altitudes in the Black forest, Harz Mountains, and Eastern Bavarian Forest. Heterozygosity was assessed on 14 to 17 isoenzymatic loci (after Müller-Starck, 1988). Interestingly the difference in heterozygosity values is larger at higher altitudes, where atmospheric pollution was more severe.

| Altitude (m) | Ho Tolerant (%) | Ho Sensitive (%) |
|---|---|---|
| 230-250 | 25.4 | 22.6 |
| 450-500 | 28.9 | 22.6 |
| 550-600 | 24.2 | 19.5 |
| 850-900 | 28.3 | 20.3 |
| 810-830 | 31.4 | 27.4 |
| 770-870 | 27.7 | 22.4 |

- ***Acclimation***

Acclimation is the phenotypic change of a single individual to gradual environmental modification, i.e. it is a reversible process. The premature leaf fall of some trees during dry summers is an example of rapid acclimation. A well illustrated case of acclimation response over the lifetime of a tree is the gradual decrease of leaf stomatal density on a single birch tree that was observed over 50 years (Wagner *et al.*, 1996) as a response to the steadily increasing atmospheric $CO_2$ concentration (Fig. 14). The genetic basis of such phenotypic response has not been elucidated, and to date it is considered to probably be a physiological adaptation to environmental changes.

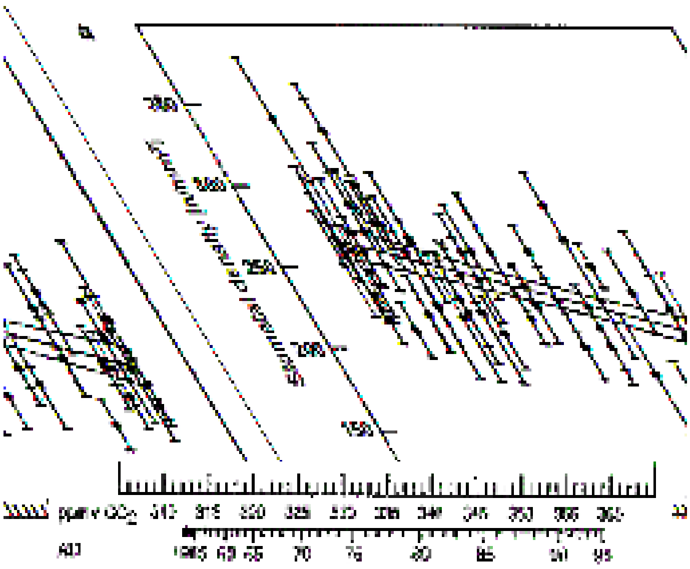

**Figure 14**. Response of stomatal density for Betula pendula to global atmospheric $CO_2$ increase in the period 1952–1995. The linear regression line, with 95% confidence limits, shows a reduction from mean maximum 275 to mean minimum 198 stomata per $mm^2$ (after Wagner *et al.*, 1996).

- ***Epigenetic response***

Epigenetic response indicates changes in gene expression due to DNA or chromatin or methylation modifications without any changes at the underlying DNA sequence. Many epigenetic responses have been documented in plants as a response to temporary, severe environmental or biotic stresses (Madlung and Comai, 2004). Epigenetic effects under milder environmental changes have not received as much experimental support, with the exception of the modifications of chromatin of target loci on vernalization in plants (Sung and Amasino, 2005). Epigenetic processes are also involved in other types of phenotypic plasticity, such as the environmentally induced transition to flowering in plants (Bastow *et al.*, 2004; He and Amasino, 2005), and they apparently mediate some types of maternal environmental effects (Rossiter, 1996; see e.g. Anway *et al.*, 2005; Cropley *et al.*, 2006). A well known case in trees is a "maternal effect", where the response of trees has been shown to be influenced by the environmental conditions prevailing during the development of the embryo in *Picea abies*. In a series of repeated experiments on offspring originating from the same parents but with the mothers raised under different weather conditions, it has been shown that the climate during sexual reproduction influences the development of seedlings (Skrøppa *et al.*, 1994; Johnsen and Skrøppa, 1997, see Fig. 15). The timing of bud break in spring, leader shoot cessation in summer, bud set in autumn and the lignification of the annual ring are all processes that will be advanced or delayed according to temperature during female reproduction. Temperature-induced regulation of the level of gene expression (through methylation) in the developing embryos is supposed to last in the progenies as an 'epigenetic memory' (Johnsen *et al.*, 2005).

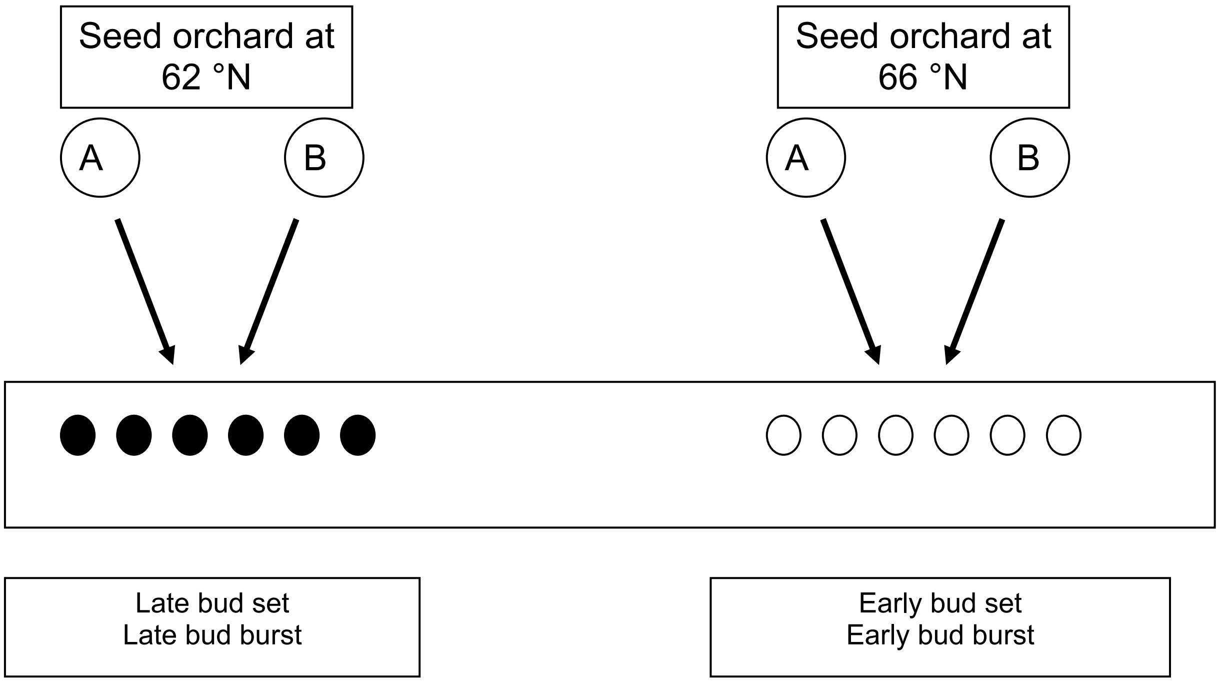


**Figure 15.** Example of environmental induced "maternal effects" enhancing local adaptation in spruce. Seedlings obtained from the same full sib crosses (parent A mated with parent B) in two different environments (seed orchards at different latitudes) exhibit different juvenile traits allowing adaptation to the environment of the maternal parent (adapted from Skrøppa *et al.*, 1994; Johnsen and Skrøppa, 1997). Later it was shown that temperature prevailing during embryogenesis is correlated to the different seedling behaviour (Johnsen *et al.*, 2005).

Mechanisms acting at the individual level will of course take place during the lifetime of a tree. However, they may not be cumulative over successive generations in a directional pattern. Individual heterozygosity would be cancelled out after each generation as meiosis and random mating will disrupt allelic associations in diploid organisms. Acclimation or epigenetic responses may also be erased when passing to the next generation, depending on their inheritance. However, recent studies indicated that epigenetic variation in natural populations can be independent from genetic variation and that in some cases environmentally induced epigenetic changes may be inherited by future generations. These novel findings are potentially highly relevant to ecologists because they could significantly improve our understanding of the responses of organisms to environmental change. The genetic basis of methylation or other epigenetic sources of change is not fully understood, and their inheritance remains speculative at this stage, at least in trees. More studies are required to better understand this process (Fig. 16).

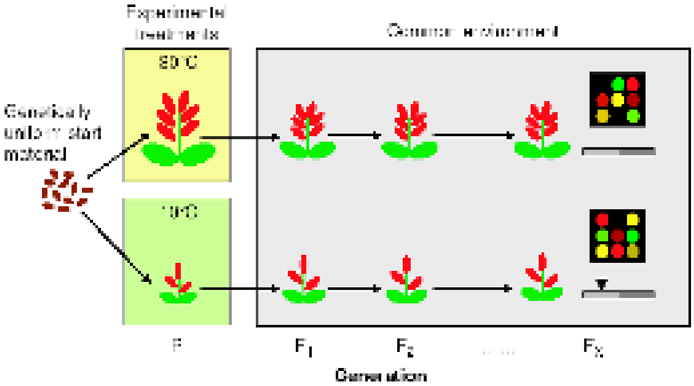


**Figure 16.** Outline of an experimental design that tests for the environmentally induced rapid epigenetic evolution. First, the same plant genotypes are subjected to contrasting environments for at least one generation. Second, their progeny is bred in a common environment for several generations, to examine whether epigenetic changes and associated phenotypic differences are passed on to the following generations. Ideally, one should demonstrate that at the end of the experiment the phenotypes and patterns of DNA methylation (black triangle) or gene expression of these environment lines are different, but not the DNA sequence (grey horizontal bars) (after Bossdorf *et al.*, 2008).

### 5.1.2 Evolutionary mechanisms at the population level

- ***Natural selection***

Local adaptation is the process by which natural selection drives populations towards higher fitness to meet the environmental changes. The response is a continuous shift in gene frequencies or phenotypic values of traits. There is ample evidence of the efficiency of natural selection shown by the large body of literature on provenance tests (see Wright (1976) and Morgenstern (1996) for reviews in North American species, and König (2005) for a review in European species). In almost any tree species for which provenance tests have been established, significant variation between populations has been observed for fitness-related traits. There are several clinal patterns of geographical variation that are congruent across species living in different continents, suggesting that these patterns result more likely from directional selection pressures than from stochastic, demographic or historical effects. For example, bud burst shows a clear latitudinal variation in all conifers, with northern provenances flushing earlier and setting bud earlier than southern populations (Wright, 1976). Moreover, clines in timing of bud set and total height growth are also reported in the literature (illustrated for 18 populations of Sitka spruce sampled across the species range spanning 30° of latitude (Fig. 17, Mimura and Aitken, 2007). Using these data, we can predict the capacity of Sitka spruce to adapt to rising temperatures. If climate change causes shifts in mean annual temperature of 3-5 °C over the generation time of Sitka, then we would expect the optimum date of but set to change by approximately 39-65 days, assuming populations are currently locally adapted. Other evidence that selection is the most likely evolutionary force responsible for provenance variation is given by the comparative analysis of ‘historical’ versus ‘geographical’ factors of variation. In oaks, it was shown that extant populations stemming from the same source (refugial) of glacial origin but growing today in different ecological sites exhibit strong phenotypic differentiation for fitness-related traits, while the populations are not differentiated for neutral genetic markers (Le Corre *et al.*, 1997; Kremer *et al.*, 2002).

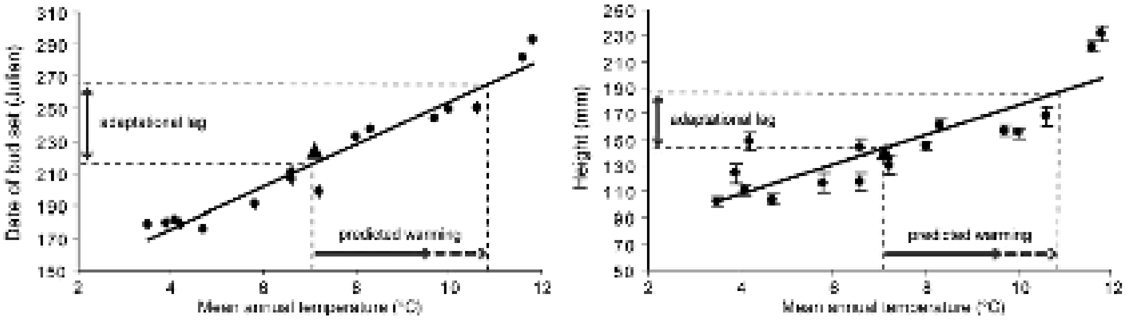


**Figure 17.** Genetic clines along a gradient in mean annual temperature for mean date of bud set and total height for 17 populations of Picea sitchensis from across the species range (data from Mimura and Aitken, 2007) as observed in provenance tests. The horizontal arrow illustrates the range of magnitude of warming predicted from global circulation models.

Natural selection would induce recurrent and cumulative directional evolutionary change over successive generations. From a theoretical standpoint, the capacity of a population to persist (avoid extinction) to the continuous directional change of the environment has been investigated by Bürger and Lynch (1995; 1997), who considered a model where fitness was due to a single phenotypic trait that is undergoing directional selection. Their practical outcome was that populations are able to be maintained as long as the rate of environmental change was below a critical value that was shown to be dependent on biological features of the populations: genetic variation, heritability of the trait, strength of selection, fecundity, and population size. When applied to trees, these predictions suggest that substantial shifts in population values can take place during natural regeneration due to the high strength of selection, the high fecundity and large population size of tree populations. These predictions are somehow also supported by the important genetic changes obtained in directional artificial breeding programmes within one generation. However it should also be considered that fitness is most likely a function of multiple traits and that stochastic environmental variation may disrupt gradual genetic shifts of the populations.

### 5.1.3 Evolutionary mechanisms at the species level

Besides the processes acting at the individual or population level, there are also important processes acting at the species as a whole, as composed of genetically interconnected populations, capable of colonizing new sites, but also susceptible to face extinction. Evolutionary mechanisms that may mitigate global change are gene flow via pollen and colonization.

Local adaptation can be increased by “incoming genes” via pollen stemming from populations exhibiting higher fitness than the receiving population. In the case of directional environmental changes towards higher temperature, it is likely that populations from more southern latitudes may constitute valuable pollen source populations in this respect. The question raised here is whether pollen dispersal distances will be of the same magnitude then the shift of isotherms and the associated bioclimatic envelopes of species.

- ***Enhancement of local adaptation by gene flow***

Gene flow may contribute to increasing the fitness of a given population that encounters severe selective pressures. Migration of alien genes through gene flow will change the genetic composition of the receiving population. Subsequent changes might be unfavourable or favourable, depending on the source population (Lenormand, 2002). If the migrating gene has a positive effect on fitness, it will rapidly increase its frequency in the receiving population. The dynamics of migrating genes (migration rates, subsequent frequency variation and change in population fitness) have never been monitored in forest tree populations, but deserve to receive more attention within the focus of climate change. Clearly, a species that has a continuous distribution across contrasting ecological sites might be able to 'import' genes contributing to higher fitness in areas exposed to severe stress. However, a species having a scattered and disrupted distribution may not be able to benefit from alien genes. Extensive research has been done on gene flow in forest trees at a rather narrow spatial scale (Austerlitz *et al.*, 2004; Smouse and Sork, 2004). Most of these theoretical and experimental studies have shown that gene dispersion has both local and large-distance components, as revealed by the existence of the 'fat tails' of the dispersion curve. The second component is, of course, more relevant in the context of climate change, as drier sites where potentially favourable genes are likely to exist, may be separated by rather long distances from the sink population that would benefit from the imported gene. Modelling approaches taking into account pollen emission, viability and deposition suggest that viable pollen of oak can be dispersed up to 100 kms (Schueler *et al.*, 2005; Schueler and Schlunzen, 2006). Dispersion from the source to the sink populations may take one or more generations, depending on the spatial connectivity between the two populations.

Gene flow studies have usually been undertaken at two extreme time scales: (1) instantaneous gene dispersion within one generation, conducted by parentage analysis; and (2) cumulative estimations over long historical time scales, derived from genetic differentiation measures. Further research is required in the frame of climate change to investigate dispersion distances over a very few successive generations at landscape scale.

- ***Colonization of new sites***

A series of papers have recently been published predicting the shift of the bioclimatic envelope of European tree species as a response to climate change (Thuiller, 2003; Badeau *et al.*, 2005; Thuiller *et al.*, 2006). The delineation of the "bioclimatic envelope" is based on the modelled association between current climatic conditions and today's geographic distribution of a species. The geographic distribution of the envelope is then projected in the future using various predictions of climatic conditions in 50 to 100 years from now, assuming that it remains stable over time. To sum up, these investigations have shown that by the end of the 21st century, the envelope of most species will be shifted from 100 to 400 kms northwards and eastwards. The projections suggest that environmental conditions at the northern and eastern limit of natural distribution may be potentially suited for immigrants of southern altitudes. Will natural migration via seed dispersal be sufficient to reach the isotherm shift due to climatic change?

Postglacial history of forest trees provides insights on the dispersal capacity of trees. Since trees were major components of past European landscapes, they produced large quantities of pollen that survive in fossil remains (Huntley and Birks, 1983). Migration rates were inferred from historical species ranges reconstructed using pollen fossil data for several European tree species (Birks, 1989) in the British Isles and on a continental scale in oaks (Brewer *et al.*, 2002) and beech (Magri *et al.*, 2006). The average rate of spreading varied between 100 and

700 metres per year, depending on species and the periods of colonization. Earlier dispersion rates (11 000 to 9 000 BP) were usually higher and strongly correlated with climate change, whereas more recent rates (6 000 to 4 000 BP) were lower, as competition between species constrained their spread (Birks, 1989). Despite the limitation of migration rates derived from pollen data (McLachlan and Clark, 2004), these figures could be used to provide some rough estimates predicting future natural dispersion. At maximum, trees would be able to shift their range from 10 to 70 km during the next coming hundred years, not taking into account that land fragmentation and agriculture would actually reduce migration. This is far less than the shifts of range predicted for oak or beech based on the bioclimatic envelopes projections (Thuiller, 2003; Badeau *et al.*, 2005). Hence, natural dispersion would need to be assisted by artificial seed transfer to cope with the shifting bioclimatic envelopes.

As we described above, shifts in tree species and biome distribution in response to warming have been described in past climate changes. However, reported evidence of such shifts under current climate warming is still scarce. At our knowledge, only one study showed tree species shifts at theirs southern limits (Peñuelas and Boada, 2003). By comparing current and 1945 vegetation distribution in the Montseny mountains, they reported a progressive replacement of cold-temperate ecosystems by Mediterranean ecosystems. Beech (*Fagus sylvatica*) forest has shifted altitudinally upwards at the highest altitudes, whereas it was replaced by holm oak (*Quercus ilex*) at medium altitudes. Even through these shifts seem mostly due to warming, land-use practice changes may have played a role as well.


**Figure 18.** Altitudinal upward shift (70 m) of beech forest to the top (1700 m) of the highest summits in the Montseny mountains (Catalonia, NE Spain in the last 55 years. (Heathland corresponds to Calluna vulgaris and Juniperus nana communities).

## 5.1.4 Evolutionary mechanisms at the community level

- ***Facilitation versus competition among tree species***

Biotic interactions are recognized as one of the most important filters of community composition (Lortie *et al.*, 2004), and their importance as potential filters of the impacts of climate changes on plant communities needs to be assessed more precisely (Brooker, 2006). Significant evidence is accumulating that interactions play a role in mediating the impact on natural communities of these environmental change drivers (Brooker, 2006; Maestre and Reynolds, 2006, 2007). However, the exact nature of that role, and how it will alter in response to environmental change, remains unclear. Competition and facilitation are known to vary along environmental gradients (Grime, 1979; Bertness and Callaway, 1994; Callaway *et al.*, 2002) but the processes inducing these changes stay largely unclear. In the context of climate changes, most experiments including the role of biotic interactions have shown that when climate change induces a decrease in environmental stress there is an increase in competition (Davis *et al.*, 1998). For example, Klanderud (2005) has predicted a general shift in species interactions from more strongly positive to more strongly negative as these environments warm, which exacerbates the impact of climate change on the species. In contrast, Wipf *et al.* (2006) have shown that facilitation may increase under global warming in cold arctic environments when environmental stress increases buffering the effect of climate changes on the beneficiaries species. In other words, climate changes and biotic interactions have two-way links: biotic interactions could mediate the response of plant communities to climate changes, whereas on the other hand climate changes could affect the strength and the direction of biotic interactions in plant communities. Hence the mitigation effect of biotic interactions among species remains largely unknown. Improving our knowledge of the shift in interactions under climate change in different climate regions will help in explaining how forest communities could react to global warming.

- ***Interspecific hybridization***

Most European tree species existing under temperate latitudes have congeneric interfertile species inhabiting Mediterranean latitudes (*Pinus, Abies, Quercus, Picea, Fraxinus* etc.). Colonization dynamics stimulated by climatic changes will reinforce the admixture of temperate and Mediterranean species and increase opportunities for hybridization and introgression among species. The combination of introgression and selection may further contribute to novel allelic associations enhancing adaptation of introgressed forms. The outcome is largely dependent on the relative fitness of introgressed forms vs parental species under the new environmental conditions, and remains at this time speculative. The process can be extremely rapid if transgressive segregation occurs, but could require as well several successive generations in case successive backcrosses are needed to achieve fitness superiority of introgressed forms.

## 5.2 Socio-economic adaptation capacity

The concept of adaptive capacity was introduced in the IPCC Third Assessment Report (IPCC TAR, McCarthy *et al.*, 2001). According to the IPCC TAR, factors that determine adaptive capacity to climate change include economic wealth, technology and infrastructure, information, knowledge and skills, institutions, equity and social capital. Most adaptive capacity research to date has been conceptual in nature, asking questions such as "what is it?", "what determines it?" and "how can it be measured?" One paper has made an attempt at quantifying adaptive capacity based on observations of past hazard events (Yohe and Tol, 2002). For the ATEAM vulnerability assessment framework, Schröter *et al.* (2004) were seeking present-day and future estimates of adaptive capacity that are quantitative, spatially explicit and based on, as well as consistent with, the scenarios produced by the IPCC in its Special Report on Emissions Scenarios (SRES, Nakicenovic *et al.*, 2000). They developed an **index of adaptive capacity** that indicates the macro-scale outer boundaries of the capacity of a region (i.e. provinces and counties) to cope with changes (Fig. 19). The index did not include individual abilities to adapt.

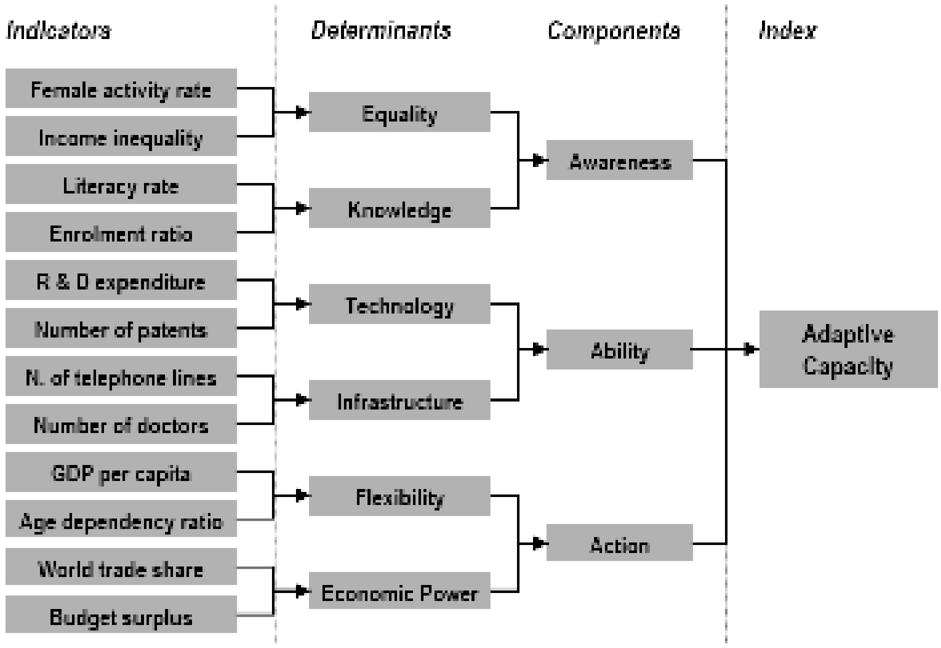


**Figure 19.** Conceptual framework developed in the ATEAM project as a three step aggregation of indicators, determinants and components of adaptive capacity into a generic adaptive capacity index. Enrolment ratio = Ratio of people enrolled in higher education programs; R & D expenditure = Research and Development expediture; N. of telephone lines = Number of telephone lines; GDP = Gross domestic product (Schröter *et al.*, 2004).

First, determinants of adaptive capacity and indicators describing them were selected. To obtain scenarios of adaptive capacity future projections for population and gross domestic product (GDP) were used together with time series data (1960-2000) for other indicators on a regional scale. Next, the functional relationships between the indicators and population and GDP data were developed. Indicator scenarios were then extrapolated using the historical functional relationships between the respective indicator and population and GDP. Finally, a conceptual framework was developed to aggregate indicators to a generic index of adaptive capacity in three steps using a fuzzy logic approach. For future scenarios of the index of adaptive capacity, the projected indicator data were aggregated per scenario and time slice.

Using this methodology, maps of the generic adaptive capacity index for the four SRES scenarios and four time slices for each of the scenarios were produced (Fig.20). The top row shows an initial step of ‘calibration’, i.e. comparing the adaptive capacity index based on observed data from 1995 with the maps of extrapolated data for the baseline year 2000. Both maps show about the same patterns of adaptive capacity, with improvements in adaptive capacity in most areas in the year 2000. Areas in the Iberian Peninsula and Greece tend to have low macro-scale adaptive capacity relative to Northern European regions. Comparing the different SRES scenarios over time, macro-scale adaptive capacity generally increases over time. In areas where it slightly decreases again towards 2080, e.g. France in A1 2020 compared to 2080, this leads to a more homogeneous pattern within Europe.

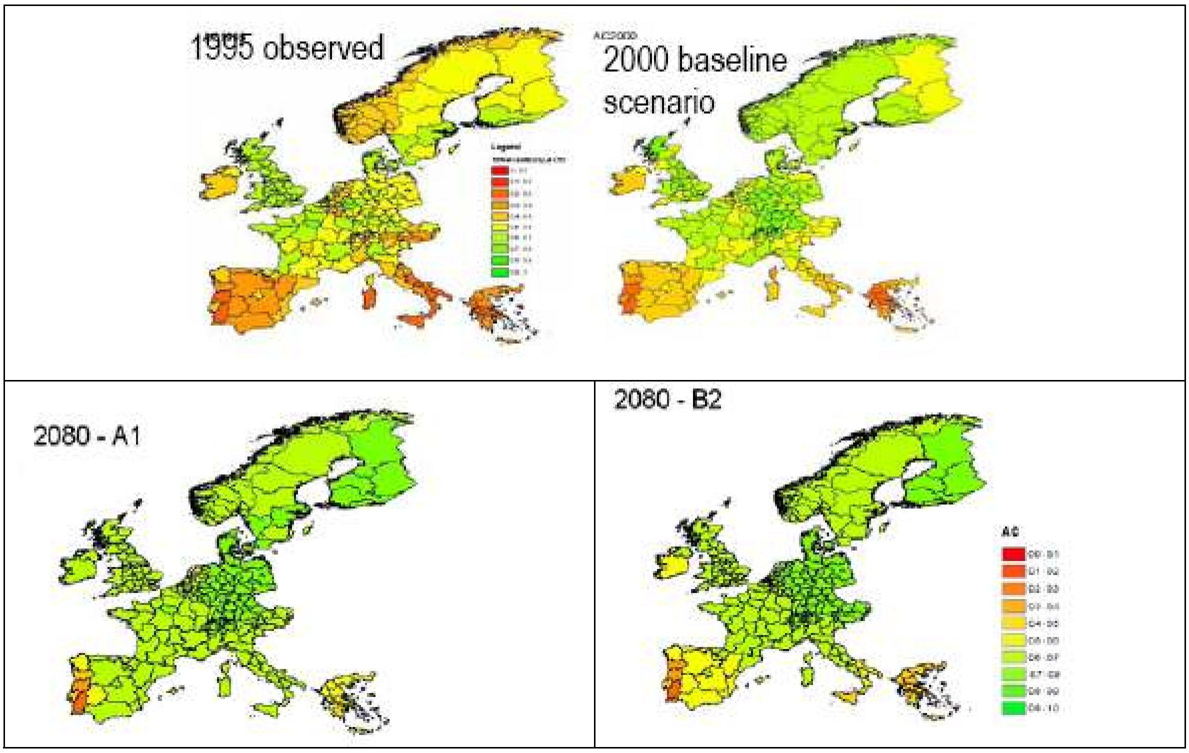


**Figure 20.** Preliminary maps of the adaptive capacity index developed in ATEAM (green = high adaptive capacity, red = low adaptive capacity). Top row, calibration maps based on observed data (1995, left map) and extrapolated data (2000, baseline, right map). The bottom row shows the projected adaptive capacity for 2080 under the A1f and B2 SRES scenarios respectively (Schröter *et al.*, 2004).

The ATEAM results have been criticised as they do not include individual adaptation ability and thus they underestimated the important social dimension of adaptive capacity (Adger *et al.*, 2007). Furthermore, some indicators used as components of the index were questioned. In the age of mobile telecommunication, 'Number of telephone lines', as used in this approach, will not adequately indicate a region's communication infrastructure. Moreover, the maps do not show large variability across Europe – reflecting the fact that differences in societies ability to adapt to climate change varies much less within Europe compared to the global scale (McCarthy *et al.*, 2001). Nevertheless, these results were the first spatially explicit projections of future adaptive capacity.

The socio-economic adaptation capacity related to the forest sector has rarely been analysed in EU 27 up to now. Keskitalo (2008) pointed out that external factors such as globalisation and demands for rationalisation and profitability are constraining the adaptive capacity in the forestry sector. Economic viability in the context of limited resources was an important issue for most of the forest stakeholders interviewed in a case study in Northern Sweden.

Adaptive capacity in case study regions in Northern Sweden and Northern Finland was found to be much higher than in the neighbouring region in Northwest Russia (Lundmark *et al.*, 2008).

Relative to the huge contrast between more and less developed countries at global scale, socio-economic conditions are comparably similar within Europe. Nevertheless, there are significant differences in socio-economic conditions within the forest sector in Europe and these will affect the adaptive capacity to respond to climate change in forestry.

Forest management is most intensive in the North of Europe. Forest sector development has been very dynamic in this region with many innovative technological developments, documenting a very high adaptive capacity. Natural resource conditions are very different in large parts of Southern Europe, where many forests on steep slopes have small potential for economic wood production and social values of forests are more important. The lack of economic activity in forestry is constraining adaptive capacity in those regions, because adaptation would need to be implemented from society with little support from the forest sector.

Forest ownership structures can also influence adaptive capacity. Management traditions and decision making structures are more variable in privately owned forests compared to large public forest holdings. Individual preferences and risk perception differ and this tends to enhance diversity in forest structures and silviculture. This diversity may support adaptive capacity. On the other hand, small and fragmented privately owned forests are often poorly managed, constituting a barrier to efficient wood resource utilisation. Forest co-operations and active support from public forestry administration are possible measures alleviating the constraints. But without them, adaptive capacity is likely to be smaller in regions with a big share of fragmented forest holdings.

Availability or shortage of forest sector work force is another socio-economic factor that differs between regions. Together with the education level of forest workers, which is more or less closely related, this will also influence the adaptive capacity in the forest sector.

A very different constraint to the adaptive capacity may be caused by societal trends and beliefs. Close-to-nature forestry has been a strong trend especially in Central Europe over the last few decades. The concept has been successfully addressing problems caused by the large scale use of even-aged monocultures of coniferous species on sites that would naturally support mixed broadleaved forests (Spiecker *et al.*, 2004). However, when the target orientation in forest management is focusing on the potential natural vegetation of the 20$^{th}$ century only, this concept may constrain the adaptive capacity of the sector by excluding potentially productive species under the changing climate conditions of the 21$^{st}$ century.

# 6 VULNERABILITY, RISKS & OPPORTUNITIES

## 6.1 Introduction

Vulnerability can be defined as the degree to which a system is susceptible to be affected by adverse effects of climate change. The vulnerability of a given system is a function of the climate variation to which this system is exposed (exposure), its sensitivity, and its adaptive capacity. Exposure and sensitivity determine the potential impacts (cf. chapter 4.2) and in combination with the adaptive capacity (chapter 5) vulnerability to climate change can be characterised (Kelly and Adger, 2000; Füssel and Klein, 2006; Metzger *et al.*, 2008).

The vulnerability of ecosystem goods and services to climate change was first assessed in Europe within the ATEAM project (Schröter *et al.*, 2005; Metzger *et al.*, 2008). The project interpreted vulnerability as "*The degree to which an ecosystem service is sensitive to global change + the degree to which the sector that relies on this service is unable to adapt to the changes*". The assessment of vulnerability, risks and opportunities for European forests was studied by Eggers *et al.* (2008). This European study represents the state-of-the-art in this field, but it has clear limitations regarding (i) the climate scenarios that were available, (ii) a relatively coarse resolution of the results due to the aggregation level of regional forest inventory data, and (iii) the lack of consideration of adaptive capacity and planned adaptation in forest management. Potential impacts of climate change were projected to be positive throughout most of the 21st century (Eggers *et al.*, 2008), because the climate scenarios were implemented with an inter-annual variability that was mimicking the 20th century trends. Only the last two decades of the century after 2080 showed more widespread adverse climate change impacts. Metzger *et al.* (2008) linked forest assessment results with an adaptive capacity index calculated across Europe to quantify vulnerability and concluded that vulnerability of the forest sector to climate change was rather low. However, due to the limitations listed above, this assessment has to be interpreted with caution. The last assessment report of the Intergovernmental Panel on Climate Change has underlined the fact that despite of a large adaptive capacity, society may not take the necessary steps for implementing adaptation (Adger *et al.*, 2007) and a comprehensive assessment of vulnerability, risks and uncertainties consequently needs to better address the adaptation capacity in the forest sector.

Very few other studies have assessed vulnerability of the forest sector to climate change in Europe. Vulnerability to climate change and extreme events increases the more dependent a region is on the employment generated by the forest sector (Lundmark *et al.*, 2008). Keskitalo (2008) studied forest sector vulnerability in a small case study in Northern Sweden and stressed the importance of globalisation and other socio-economic changes superseding vulnerability to climate change. When studying vulnerability of reindeer husbandary to climate change, also Rees *et al.* (2008) found that socio-economic changes in the north European study region were more important than climate change. A recent study for Austria Seidl *et al.* (in prep.) found managed mountain forests highly vulnerable to climatic changes, particularly in the second half of the 21st century. Major causes were high sensitivities of indicators that can be linked with ecological and socio-economic adaptive capacity: sustainable forest management indicators such as productivity and disturbances and also ecosystem state indicators decreased significantly under climate change. With the exception of the subalpine vegetation belt vulnerabilities were considerable over all altitudes and were highest on shallow to medium drained calcareous site types (Seidl *et al.*, in prep.).

Because of the weak evidence from the literature, the following qualitative evaluation of vulnerability to climate change in the different bioclimatic regions in Europe will be entirely based on expert judgement. For each of the bioclimatic regions we will connect the climate change exposure with the potential impacts and the adaptive capacity to identify some important threats and opportunities posed by the changing climatic conditions. As most of the available knowledge is limited to potential impacts and sensitivity to climate change, it should be noted that this interpretation is of qualitative nature and less robust then other parts of the study.

**The assessment of regional vulnerability to climate change including quantified risks and opportunities requires more investigation and constitutes a clear research need**.

## 6.2 Assessing vulnerability: a bio-geographical overview

| Boreal | |
|---|---|
| **Expected climate changes** | ▪ Temperature increases between +3.5 - +5 °C by the end of the century, with higher increase during winter (+4 - +7 °C) than in summer<br>▪ Precipitation is projected to increase up to 40%. Winters are projected to become wetter |
| **Potential impacts** | ▪ Increased forest growth rates and higher wood yield projected for most of the region<br>▪ In the south, certain species may have competitive disadvantages and decline under higher temperatures<br>▪ Warmer temperatures in winter shorten frost periods, which can negatively affect harvesting and transport of timber<br>▪ Risk and frequency of snow and wind damage may increase<br>▪ Northward expansion of closed forests and the associated shift of the tree line will strongly affect species distribution and biodiversity<br>▪ Biotic pests are expected to have increased damage potential |
| **Uncertainties** | ▪ The response of tree species and provenances to temperature warming at the southern distribution limits<br>▪ Models differ in the projected impacts of climate change in the southern Boreal region. Particularly the response of Norway spruce to climate change in this region is uncertain |
| **Adaptive capacity** | ▪ Adaptive capacity is relatively large in Finland and Sweden |
| **Key threats** | ▪ Vulnerability to climate change is small compared to other socio-economic pressures on the forest sector<br>▪ Reduced availability of timber due to inaccessibility of forest resources on wet soils outside the frost period will pose a threat to the industry as long as no alternative technical harvesting and transport solutions are found |
| **Key opportunities** | ▪ Improved forest productivity particularly in the northern part of the Boreal region<br>▪ Improved opportunities for increased utilisation of forest resources in the mid- to longer term |

| Temperate Oceanic | |
|---|---|
| **Expected climate change** | ▪ Temperature increase +2.5 - +3.5°C, slightly less in the UK and Ireland<br>▪ Summers are likely to become dryer and hotter<br>▪ Extreme events are projected to become more frequent<br>▪ Higher volumes and intensities of precipitation are expected particularly in winter |
| **Potential direct and indirect impacts** | ▪ Tree growth rates may increase in part of the region, but may also decrease in water limited areas<br>▪ Risk and frequency of wind damage is expected to increase<br>▪ Shifting natural species distribution ranges may negatively impact especially rare species living in isolated habitats<br>▪ Biotic pests are expected to have increased damage potential |
| **Uncertainties** | ▪ Climate change impacts will strongly depend on the future amount and distribution of precipitation<br>▪ Extreme events may be crucial for forests health and productivity, but their frequency and intensity under climate change is still largely unknown |
| **Adaptive capacity** | ▪ Adaptive capacity in the forest sector is relatively large |
| **Key threats** | ▪ Extreme events such as storms, droughts, flooding, and heat waves<br>▪ Increased winter rainfall and high wind speeds in combination may lead to large storm damages<br>▪ Several biotic disturbance agents may impose significant threats, particularly in warm and dry years<br>▪ Conservation of rare species may be threatened because of fragmentation of valuable habitats that is hindering migration to new suitable habitats |
| **Key opportunities** | |

| Temperate Continental | |
|---|---|
| **Expected climate change** | ▪ Temperature increase +3 - +4 °C, slightly more in continental regions of Central Europe and the Black Sea Region<br>▪ Precipitation is expected to increase (up to 10%) mainly in winter, while summer precipitation may decline in several areas |
| **Potential direct and indirect impacts** | ▪ Tree growth rates may increase in part of the region, but may also decrease in water limited areas<br>▪ Risk and frequency of wind damage is expected to increase<br>▪ Shifting natural species distribution ranges may negatively impact especially rare species living in isolated habitats<br>▪ Biotic pests are expected to have increased damage potential |
| **Uncertainties** | ▪ Climate change impacts will strongly depend on the future amount and distribution of precipitation<br>▪ Extreme events may be crucial for forests health and productivity, but their frequency and intensity under climate change is still largely unknown |
| **Adaptive capacity** | ▪ Adaptive capacity is more strongly affected by socio-economic constraints than in the Temperate Oceanic and Boreal regions |
| **Key threats** | ▪ Drought risk is an important threat especially under water limited conditions<br>▪ Extreme events and connected disturbances due to storm, flooding, and fire are important threats<br>▪ Biotic disturbance agents may impose significant threats |
| **Key opportunities** | ▪ |

| Mediterranean | |
|---|---|
| **Expected climate change** | ▪ Temperature increases +3 - +4 °C, larger increases during the summer (+4 - +5 °C) and smaller increase in winter<br>▪ Annual rainfall is expected to decline up to 20% with even stronger reduction in summer<br>▪ Precipitation is expected to increase in winter<br>▪ Extreme events such as heat waves and heavy precipitation events are likely to become more frequent |
| **Potential direct and indirect impacts** | ▪ Tree growth is expected to decline in large areas due to more severe drought limitations<br>▪ The fire risk is increasing with potential negative impacts on most forest goods and services |
| **Uncertainties** | ▪ Climate change impacts will strongly depend on the future amount and distribution of precipitation<br>▪ The degree to which increasing water limitations may be partly compensated by increased water use efficiency under increasing CO2 concentrations in the atmosphere is uncertain<br>▪ Frequency, intensity and duration of heat waves under climate change are still not well known |
| **Adaptive capacity** | ▪ Forests of the Mediterranean region are naturally adapted to withstand extreme and unpredictable dry climate conditions<br>▪ The inner capacity of Mediterranean forests to adapt to climate change largely depends on their actual level of ecological functionality; degradation processes, either recent or relict, have significantly reduced forest ecosystem stability, especially in the semi-arid zones of the Mediterranean region<br>▪ The lack of active forest management in large areas (e.g. neglected rural lands) is an additional factor strongly limiting the technical adaptation potentials |
| **Key threats** | ▪ The extreme forest fire risk is the largest threat in the Mediterranean region<br>▪ Increasing drought limitations are threatening the survival of many forest species<br>▪ Both productive and social forest functions and services may decline at least in parts of the region |
| **Key opportunities** | |

| Mountainous regions | |
|---|---|
| **Expected climate change** | ▪ Similar to the surrounding bioclimatic regions<br>▪ In the Alps temperature increase is expected to be more pronounced in the summer and run-off will be increased due to higher precipitation |
| **Potential direct and indirect impacts** | ▪ While high altitude forests may show increased growth rates due to longer vegetation periods, the forests in lower altitudes will show similar responses like in the surrounding bioclimatic regions, including potential growth decline in water limited areas<br>▪ Biotic damages are expanding into higher elevation areas formerly unaffected<br>▪ Melting permafrost soils and high precipitation events may increase debris flows and the risk of landslides and flooding<br>▪ Winter tourism is going to be negatively affected by shrinking areas with reliable snow cover |
| **Uncertainties** | ▪ Similar to the surrounding bioclimatic regions |
| **Adaptive capacity** | ▪ Similar to the surrounding bioclimatic regions |
| **Key threats** | ▪ In addition to the factors in common with the surrounding bioclimatic regions, there are specific threats in mountain regions in relation to the maintenance of the protective function of the forests<br>▪ Disturbances including storms, insect outbreaks, and fire may negatively affect the forest structure or even completely destroy the forest cover with subsequent negative effects on the protective function of the forest |
| **Key opportunities** | ▪ |

# 7 ADAPTATION STRATEGIES

According to the IPCC (2007) adaptation is defined *as adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.* Related to forestry two different fields of adaptation measures can be distinguished accordingly: (i) management of trees, stands, and combinations of stands in the landscape, and (ii) activities changing the socio-economic and political frame of forest management.

According to Parry *et al.* (2005) developing adaptation strategies should include the analysis of past and current climate vulnerability, the assessment of existing coping strategies, and suggestions on options on how management might be modified with climate change. Reducing vulnerability involves both a reduction to the exposure to climate stress and an increase in adaptive capacity.

Climate change may be too fast for autonomous adaptation of forest ecosystems. On the other hand, due to its gradual progression with huge interannual variability it is at the same time too slow for decision makers to have a clear idea of its direction and the consequences for the forests they manage. Hence, decisions must inevitably be made in the face of great uncertainty. Given the huge stakes involved with forest resource management anticipatory adaptation thus implies that suitable strategies need to hedge against risks by increasing the flexibility in forest management to adequately respond to emerging climatic changes or by diversifying through portfolio-like strategies. Adaptation strategies will thus be different for small-scale forest owners compared to large-scale ownerships.

On vast areas in the past tree species have been promoted outside their natural range close to the limits of their physiological niches. These mainly coniferous forests are prone to an array of insect and disease organisms already under current climate and efforts have been underway to stabilize these forests by conversion to mixed species stands better adapted to the prevailing site conditions (e.g. Spiecker *et al.*, 2004). Thus, for these forests adaptation to climate change meets with already existing measures and debates about vulnerability to climate change makes insistence on good forest management practices more important.

In this chapter, possible emerging adaptation options for European forests will be identified. European forestry is rich in diversity both in forest types and socio-economic conditions. The ownership structure and related interests of owners and stakeholders do not allow for one-fits-all solutions. Local and regional assessment of vulnerabilities and adaptation measures are crucial to identify efficient and cost-effective adaptation strategies. Different measures are first presented according to different types of actions. Some of these are very specific to address a particular climate change impact, whereas others are more general in nature. There are certain measures which focus more on natural forest conditions, while others are more suitable for intensive plantation forestry. In chapter 8, meaningful combinations of adaptation measures are analysed regarding their feasibility, reliability, and cost-effectiveness.

## 7.1 Screening adaptation options

In this chapter the results of a comprehensive literature review of potential adaptation options for forestry in Europe are presented. The adaptation measures include responses to both risks and opportunities brought out by climate change and they are classified into eight groups covering all stages of forest resource management at stand level and higher spatial scales:

| Level of action | Type of adaptation actions |
|---|---|
| Stand level | • forest regeneration<br>• tending and thinning of stands<br>• harvesting |
| Forest management | • management planning<br>• forest protection |
| Policy level | • infrastructure and transport<br>• nurseries and forest tree breeding<br>• Further adaptation integration in risk management and policy |

For groups where the major adaptation options are different between bioclimatic regions, tables will be provided highlighting these differences.

In general, conclusive targeted research results on adaptation options are scarce in all regions. Adaptation options presented in the scientific literature are mostly recommendations made on the basis of climate change impact studies missing explicit design and analysis for adaptation. The findings from the literature are complemented with some expert assessment where suitable references could not be found.

**Key findings for different type of adaptation actions** are:

- Forest regeneration offers a direct and immediate opportunity to adapt tree species or provenances to the changing climatic conditions.
- Proposed changes in the frequency and intensity of tending and thinning are mostly aiming at improving stand structure to reduce susceptibility of stands to disturbances.
- Harvesting activities should take place at smaller scales than currently.
- Forest decision support systems are tools for supporting adaptive forest management under conditions of climate change. Co-operation of scientists, decision makers and stakeholders will lead to more comprehensive understanding of the complex problems.
- Silvicultural strategies to cope with the effects by biotic agents are targeted on changes in species composition. The sensitivity of a stand to abiotic damages is controlled by tree, stand and site characteristics.

- Development of an appropriate road network and targeted road maintenance can help to improve infrastructure and transport under climate change. Shortened frost periods and wet soils require development of innovative harvest and transport technology.
- At the nursery stage seedlings mixture increases diversity of reproductive material.
- Development and evaluation of adaptation strategies should be a participative process involving decision-makers, stakeholders, experts and analysts.

## 7.2 Forest regeneration

Forest regeneration encompasses

- choice of tree species and provenances,
- change of species composition,
- silvicultural systems as well as techniques for forest regeneration.

Forest regeneration offers a direct and immediate opportunity to select tree species or provenances that are believed to be better adapted or adaptable to the changing climatic conditions. On the other hand the regeneration phase is sensible to changes in climate (Spittlehouse and Stewert, 2003) as young seedlings and plants are particularly sensitive to drought (Oliet *et al.*, 2002) or other extreme climatic conditions. Thus, regeneration processes and techniques may warrant modification and adaptation itself.

A selection of a wider range of species and genetic diversity may improve the resilience of forests to climate change autonomously. This diversity can be supported by use of natural regeneration techniques (Spiecker, 2003; Badeck *et al.*, 2005; Broadmeadow *et al.*, 2005; Resco De Dios *et al.*, 2007). Whether natural or artificial, regeneration is the stage at which the species and genetic composition of the stand gets established, where diversity can be manipulated the most. Later silvicultural steps may modify to some extent the initial composition but cannot correct insufficient suitability for current or future site conditions. Basic requirements in terms of suitability and diversity at the species and genetic level therefore need to be fulfilled at the regeneration stage. In this context all spatial and biological levels should be considered, as the species and genetic composition can be manipulated from the stand to the forest or regional levels (cf. chapters 7.5 and 7.9).

Of great importance for forest regeneration is that successful establishment and early growth of young stands may be strongly influenced by soil preparation, selection of species and provenances, quality of plant material and weed control. These factors might gain importance in ensuring successful regeneration under climatic changes (Kellomäki *et al.*, 2000; Spiecker, 2003).

Climate change may also offer opportunities for improved regeneration success, as the warming climate improves regeneration conditions at the northern timberline. During the last decades, natural and artificial regeneration have succeeded well in forests near the timberline because of warmer temperatures during the vegetation period (Varmola *et al.*, 2004).

### 7.2.1 Natural regeneration

Wherever possible, natural regeneration is to be enhanced because evolutionary processes are less disturbed. However, this requires that the gene pool of available seed trees is suitable for the site (Geburek, 1994). Under a changing environment, using natural regeneration allows natural selection to take place. This will drive the population to meet the fitness optimum corresponding to the local environmental conditions. The population will lag behind the fitness optimum if the environment changes continuously (Bürger and Krall, 2004). The lag causes a reduction of fitness, and it should not reach a critical lower level at which the population cannot replace itself (Bürger and Lynch, 1997). This critical level is dependent on demographic and genetic properties of the population: genetic variation, demographic rate of population increase (fecundity), and population size. Measures should therefore be taken so that these properties are kept at sufficient levels to safeguard adaptation of the population to environmental changes. Although forest trees exhibit in most cases high levels for these properties (Aitken *et al.*, 2008), easy to implement indicators may be defined that can be used in regeneration operations to check that these levels are met (Namkoong *et al.*, 2002). The following strategies reduce the risks of maladaptation of populations:

- **Increasing diversity in the regeneration.** Because the genetic composition of populations needs to be shifted to cope with environmental changes, diversity levels should be set at higher levels than under standard regeneration conditions, ie without environmental change. This can be achieved by benefiting from successive fruiting years, thereby increasing gene flow from external male parents. Isolated populations or scattered distributed species will deserve in this respect special attention.
- **Maintaining population size**. Natural regeneration should result from the contribution of a sufficient number of parental genitors. This can be achieved by monitoring the fruiting level, preventing that seeds are only produced by very few maternal parents. Cumulating successive fruiting years and/or supplementing with seed from local origin are additional operational solutions.
- **Maintaining reproductive potential and fecundity**. Flowering and fruiting can be affected by environmental change, as result of phenological modifications. Therefore it should be assessed whether levels of reproduction have shown continuously decreasing trends in recent years.

Whenever these criteria are met, natural regeneration will allow obtaining a large number of seedlings on which natural selection induced by environmental changes will act. The larger the size of the seedlings population, the stronger the selection intensity can be and the larger evolutionary change within the population will occur. Figures on how much evolutionary change populations can support depend on the heritability of the trait and on the above mentioned properties (Bürger and Lynch, 1997). For example, a standing adult tree population of size 1000, where each tree produces on average 1000 new seedlings, will generated a new population that can shift its mean value for a trait up to 20% to 30% (of the phenotypic standard deviation of the trait) without compromising the maintenance of the population. These figures hold for most common traits in trees (with heritability values varying between 0.10 and 0.20). Genetic constraints to adaptation are therefore rather limited if diversity, population size and reproductive potential are maintained during natural regeneration.

### 7.2.2 Artificial regeneration

The general reasoning about natural regeneration holds also for artificial regeneration, in terms of evolutionary changes expected in response to environmental changes. But because the genetic composition of regeneration can be artificially manipulated, additional measures can be recommended.

The size of the seedling population is far lower in the case of artificial than in natural regeneration, unless artificial sowing is used. In most cases plantation is the method adopted, and the density of trees is lower than under natural or artificial sowing. In order to maintain high levels of genetic diversity, seedlings coming from different seed stands can be mixed at the nursery stage (cf. chapter 7.8).

Enrichment planting in naturally regenerated stands is another option to introduce plants with different genetic characteristics. Introducing new reproductive material should be seen as complementing local seed sources, and never as replacing local material. Natural selection will sort out local and foreign trees and genes and generate a new population better adapted to the local conditions. Mixing would increase the opportunities for new genetic associations to increase the fitness of the planted population.

The establishment of "pioneer populations" (i.e. species populations outside their current area) could enhance the migration and spread of tree species under climate change. Pioneer populations could be established via planting species in regions where they are not established yet, but where future climatic and environmental conditions are expected to be favourable for the selected species (Müller, 1994).

When forest regeneration is done artificially, it is crucial for the regeneration success that the trees do not suffer from drought directly after planting. In regions with low water availability in spring and summer potential adaptation measures include the shifting of planting activities to the autumn to give roots more development time to better cope with dry periods in spring and summer, depending on the seasonal growth pattern of the tree species. Also the planting of saplings with pots might reduce the risk of immediate drought impacts and may increase regeneration success due to the independency from spring/ autumn planting seasons (Badeck *et al.*, 2005; Czajkowski *et al.*, 2005). Favouring tree species with good sprouting potential may also increase future flexibility in stand regeneration as sprouts are less vulnerable to drought compared to regeneration of seed origin.

### 7.2.3 Selecting and introducing better adapted reproductive material

The **choice of reproductive plant material** for stand regeneration is highly important and should suite the changing climate (Zebisch *et al.*, 2005). Geburek (1994) proposed two possible strategies for selecting reproductive material:

- choosing forest reproductive material of high genetic diversity to maintain or increase genetic adaptability (as discussed before)
- to promote reproductive material which is adapted to the projected climatic conditions, even if this leads to stands which are adapted in a suboptimal way to current conditions (Broadmeadow et al., 2005). This option includes considerable risk given the high uncertainties in projections of future climate at local and regional scales.

Because of the uncertainties in the timing and extent of climatic changes, the decision maker has to trade-off whether to favour the species best adapted for current conditions or those for the expected future climatic conditions (Lindner, 2007). Required rotation lengths and width of the niche of involved species related to expected climatic changes are decisive factors for this decision.

When selecting new reproductive material, the main questions are “Where should the external sources come from? How far from the local populations?” The range and direction of transfer of material can be based on two different arguments: (1) expected shifts of bioclimatic envelopes, or (2) geographic pattern of genetic variation inferred from provenance tests.

***Future bioclimatic envelopes***

Future bioclimatic envelopes were constructed for most European species under different climatic scenarios and models of greenhouse gas emissions (Thuiller *et al.*, 2005). Populations occupying today sites that exhibit bioclimatic data that would be similar to distant sites in about one century, would be candidate sources for seed collection dedicated to the distant sites. The basic assumption is that these populations would comprise genes that maintain the same fitness values in the distant sites.

In Boreal and northern Temperate regions some studies have shown the advantages of introducing *Fagus sylvatica* or other broadleaved species into Norway spruce stands (Ammer *et al.*, 2008). Simulation studies of adaptive forest management strategies at the scale of management units in Northern Germany and Finland have indicated a shift in the natural species composition from coniferous dominated forests towards broadleaved species. Thus one adaptation option could be to increase the share of deciduous species (Badeck *et al.*, 2005). A similar trend was also reported by Lexer *et al.* (2002) in a large scale climate change impact assessment for Austria. Cuculeanu *et al.* (2002) conducted a simulation study, to examine the possibility of introducing species from other geographic zones to Romania in the context of climate change adaptation. The simulator JABOWA was applied to assess the performance of North American species in Romanian forest including the Carpathians. The results showed that red maple (*Acer rubrum*), white pine (*Pinus strobus*) and red oak (*Quercus rubra*) indicated favorable development conditions according to the underlying climate change scenario (Cuculeanu *et al.*, 2002). However, this study was conducted neglecting interaction with the present species composition and potential conversion trajectories and thus has to be seen as mere theoretical feasibility study rather than a silvicultural recommendation.

In drought prone areas it is recommended to use drought tolerant species and provenances and wide initial spacing to counteract drought stress (Spiecker, 2003) even though this may reduce the genetic diversity at stand level. Czajkowski and Bolte (2005) recommended the introduction of drought-adapted provenances to decrease the vulnerability of Central European beech stands to drought. Similarly, Müller (1994) proposed to enrich stands in Austria with more drought tolerant and/or broadleaved tree species which are likely to be able to cope better with climate change.

In special habitats, which might be very dry or where maintaining of tree cover is difficult, exotic species might come into question. Müller (1994) suggested that exotic species like *Pseudotsuga menziesii, Robinia pseudoacacia, Quercus rubra* and *Juglans sp.* would perform better under projected climatic conditions, which are drier than today, compared to major current species such as *Fagus sylvatica* and *Picea abies*. However, it is important to note that many neophytic tree species which have been recommended for use so far, have not been evaluated thoroughly for their sensitivity to drier and warmer climatic conditions. The introduction of neophytes is also associated with risks and threats. For instance, native biodiversity may be substantially reduced (Spiecker, 2003). Although well adapted to dry and warm conditions, an especially aggressive species in this respect is *Robinia pseudoacacia* (Walter *et al.*, 2005).

### *Applying results from provenance tests*

Applying results from provenance tests installed under various environmental conditions can also help to select more suitable productive material. Plant species tend to be composed of populations genetically suited to different climates, as result of natural selection prevailing under these climates. The original goal of provenance tests was to identify the most suitable provenances (seed sources) to be planted in different environments. Provenance tests provide extensive information on the level of genetic differentiation of tree populations and the geographic distribution of differentiation (Langlet, 1971; Wright, 1976; Matyas, 1996; Morgenstern, 1996). With continuous directional shifts in climate, genotypes other than those of the contemporary populations eventually will become better suited to the novel climate. As the climate changes, planting programs that transfer appropriate genotypes between climate zones can accomplish in a single generation what would require several generations in nature. Directions and range of transfers will depend on the geographical patterns that were observed in provenance tests. Quite often continuous patterns were observed that follow environmental gradients: these patterns are called clines. Clines that are parallel to predicted environmental changes would constitute valuable information to decide on the direction of seed transfers (see Annex 7).

The reported data document for most of the studied species considerable geographical variations with respect to physiological traits. For some traits, opposite clines can be observed in different species, thus revealing that relationships between trait value and fitness may vary between species. This is the case for spring phenology, where early flushing populations exist in northern latitudes for conifers and in southern latitudes for oaks. As a result, transfer recommendations have to be done on a species by species basis, taking into account also the different traits together. Decisions on the direction of transfer can be opposite for different traits. In this case it would be preferable not to recommend transfers. Transfer of seeds should be based on the potential increase of the overall fitness of the population, when the inferences drawn from all the traits suggest the same direction of transfer.

In conclusion, the present results demonstrate the importance of considering extant genetic variation among populations for recommending seed transfers. They also suggest that a meta-analysis of all existing provenance test should be made before taking recommendations. For most European species, many provenances test have been established at a national, local or international level. They need to be analysed in a standardized way in order to recommend directions and range of seed transfer (see as examples Wang *et al.*, 2006; Reich and Oleksyn, 2008). Climate based seed transfer are now recommended at an operational scale in Canada (Ministry of Forests and Range, 2008) based on current research and science in ecology and genetics. Basically the new climate seed transfer system integrates knowledge on genetic variation among populations and predicted climatic change. Examples of climate based seed transfer were recently developed for lodgepole pine, either based on response functions (Wang *et al.*, 2006), or combining ecological and genetic data (O'Neill *et al.*, 2008). In

European species, similar approaches were used for Scots pine by Reich and Oleksyn (2008), who concluded that transfer of populations would need to be made over increasingly larger distances in the south and across narrower distances in the north. However, when transferring populations the suitability of other environmental factors like soils and hydrology needs careful consideration as well.

## *7.3 Tending and thinning of stands*

Tending of stands means any treatment carried out to enhance growth, quality, vigour and composition of the stand after establishment or regeneration and before final harvest. Most of the adaptation measures found in the literature focus on the **modification of tending and thinning practices, regarding the frequency and intensity of operations**. These proposed changes are mostly aiming at reducing drought effects (e.g. Sabaté *et al.*, 2002) for the Mediterranean region, and aiming at improving stand structure for Temperate and mountainous regions to reduce susceptibility of stands to disturbances. For an overview table 17 will highlight the differences between the bioclimatic regions.

In Temperate (Oceanic and Continental) regions adaptation measures are often focused on increasing diversity in structure and species composition via altered tending and thinning practices (Jacobsen and Thorsen, 2003; Laurent, 2003; Spittlehouse and Stewert, 2003; Ammer *et al.*, 2008). According to Spiecker (2003) **tending of young stands** should foster mixed stands (see section on forest regeneration). Furthermore, **intensified thinning** treatments should result in an increased proportion of valuable large-dimensioned timber on the total harvest volume. Additionally, intensified thinning may have some effect on site productivity by altering the nutrient cycle and reducing competition for light, nutrients and water (Kellomäki *et al.*, 2000; Spiecker, 2003). At drought prone sites more intensive thinnings are reducing stand evapotranspiration and thus counteracting increasing drought stress (Kellomäki *et al.*, 2000; Spiecker, 2003). This argument is supported by Misson *et al.* (2003) who investigated the effect of thinning intensity on drought response in a field experiment in *Picea abies* stands in the Ardennes, Belgium. Such management, with more intensive thinning and proper technique provided, is assumed to be able to increase stability by reducing large scale susceptibility to disturbances, improved biodiversity and soil conservation as a result of more abundant understory vegetation. In Belgium this intensified tending and thinning approach is called “dynamic silviculture” (André *et al.*, 1994; in Laurent, 2003). This open-stand structure can be encouraged through subsidies for regeneration which impose a certain planting density range, subsidies for early thinning and extension resources such as guides to good practices.

An increase in **structural diversity** is also important for mountainous regions to support the protective forest functions (Müller, 1994). For Swiss protective forests Bürgi and Brang (2001) are stating that already the current standing stock is too high from a risk perspective as well as with regard to regeneration processes. With regard to climate change adaptation they recommend to reduce the standing stock via thinning and harvesting in order to enhance regeneration. As a side effect, proper silvicultural techniques provided, the stability against wind throw could be increased. It is stated that such a reduction in growing stock has to be carried out very carefully to produce the desired effects (i.e too heavy thinnings can decrease the stability of the stand and increase wind throw risks). With respect to protective forests, regeneration should be particularly fostered in over-aged forests (Bürgi and Brang, 2001).

Thinnings of intermediate intensity in even-aged beech forests seem to provide a valuable yield and to assure a smooth growth response to climate variability by regulating the competition regime compared to densely stocked stands (Cescatti and Piutti, 1998). The beech response to climate, temperature regime and water availability, is significantly affected by intra-specific competition. When competition is strong, trees show a high sensitivity to variation in the water balance. When competition is low, trees may react positively to high temperatures.

Management adjustments, in terms of **thinning**, will also be required to account for accelerating growth rates due to more favourable growing conditions in a warmer climate particularly in mountain areas and boreal conditions to control average growing stock and subsequently the stability of forests (Spiecker, 2003).

Carrying out thinnings systematically, disregarding any qualitative aspects, would enhance the adaptive capacity in the long run due to maintaining a high within-stand genetic diversity (as proposed for genetic reserves; Food and Agriculture Organization, 1992; Geburek, 1994). However, this approach is in strong contrast to current thinning guidelines in Central Europe recommending selective thinning approaches.

**Table 17.** Major climate change adaptation options for stand tending and thinning in different bioclimatic regions.

| Bioclimatic region | Adaptation options | Comments |
|---|---|---|
| Boreal | Change thinning intensity and frequency | ▪ Due to increasing growth rates, which otherwise might adversely affect the stand stability<br>▪ High stand densities can increase the susceptibility of forests against biotic and abiotic disturbances |
| Temperate Oceanic | Tending and thinning practices improving structural and species diversity | ▪ Aim at increasing stand stability<br>▪ The reduction of susceptibility against abiotic and biotic disturbance factors is of high priority |
| Temperate Continental | Tending and thinning practices improving structural and species diversity; management of stand density | ▪ Due to a higher risk of drought |
| Mediterranean | Modified tending and thinning intensity and frequency | ▪ Balance water demand and supply to mitigate drought effects |
| Mountainous regions | Change in thinning intensity and frequency; change thinning approaches | ▪ Due to increasing growth rates, which otherwise might adversely affect the stand stability<br>▪ To avert high stand densities increasing the susceptibility of forests against biotic and abiotic disturbances<br>▪ To promote structural and compositional diversity to foster stability and therefore inter alia the protective function |

## 7.4 Harvesting

Harvesting in the context of this report is defined as taking mature trees out of the forest where the definition of maturity depends on the respective management objective. This also separates harvesting from tending operations. In accordance with the arguments listed in the section on forest regeneration (cf. chapter 7.2), in general, harvesting activities should take place at smaller scales and where possible according to the principles of natural regeneration.

Increased attention should be paid to avoid increasing the susceptibility to disturbances by harvesting operations such as producing open stand edges exposed to prevailing winds and strong direct sunlight. The former will increase risk of wind throw, the latter negatively impact tree vitality which subsequently may increase the susceptibility against bark beetles. Some of the reasoning for thinning operations presented above might be also valid for harvesting to some extent.

Susceptibility to disturbances may also increase due to a prolonged lack of harvesting activities. Biotic and abiotic disturbances occurring in neglected coppice forests are, at least partially, an effect of the lack of management which causes increased fuelwood accumulation. On the other hand, increased attention shall be paid to harvesting operations in managed coppices; to avoid increasing susceptibility to soil erosion risk in coppices, the maximum allowable cut size should be adapted to local conditions (e.g. soil erodibility, slope); also the length of the rotation period shall be increased, in order to maintain a continuous forest cover for longer periods of time.

## 7.5 Forest management planning

Forest management and planning is becoming more challenging in the perspective of climate change. In the past management planning has been primarily aimed at preserving the status quo rather than allowing or even explicitly aiming for change. However, there is evidence of an increasing awareness to include climate considerations in strategic and operational planning, particularly in Europe. Forest managers are already adapting to the observed effects as they increasingly perceive the need for adaptation. For example some biotic disturbances have forced forest management and planning effort in disturbed regions to conform with the new conditions (Ogden and Innes, 2007).

These effects of climate change highlight that a climate change adaptation strategy should be viewed as a risk management component of sustainable forest management (Spittlehouse and Stewert, 2003; Vanhanen *et al.*, 2007). Generally, the capacity to adapt to climate change must be integrated into forest management (Ogden and Innes, 2007).

The shortening of rotation periods can be an appropriate management response to accelerated growth in mountainous or boreal environments (cf. chapter 4.2). It might furthermore help to mitigate risks in stands susceptible to wind throw, bark beetle attacks or other disturbances occurring in later development stages. The reduction of the rotation length will reduce the risk of financial losses due to calamities (increased share of damaged wood, high harvesting costs, low timber prices etc.) and counteract the reduced management flexibilities induced by excessive levels of sanitation felling. In executing climate change adaptation measures at stand level, e.g. the conversion of a highly vulnerable secondary spruce stand, a reduction of the rotation age for the prevailing stands can accelerate the adaptation process and thus reduce the considerable lead times of silvicultural measures. On the other hand silvicultural flexibility with regard to techniques aiming at increased spatial structure and natural regeneration is generally decreased by distinctly lowered rotation ages. Moreover, if implementation of lower rotation periods would be implemented at larger scales in a fast pace, this could result in large surplus timber supplies to the markets with potentially negative economic effects. Finally, structural changes of lower rotations lengths need to be considered also with regard to other forest services (e.g. loss of large diameter trees for biodiversity, decreased in situ carbon storage).

According to Noss (2001) "[…] Good forest management in a time of rapidly changing climate differs little from good forest management under more static conditions, but there is increased emphasis on protecting climatic refugia and providing connectivity. […]". Climatic refugia as mentioned by the author are places of refuge that harbour species during times of unfavourable climate. However, other authors see substantial need for altered planning and management systems. Spiecker (2003) states that new planning and decision tools have to be applied to deal with uncertainty and risk in long-term forest planning. Traditional anticipation of goals and means, on the one hand, may not be adequate when managing forests under risk and high uncertainty. Therefore flexible adaptive planning, which takes into account all conceivable scenarios and allows to consider multiple options for future development may be the best suited alternative (von Gadow, 2000). Furthermore, there is a demand for forestry to be adaptive to future societal demands, sustainably providing multiple functions in the future. The complexity of the decision problems evolving from this situation show that solutions have to be developed in a multi- and transdisciplinary cooperation of scientists, decision makers and stakeholders. Such cooperation will lead to a more comprehensive understanding of the complex problems involved in decision making and will provide a more realistic and reliable basis for decision support for management in future forest ecosystems (Spiecker, 2003).

Management planning at the landscape level for management units offers many possibilities to combine different adaptation measures. A strategy may involve regenerating different stands in different ways. For example some stands could be regenerated naturally with current species adapted to the current site conditions, whereas other stands could use species or provenances adapted to different future scenarios.

Several studies showed that the combination of process-based forest ecosystem models and multi-criteria analysis (MCA) methods are an efficient tool to support adaptive planning, management and decision making under climate change (Ohlson *et al.*, 2005; Amaral *et al.*, 2006; Fürstenau *et al.*, 2007; Kimmins *et al.*, 2007; Briceño-Elizondo *et al.*, 2008; Garcia-Gonzalo *et al.*, 2008). However, there is still need for improved evaluation approaches to capture risks and uncertainty in a sound and consistent way.

Because of the complexity of the decision making problem that is involving multiple objectives as well as different time horizons and geographic scales, forest decision support systems (DSSs) are indispensable tools for supporting adaptive forest management under conditions of climate change ( cf. Box 5). A recent IUFRO Task Force underlined the impacts of decision models and systems on both the efficiency and the effectiveness of forest management. The European Union (EU) Forest-Based Sector Technology Platform further emphasized the importance of advanced and innovative planning methods and computer tools for addressing multifunctionality and sustainability of forests.

But not only planning and decision making has to be improved under climate change. Bürgi and Brang (2001) highlight the necessity of an effective controlling in forest management, which is getting even more important under climate change conditions and is a key component of adaptive management (e.g. Rauscher, 1999).

**Box 5. Decision support systems and climate change**

So far, in existing DSSs for forest management (e.g. Heureka in Sweden, Mela, Monsu, and SIMO in Finland, Monte in Spain, SADfLOR in Portugal, SAGALP in Germany, CAPSIS in France, FORRUS-S in Russia, SGIS in Norway, DRYMOS in Greece) adaptation to climate change was not specifically addressed. DSD (Lexer *et al.*, 2005) provides an example how climate change can be considered in DSS: in DSD, the sensitivity of tree species and species mixtures to two climate change scenarios can be analysed in a simplified static approach.

The role of computer and web based decision support tools in adapting forests and forest management processes to climate change may vary depending on the needs and the background of the user. Thus, there is no single answer as to how a DSS for adaptive forest management should look. However, following the generic model of decision making (Rauscher, 1999; Buffo *et al.*, 2007) the first step is the identification of the sensitivity of current forests to climate change. Based on this, a generic vulnerability assessment scheme will be a key component of any DSS on climate change adaptation. Assessment of vulnerability is a requirement for the design of any targeted adaptation strategy. Multi-stakeholder settings will be in urgent need for tools to support informed discussions and negotiations for feasible adaptation solutions. Thus, robust projections of likely consequences of adaptive strategies in combination with approaches to compare alternatives and to model trade-offs will be urgently needed. A new FP7 Integrated Project (MOTIVE) will address these needs, aiming at the development of a tool box for improved forest planning under climate change.

## *7.6 Forest protection*

### 7.6.1 Pests and diseases management

A key finding of the literature review on potential effects of climate change on the health status of European forests is that the probability of damaging effects by biotic agents, such as insect pests and pathogens, will definitely increase. **In all bioclimatic zones, forests are likely to become more vulnerable to disturbances** given expected changes in temperature and patterns of precipitation. According to the reviewed papers, conifer species, especially of the genera *Picea* and *Pinus,* as well as forest stands of *Quercus* spp. are expected to be most affected by an increasing negative impact of biotic disturbance agents. These tree species groups are of high economic importance, so that the higher occurrence of detrimental events might put European wood production at high risk.

Consequently, recommendations for **silvicultural strategies** to cope with the effects of warming are targeted mainly on **changes in species composition**. As an example, Thomas *et al.* (2002) suggest for Central Europe the replacement of the drought sensitive *Quercus robur* in the long term by *Quercus petraea*, which may be better suited to increases in temperature and might be less prone to insect defoliation and pathogen attack. In general, the reforestation with species and provenances better adapted to relatively warm environmental conditions may help to improve the future health status of forests and to diminish their susceptibility to pest and pathogen attacks (Resco De Dios *et al.*, 2007). Damages in the regeneration phase of forests might be reduced by preferring naturally grown seedlings to artificially reforested plants.

A great effort will be necessary to contain **likely increasing epidemics of bark beetles in conifer forests**. In case of non-autochthonous, uniform pine and spruce stands highly prone to storm damage and infestation by bark beetles, the only alternative may be the conversion to stands of tree species native to the forest sites. As an example, the replacement of spruce by *Abies alba* or *Larix decidua* is recommended as strategy to anticipate attacks by *Dendroctonus micans* in the French Massif Central (Rolland and Lemperière, 2004).

The spruce bark beetles, *Ips typographus* and *Pityogenes chalcographus,* pose a severe threat also to autochthonous spruce forests, especially in mountainous regions. Under a climate change scenario, prophylactic measures such as the removal of forest residues, wind throw clearings and sanitation fellings will not alone be sufficient to decrease the hazard of mass outbreaks. Silvicultural adaptations will be inevitable in the long run, aiming at the establishment of ecosystems with highly diverse tree composition, age, structure and ground vegetation (Wermelinger, 2004).

When deciding for appropriate silvicultural adaptation measures, the key question is how to reduce the susceptibility of forests and individual trees to attacks by pathogen species and insect pests. Given the heterogeneity of European forest ecosystems and of potential biotic damaging agents, general predications such as the simple replacement of susceptible tree species or the avoidance of plantation forestry are of no avail. In contrast, comprehensive knowledge on the complex causalities of disturbance on a regional scale is demanded. However, such condensed information is mostly lacking on the forest management level and is also underrepresented in scientific literature.

Specific site and stand related characteristics influence the local or regional probability of disturbance. Knowledge about such relationships can be used for the development of silvicultural strategies. Several authors developed knowledge-based expert models allowing the identification of parameters responsible for increased forest susceptibility to a range of biotic and abiotic agents (comp. Netherer and Führer, 1999; Nopp, 1999; Führer and Nopp, 2001; Netherer, 2003; Netherer and Nopp-Mayr, 2004). The broad knowledge compiled in these predisposition assessment systems, which were based on comprehensive literature reviews, shall support forest managers to gain an overview on the opportunities for and limits of damage prevention. Such awareness of the scope of potential activity gains importance especially with regard to climate change. Combined with models to simulate seasonal development of insect pests on a spatial and temporal scale, as was done for the bark beetle *I. typographus* (PHENIPS) by Baier *et al.* (2007), vulnerable areas of forest stands and sites can be identified both in space and time.

The following Tables 18 and 19, compiled according to the mentioned expert models, summarise suggestions for silvicultural adaptation measures in order to decrease the predisposition of European forests to two species of pest insects (the European spruce bark beetle, *Ips typographus* and the Little spruce sawfly, *Pristiphora abietina)* and two pathogen species (the root rot, *Heterobasidion annosum* and *Armillaria spp*.).

**Table 18.** Management options in order to decrease the vulnerability of forests to insect pests.

| Insect pests | Site conditions | Species composition | Stand age | Stand structure | Stand density | concepts and intensity of management |
|---|---|---|---|---|---|---|
| *Ips typographus** | enhanced probability of infestation in areas with high thermal sums and low precipitation (< 360mm April-October); vulnerable topographical features: hilltops, ridges, plateaus, upper and middle slopes; avoid establishment of *Picea abies* on both (moderately) dry to xeric sites and wet or saturated sites, and (pseudo)gleysols; enhanced probability of infestation in case of low soil depth, high proportion of soil skeleton, moderately high to very high site index; reduce predisposition of stands to wind throw and snow breakage | reduce proportion of *Picea abies* to < 50%; promote broadleave and alternative conifer species | avoid mature to overmature forests of *Picea abies* (>100 yrs.) | reduce proportion of dominant trees and stand edges; reduce favoured locations of primary infestation (structural features exhibiting increased temperature conditions and exposure to solar irradiation) | aim for optimal crown cover (40-80%); avoid forest gaps (increased solar irradiation); avoid too dense stocking of trees (reduced vitality) | improve accessibility of forest stands, monitoring for population density and sanitation measures, remove wind-thrown trees |
| *Pristiphora abietina*** | avoid establishment of *Picea abies* on altitudes lower than 600m and outside autochthonous area; enhanced probability of infestation in areas with precipitation sums <1000mm per yer and <350mm June-August), on sun-exposed sites (S, SE, SW), on sites with deposition of nitrogen, as well as on sites of low base supply, pH values <5 and duff | reduce proportion of *Picea abies* to < 40% | increased susceptibility of thickets and pole woods of *Picea abies* | avoid even stand layer; promote herbaceous and grass vegetation | avoid closed and densely stocking stands (crown cover >80%) | |

Sources:
* (Führer and Nopp, 2001; Netherer, 2003; Netherer and Nopp-Mayr, 2004)
** (Netherer and Führer, 1999)

**Table 19.** Management options in order to reduce the susceptibility of forests to pathogen species

| Pathogens | Site conditions | Species composition | Stand age | Stand density | concepts and intensity of management |
|---|---|---|---|---|---|
| *Heterobasidion annosum*+ | avoid establishment of *Picea abies* on altitudes lower than 800-1000m and sites of high thermal sums; increased susceptibility of forests on (moderately) dry sites or with extremely irregular water regime, on sites with soil compaction and sites of high pH value (>7), medium to high base supply and high supply of nitrogen (but also very low supply of nitrogen); reduce predisposition of stands to rock slide and debarking by deer | reduce proportion of *Picea abies* to < 90% | avoid mature to overmature forests of *Picea abies* and *Abies alba* | don't establish stands with more than 8000 trees per hectare; reduce stems in young stands; avoid high frequency of thinnings | don't establish forest stands on former agricultural areas, prefer natural regeneration; avoid and monitor forests for stem wounds |
| *Armillaria spp.*+ | enhanced probability of damage in areas of low precipitation, (moderately) dry to xeric sites, but also on wet and saturated sites and sites of irregular water regime; avoid the establishment of stands composed of *Picea abies* and *Pinus spp.* on meso- to oligotrophic sites, sites with soil compaction and pH values <5; reduce predisposition of forests to frost damage and insect defoliation | reduce proportion of *Picea abies* and/ or of *Pinus spp*. to < 70% | avoid mature to overmature forests of *Picea abies* and *Pinus spp.*; in case of a high proportion of conifer trees also consider the high susceptibility of thickets and young stands | reduce stems in young stands and avoid thinnings of high frequency and increasing grade with time; avoid intense height increment (>2m since the last thinning operation) | don't establish stands of *Picea abies* and *Pinus spp.* on former areas of decidous forest; prefer natural regeneration; monitor for moderate to high defoliation by other fungi of phytophagous insects |

Source: + (Nopp, 1999)

### 7.6.2 Abiotic disturbances

Adaptation to reduce impacts of abiotic disturbances need to address: forest fires, snow damage, wind throws, and landslides in mountainous terrain.

***Forest fires prevention***

In the Mediterranean region, the majority of fires are human induced, mostly due to deliberate lighting of forest fires and negligence. Since the beginning of the 1990's, improved fire protection contributed to reducing the average size of fires. However, given the fact that natural causes are responsible only for a small percentage of all fires, fire prevention should be targeted not only at forest management and it needs to consider also socio-economic conditions and policies at different levels. A Spanish study suggested that climate change with increasing daytime temperature and a decrease in moisture which affects vegetation growth, fuel structure and combustibility has already contributed to the increase of burned areas (Resco De Dios *et al.*, 2007).

Several studies deal with adaptation to a changing fire regime in Russian and Canadian boreal forests (Stocks *et al.*, 2003; Flannigan *et al.*, 2006). Proposed adaptation strategies include developing fire-smart landscapes by using harvesting, regeneration, and stand-tending activities that manage fuels and control the spread of wildfire (Spittlehouse and Stewert, 2003). However, due to different forest physiognomy, policies and infrastructure, the measures cannot always be applied to the situation in European countries. Furthermore, there are also differences between the bioclimatic regions as highlighted in Table 20.

Fire protection will be mainly important in the Mediterranean and temperate continental forests (Baeza *et al.*, 2002; Fernandes and Botelho, 2004). Conditions leading to forest fires are extremely variable (Dellasala *et al.*, 2004). Different forest types might have different fires regimes, which require specific fire-management policies. Adaptation measures to enhance fire protection or to reduce risks of fire include:

- modification of forest structure (e.g., tree spacing and density, regulation of age class structure),
- removing standing dead trees and coarse woody debris on the forest floor,
- changing species composition,
- creating a mosaic of forest types including species with reduced flammability, and
- fuel management through thinning and biomass removals, grazing or the use of prescribed burning

It is a common view in the Mediterranean countries that the option of fighting all fires might simply be technically impossible and economically unfeasible. It appears necessary to determine where and when a fire is unacceptable at any cost and where or when it can be tolerated or even be desirable to minimise the risk of an uncontrolled fire. This can be done by implementing **forest management systems** that contemplate the use of prescribed burning (Rodríguez y Silva, 1997, 2004). This practice is already applied in some countries (e.g. Spain) and will be even more necessary in the future. Use of prescribed burning is useful in protecting areas of economic value (with buildings adjacent to forested areas) or areas which are particularly sensitive to wildfire; e.g. tree plantations (Moreno, 2005). When increasing the use of prescribed burning to minimize fuel loading there is a need to consider risks and cost-efficiency (Spittlehouse and Stewert, 2003; Spittlehouse, 2005).

According to Moreno (2005) there is a need in the Mediterranean regions to fundamentally revise fire fighting policies through changes in prevention strategies. Fuel management techniques (whether these involve clearing, prescribed burning, the use of herbivores or others) should advance through knowledge of plant species and ecosystems, in order to allow for the integrated management thereof, and should contemplate, apart from fire prevention, the conservation of biodiversity, carbon fixation and the fight against desertification.

Developing reforestation plans should be a priority in areas with greater danger of erosion in Spain, because in the event of a fire, these allow for faster recovery of plant cover to reduce soil erosion risk. Concerning other policies, as the demand for use of forests and wild lands will increase, improved education will probably lead to greater sensitivity to risk and less dangerous practices (Moreno, 2005). More intense recreational use of forests and wild lands, however, together with longer periods of activity due to the milder temperatures, could give rise to serious risks factors difficult to quantify.

Fire risk should also be considered in **regional/local land planning** (e.g. reclassifications) and legislation ought to be reinforced in relation to fire protection in the urban-forest inter-phase. Technological development allows improving surveillance and warning systems in fire fighting, which, according to an assessment of the Spanish Ministry of Environment, will facilitate widespread application, and enable shortening of detection and response times (Moreno, 2005). Rapid and appropriate responses can also be facilitated by making available fuel maps with high spatial resolutions, showing the condition of the fuel (moisture content).

The increase in fire risk may require to change the species composition, especially in continental and boreal forests (Maracchi *et al.*, 2005). Adaptation measures in these regions seek to change tree species (broadleaved forests instead of coniferous forests) in areas with high fire risks.

**Forest fire prevention and warning systems** should be developed also to reduce fire risk in the Temperate Continental region, e.g. in the state of Brandenburg, Germany, where large monocultures of Scots pine are very susceptible to fire under projected scenarios of climate change (Badeck *et al.*, 2004). Similar activities are also ongoing in Austria, where the Austrian Forest Fire Research Initiative (AFFRI) aims at the development of such monitoring and warning systems.

**Table 20.** Major climate change adaptation options in the field of forest protection against fire in the different bioclimatic regions.

| Bioclimatic region | Adaptation options | Comments |
|---|---|---|
| Boreal | Changing the tree species composition in areas with high fire risks and development of fire-smart forest landscapes | Broadleaved instead of coniferous tree species |
| Temperate Continental | Tree species change and the development of fire prevention and warning systems | Broadleaved instead of coniferous tree species |
| Mediterranean | Large-scale fuel management (clearing, prescribed burning, grazing) management activities influencing stand structure and modifying species composition in simplified forest ecosystems | Counteract fuel accumulation; prescribed burning can be an efficient fuel management practice, but know-how is highly required to control prescribed fire intensity and size spacing, density, dead wood volume etc. |

### *Wind damage management*

The susceptibility of a stand to wind damage is controlled by tree (i.e. species, height, diameter, crown area, rooting depth and width) stand (i.e. density) and site (i.e. soil depth, water regime) characteristics. Since tree and stand characteristics change dynamically along with forest growth, the risk of wind damage will also change. Shallow rooting evergreen species (especially Norway spruce and Sitka spruce) and old stands show higher damage risk and are more susceptible than deciduous species and younger stands. The highest risk of wind damage is associated with sudden changes in wind loading patterns as long as trees are not (yet) accustomed to it, e.g. on recently clear-felled areas or in stands that have recently been thinned intensively (Zeng *et al.*, 2004). Size and location of clear-cut area influence wind speed as well as the surrounding landscape (Schelhaas *et al.*, 2007). With a proper intensity, interval and placement of cuttings (thinning and harvesting), it is possible to reduce the risk of wind damage in a forest (Zeng *et al.*, 2007b). On the landscape level, at least in intensively managed regions, the risk of wind throws may not increase due to clear cuttings. This is because old stands, which are usually most vulnerable to be damaged, are cut (Zeng *et al.*, 2007a).

Shorter rotation length is applied to reduce risk of wind damage in regions with strong winds (Gardiner and Quine, 2000). Continuous cover forestry and avoiding open clear cut areas could be another option to increase stand stability and to reduce the amount of damage in risk prone regions.

### *Snow damage*

The first step towards reducing snow damages in forestry is to identify specific parts of forested areas subject to particular levels of damage risk. With models it is possible to assess the risk of snow damage to individual stands at different stages in tree or stand development (Kellomäki and Peltola, 1999; Peltola *et al.*, 1999) and to select site-specific silvicultural methods. The risk of snow damage can be minimized by avoiding heavy thinning, especially in high risk areas. In areas, where large deposits of snow in the crowns of the trees can be expected, the thinning should be less intensive. Thinning from below, with a thinning intensity of more than 20% of the basal area of the stand, develops a high taper, which reduces snow damage, at least in the form of stem breakage (Päätalo, 2000). In thinning, high-risk trees with low taper should be removed (Päätalo *et al.*, 1999).

## 7.7 Infrastructure and transport

Literature dealing with adaptations of infrastructure and transport in forestry due to climate change was difficult to find. Some information was found for the Boreal, Temperate and mountainous regions; the differences are presented in Table 21. It is likely that some literature targeting other sectors such as the building and water sectors could also be relevant for this chapter, but it was beyond the scope of this study to screen all literature on this subject.

To adapt Romanian forests to increasingly dry conditions Cuculeanu *et al.* (2002) propose an augmentation of storage lakes and **irrigation** canals to reduce drought stress in susceptible areas. Referring to central European forests, Zebisch *et al.* (2005) suggest that in drought prone areas measures should be taken to prevent decreasing ground water tables. For instance, they propose the restoration of the water regime in floodplain forests or the deactivation of drainage systems.

The development of an appropriate **road network** is very important especially in mountain forestry to ensure the proposed small scale management activities (cf. chapter 7.2) and to provide accessibility necessary for sanitation felling. Both aspects are of particular importance for management of protective forests. In northern regions it is of special importance to reconstruct roads in order to minimize sediment runoff due to increased precipitation and permafrost melting (Spittlehouse and Stewert, 2003). Under changing climate conditions more **road maintenance** is needed and increased sanding costs of wet roads and ice removal following re-freezing of melt water on roads may require financial subsidies for example in Sweden (Keskitalo, 2008).

The shortened frost periods in boreal forests pose a significant challenge for harvest and transport technology. Innovative **machine technology** is needed to enable continuous harvest operations without soil damage on wet soils.

Suitable infrastructure is also important for round timber storage after large scale wind throws. For this purpose wet or foil **storage facilities** should be prepared for fast disturbance mitigation in order to prevent pest outbreaks and to disburden the wood market (Odenthal-Kahabka, 2005).

**Table 21.** Major climate change adaptation options with regard to infrastructure and transport, in the different bioclimatic regions.

| Bioclimatic region | Adaptation options | Comments |
|---|---|---|
| Boreal | ▪ Road maintenance<br>▪ Machinery | ▪ Changes in frost periods<br>▪ New harvest and transport |
| Temperate Oceanic | ▪ Suitable road density<br>▪ Round wood storage facilities<br>▪ Restoration of the ground water regime<br>▪ Deactivation of drainage systems | ▪ Small scale management<br>▪ Coping with large scale disturbances<br>▪ Drought prone stands |
| Temperate Continental | ▪ Adequate road density<br>▪ Storage lakes and irrigation channels | ▪ Small scale forest management<br>▪ Counteract drought effects at least in the short term |
| Mountainous regions | ▪ Road network improvement<br>▪ Preparation of storage facilities for wet or foil storage | ▪ To enable small scale forest management<br>▪ To provide access for forest sanitation measures<br>▪ To enable proper management of protective forests<br>▪ To mitigate effects of large scale wind throws |

## 7.8 Nurseries and tree breeding

For nurseries and tree breeding some valuable recommendations have been made already in the section on forest regeneration, which are also valid for the production of forest reproductive material.

In order to increase **diversity of reproductive material** used in artificial stand regeneration, it is suggested to mix seedlings at the nursery stage coming from different seed stands of the same provenance regions. In some countries this procedure is already recommended and would generally be permitted by European regulations about trade and use of forest reproductive material (either OECD guide lines or the European directive 105/99/E). Mixing could be enlarged to the extent of merging seedlings from local and more distant seed sources (outside the local provenance region). Such practices would however not be allowed by the existing European regulations, unless these regulations are changed accordingly.

Especially after larger stand replacing disturbances (e.g. big storm events) a shortage of suitable **plant material** is possible. Nurseries are limited in their flexibility due to biologicial, technical, economic, and regulation constraints. Regulations asking for the use of local adapted plant material can be relaxed under circumstances of plant material shortages. However, especially in the context of adaptation to climate change it is important to avoid the use of maladapted provenances in the artificial regeneration. To reduce the risk of bottle necks in the production of suitable plant material in nurseries it could be considered to increase the storage of seeds for species with seeds that sustain longer storage without loss of viability (i.e.

many coniferous species). For other species, the long term storage of seeds is not possible. To be prepared for unpredictable increases in plant demand, the only option here would be to produce plant material beyond the average market demand. However, this could for economic reasons only be done with specific subsidies for the nurseries.

Most breeding programmes of tree species in Europe were implemented in the past towards improving trees for production and quality traits. New selection criteria related to adaptation to higher $CO_2$ or to higher temperatures have not been included as such, or very recently (Teissier du Cros, 2000). Traditional methods of breeding based on progeny testing and seed orchards may take from 10 to 20 years before producing commercial varieties improved for such novel traits. However more sophisticated methods based on biotechnologies (in vitro propagation, somatic embryogenesis, gene transfer) may significantly shorten these delays, once genes of adaptive significance have been identified (Fenning *et al.*, 2008; Nelson and Johnsen, 2008). Research efforts are currently searching candidate genes related to traits that will be responding to climate change: bud burst (Scotti-Saintagne *et al.*, 2004; Casasoli *et al.*, 2006; Yakovlev *et al.*, 2006; Yakovlev *et al.*, 2008), bud set (Frewen *et al.*, 2000; Hurme *et al.*, 2000), water stress (Lauteri *et al.*, 1997; Brendel *et al.*, 2008). But the achievements obtained so far are not at the stage of introducing these genes (by crosses or other means) in commercial varieties. For the time being these approaches are limited to the search of candidate genes and the exploration of their diversity in extant populations (Gonzalez-Martinez *et al.*, 2006; EVOLTREE, 2008; TREESNIPS, 2008). Additional research directions are addressing plasticity on woody species and its genetic control (Kvaalen and Johnsen, 2008; Rohde and Junttila, 2008). As a conclusion, for the time being, the only way that breeding activities may take into account climate change requirements is to **maintain diversity within the varieties** produced by seed orchards at levels that would be higher than for standard utilizations. This can be done by supplementing seed lots harvested in seed orchards with seeds stemming from other origins or other seed orchards. More rapid applications may be expected for species where clonal commercial varieties are used and where biotechnologies are being manipulated at the operational scale for producing varieties (e.g. poplars in Central Europe and eucalyptus in Southern Europe)

## 7.9 Further adaptation options in risk management and policy

Adaptation to climate change includes also adjustments in social and economic systems in response to actual or expected climatic stimuli and their impacts. Obstacles to be addressed are for example institutional and policy barriers, as current guidelines (e.g. for plant production in nurseries) are often designed for a stable climate regime (Spittlehouse, 2005).

The development and evaluation of **adaptation strategies** should be a participative process involving decision-makers, stakeholders, experts, and analysts. Early management approaches to climate change impacts and adaptation emphasized scenario-driven impact assessment methods. More recently, **vulnerability assessment methods** have been promoted where key system vulnerabilities are first identified, and adaptive strategies are developed and evaluated in the context of existing decision processes. This kind of approach is necessary, because the practicability of adaptive measures depends on the circumstances. In some cases, it might be most appropriate to allow adaptation to occur autonomously, in a natural and unmanaged way. Under other circumstances, probably more often, it might be most appropriate to undertake adaptation in a planned, proactive manner (Ohlson *et al.*, 2005).

Practitioners and forests managers require simple, straightforward guidance for gaining practical experience in developing and evaluating climate change adaptation strategies. Ohlson *et al.* (2005) outline a simple, **flexible planning framework** that incorporates key principles of structured decision-making and risk management:

1. Define the problem and set management objectives,
2. Assess system vulnerabilities,
3. Develop risk management strategies and
4. Evaluate and decide.

Literature also emphasizes the increasing importance of a consistent risk management in forestry. This could be promoted by educational efforts, e.g., through training courses focusing on identification, prophylaxis and prevention of risks and furthermore on mitigation of occurred damages (Zebisch *et al.*, 2005). As the existing copying strategies may not be sufficient under climate change, new insurance concepts should be developed to distribute risks (Fuhrer *et al.*, 2006).

It was proposed to establish forest reserves for the investigation and monitoring of climate change impacts which can be valuable for science in a general sense and for the development of adaptation strategies in particular (Müller, 1994). Nature conservation principles and guidelines designed for current climate may need improvement and modification. Furthermore, it is recommended to **reduce forest fragmentation** in some areas through afforestation and by establishing connecting corridors between densely forested regions (Spiecker, 2003). This is particularly important in the complex Alpine landscapes and other regions where forests are intensively managed. This conforms to the need to promote management that reduces adverse environmental impacts on forest site conditions.

Most adaptation measures described in the previous sections focus on the stand level, but it is important to recognize that forest management strategies need to go beyond individual stands. A key approach in risk management is **diversification** of tree species mixtures and management approaches between neighbouring forest stands or within a forestry district to increase adaptive capacity and to act as an internal insurance by improving the overall resilience of forests to climate change (Lindner, 2000; Bodin and Wiman, 2007; Lindner, 2007). As there is uncertainty about the timing of changing species or provenances in forest regeneration (cf. chapter 7.2.) it should be considered at the scale of management units that more conservative and more rapid adaptation strategies can be applied simultaneously in different forest stands.

Individual response strategies as described in different sections of this chapter can often be mutually exclusive. For example, preferring natural regeneration in mixed forests with long rotation cycles and small harvest patches is impossible to combine with planting productive genotypes managed with short rotation cycles to minimize wind throw disturbance. At larger geographical scales of management units and forest landscapes, however, such strategies can also be combined.

# 8. FEASIBILITY, RELIABILITY AND COST-EFFECTIVENESS OF ADAPTATION MEASURES

## 8.1 Introduction

This chapter discusses the feasibility, reliability and cost-effectiveness of adaptation options. Due to the lack of detailed quantitative analysis, the three aspects (feasibility, reliability and cost-effectiveness) will be assessed by expert judgement using an ordinal scale (low, medium, high). Moreover, the measures are not discussed at the same level of detail than in previous chapter. Instead, five adaptation approaches are distinguished, which include a combination of several specific adaptation measures.

- ***Feasibility***

In the context of this study, an adaptation measure is judged feasible when (a) the vulnerability of value chains providing goods and services will be reduced and when (b) the proposed measures can be technically and logistically implemented. Adaptation options with adverse effects on forest services and/or major limitations in their implementation are assessed to have low overall feasibility. Additional pressures due to non climate related impacts like e.g. browsing have to be accounted alongside possible adaptation measures.

- ***Reliability***

A measure is judged reliable if the underlying knowledge base is scientifically proven and sound with regard to the mechanisms leading to reduced vulnerabilities. Time lags of expected effects of adaptive measures as well as persistence of expected effects are considered.

- ***Cost-effectiveness***

Regarding cost-effectiveness alternatives will be compared with regard to associated costs as well as effectiveness of the adaptation measure. It can, for instance, be assumed that the costs of a full species conversion program are higher than those associated with altered management intensities. However, the long-term effectiveness of changed management intensities with regard to reducing adverse climate change effects is limited whereas the potential effectiveness of introducing an adapted species composition is high.

Table 22 summarises the evaluation of **key adaptation strategies,** which are discussed in more detail in the following sections (8.2 to 8.6).

**Table 22.** Summary of the evaluation of adaptation strategies. The strategies are combinations of measures described in Chapter 7 and are further described in detail in sections 8.2 – 8.6.

| Strategy | Description | Feasibility | Reliability | Cost-effectiveness |
|---|---|---|---|---|
| Promoting adapted species composition | ▪ Fast (a) and gradual (b) silvicultural pathways possible: a) clear-cutting and afforestation/ regeneration approaches and b) gradual conversion of stands<br>▪ Artificial and natural regeneration (including coppices natural regeneration) can be considered<br>▪ Where possible natural regeneration with long regeneration phases in small patches is to prefer<br>▪ The choice of forest reproductive material is crucial<br>▪ Initial spacing and mixture type are important.<br>▪ Foreign tree species can help to provide forest goods and services but might cause adverse effects<br>▪ Proper tending and thinning is of high importance | **Medium - high** on small and medium scales with regard to forest owners' objectives.<br>On large scales decreasing feasibility due to bottlenecks in nurseries with regard to suitable reproductive material. | **Medium - high** on small scale due to long lasting efficacy of measures.<br>**Low - medium** on larger scales due to time lags before the measures can unfold their effects. The substantial share of non industrialized private forest owners, with diverse management objectives, might complicate the implementation of large scale adaptation policies. | Stand conversion programmes are cost intensive especially for artificial regeneration; therefore the costs are estimated to be **high**.<br>The potential effectiveness can be **high** due to the distinct and focused alteration of stand characteristics. |
| Increase diversity | ▪ Increasing diversity in terms of species- and structural diversity (stand level as well as landscape level diversity) can act as a hedge against potential climate change induced risks<br>▪ The choice of the forest reproductive material is of high importance<br>▪ To achieve a mixed structure also in later development stages proper tending and thinning has to be provided<br>▪ Thinning operations should aim to create structural diversity in age, diameter, height and spatial distribution<br>▪ A combination of high diversity and adapted species compositions (see above) could even increase the potential of adaptation measures | **Medium** because strongly depending on local conditions (good and services portfolio, owners' objectives, professional skills, education levels, reproductive material availability, etc.). | **Medium - high** on small scale due levels to long lasting efficacy of measures.<br>**Low - medium** on larger scales due to time lags before the measures can unfold their effects. The substantial share of non industrialized private forest owners, with diverse management objectives, might complicate the implementation of large scale adaptation policies. | The economic investments can be expected as **medium - high** with regard to increasing species diversity and as **medium** for the promotion of structural diversity.<br>The effectiveness with regard to the adaptation goals is estimated to be **medium - high**. |

| Strategy | Description | Feasibility | Reliability | Cost-effectiveness |
|---|---|---|---|---|
| Increase management intensity | ▪ Intensified management can entail: wider initial spacing, weed control in initial stages, intensified tending and thinning and shorter rotation periods<br>▪ Especially in drought prone regions it is necessary to adapt the growing stock and rotation periods to the local water availability<br>▪ Reducing the growing stock aims to restrict the leaf area and consequently water demand, and contributes also to mitigate risks towards an array of disturbances<br>▪ In the Boreal region and many alpine areas climate change is likely to increase growth. This should not lead to higher levels of standing stock, favourable for drought stress and susceptible to disturbances. Especially for stands in higher elevations where the protective function is relevant new dynamics due to climate change need to be considered in an intensified management regime | **High** in areas with respective forest infrastructure. This strategy does not require major structural changes in management and has the potential to enhance short- to midterm economic performance. | **Medium**, because impacts of altered management intensities might come into effect already on short to mid terms, but increasing thinning intensities can lower stand stability for short time periods following the interventions.<br>On larger scales the reliability of this measure will be heavily influenced by ownership structure. Numerous management objectives (e.g. small scale owners) might limit the implementation of coherent adaptation policies. | Increasing management intensities are associated with **low** costs or even positive economic effects.<br>The adaptive potential of such measures is also limited. Thus the overall effectiveness is estimated to be **medium - low** in comparison to the previous two adaptation options presented |
| Landscape level management measures | ▪ Different adaptation measures that are mutually exclusive at the stand level can be combined at the landscape level<br>▪ Uncertainties about future climate conditions can be considered in choosing different species and provenances in neighbouring stands<br>▪ Landscape level management planning can reduce susceptibility to disturbance risks | **High**<br>Measures can build on existing diversity of forest stands and applies existing management strategies | **High**<br>diversifying risks of adverse unexpected outcomes and applying multiple strategies are secure risk management options<br>**Medium**<br>disturbance impact can only be reduced, but not avoided | **Low - high** costs depending on the combined individual measures<br>**High**<br>disturbance induced losses are reduced with limited extra costs |
| Improvement of road density and infrastructure | ▪ Improvement of road networks and infrastructure in forests with low road densities (e.g. mountain forests) as a prerequisite for sanitation fellings and pro-active forest protection measures to tackle increasing disturbance frequencies and intensities under climate change<br>▪ For the mitigation of large scale economic effects due to large scale disturbances the preparation of wet storage facilities should have high priority to avoid distortions of the timber market | **Low - high** dependent on the local geomorphology | **High** for disturbance management due to practically immediate effects.<br>**Medium** for general adaptation because of road construction related threats with regard to forest health (e.g. changed water drainage on slopes) and the dependency on other adaptation measures to unfold effects. | **Low - high** costs depending on the local geomorphology<br>**Medium** effectiveness in general, depending on the initial state of the road network. |

## *8.2 Promoting site-adapted species composition*

- ***Description***

Species can be regarded as site-adapted if projected site climatic conditions are within the envelope of its fundamental niche. Moreover, future adaptive capacity to climate change can be increased by fostering the genetic diversity within populations of site-adapted species. The promotion of a site-adapted species composition can be achieved in several ways. In the regeneration phase, stands can be gradually converted by means of natural regeneration or by converting them with artificial regeneration. During the tending and thinning phase, the species composition can be influenced by reducing the share of maladapted species. Especially when gradually converting stands the adaptation of the seed trees to the current and future site conditions is of high importance for climate change adaptation. Furthermore, the larger the genetic variability the larger is also the potential genetic adaptability. Therefore for natural regeneration small regeneration patches with long regeneration phases should be favoured. For artificial regeneration the choice of species, the species' provenance and the initial spacing as well as mixture type are of relevance. Foreign tree species can help to provide goods and services (e.g. timber production) under climate change, but possible adverse effects on biodiversity need to be considered.

For proper development of stands correct tending and thinning is crucial. Overall, the promotion of well-adapted species has been found to enhance a number of forest services. Considerable long-term potentials to reduce productivity losses and vulnerabilities to for instance insect damages have been assessed in simulation studies at different scales.

- ***Feasibility***

Promoting site-adapted species composition is considered feasible as long as it can be brought into agreement with the local goods and services portfolio and it reduces the respective vulnerability to climate change. I.e. the tree species chosen for climate change adaptation have to meet the owners' objectives and simultaneously reduce the related vulnerabilities. The feasibility, of small to mid scale conversion efforts will be medium to high. This is underlined by the fact that tree species conversion can alleviate a number of adverse climate effects beyond productivity decreases such as declining stand stability and reduced biodiversity. Yet, when promoted on large scale bottlenecks in nurseries with regard to suitable reproductive material may hamper feasibility.

- ***Reliability***

At watershed scale the reliability of this adaptation measure can be estimated as medium to high, due to the long lasting efficacy of stand conversion with site adapted species. The effect of genetic adaptation due to a high genetic variability will likely take more than a rotation period to be effective. For an implementation at larger scales, e.g. at the level of regions the time lags before such measures will be fully implemented and unfold their effects can be substantial. Thus, at larger scales the reliability of this adaptation option is decreasing. Additionally, the forest ownerships structure in Europe and particularly in the Alps is characterized by a substantial share of non industrialized private forest owners. The resulting diverse management objectives might also hamper the implementation of large scale adaptation policies.

- ***Cost-effectiveness***

Stand conversion programmes are relatively cost intensive. This is especially true for conversion with artificial regeneration. Therefore the costs are estimated to be high. However, the potential effectiveness likewise can be quite high due to the distinct and focused alteration of stand characteristics. Introducing drought tolerant species to better cope with anticipated drought may result in short term productivity loss (because growth rates of tolerant species may be lower), which needs to be balanced against the potential drought damage and secondary disturbance risk in stands without species conversion. Cost-effectiveness in this case would then be a question of the balance of stand conversion costs and reduced short-term wood production potential on the one side, and potential revenue loss through drought and disturbance damages on the other side.

## 8.3 Increase species and structural diversity

- ***Description***

Increasing diversity of forests in terms of species- and structural diversity can act as a hedge against potential climate change induced risks. An increased species and structural diversity can be beneficial due to a better resistance against various forms of damages, increased biomass productivity and enhanced soil fertility. The promotion of mixed and structurally diverse management concepts is also found beneficial in detailed studies.

The choice of the forest reproductive material is of high importance for climate change adaptation, whether regenerating artificially or naturally. Furthermore, to achieve a mixed structure also in later development stages proper tending and thinning has to be provided. Thinnings should aim to create structural diversity in age, diameter, height and spatial distribution resulting in a lower susceptibility to disturbances and a potentially increased protective functionality. This enhancement of protective functionality would be mainly due to increased regeneration activity and structural richness, counteracting large homogeneous late-serial stages prevailing in parts of the Alps today. Overall, increasing structural and species diversity could be a strategy to enhance forests with regard to multiple objectives. Particularly with regard to alpine conditions such management strategies might be well suited to ensure sustainable provision of crucial forest services such as protection also under changed environmental conditions. However, as demonstrated by Seidl *et al.* (2008a), a combination of high diversity and site-adapted species compositions (see above) could even increase the potential of adaptation measures.

- ***Feasibility***

Promoting tree species diversity on a large scale will cause considerable changes in the forest sector and the wood processing industry. Nevertheless, with regard to the local goods and services portfolio this measure seems feasible due to a considerable reduction of vulnerabilities to climatic change. However, mixed, structured forest management in complex alpine terrain will depend on high professional skills and educational levels in forest operations and management planning, e.g. compared to forestry in even aged monocultures. A steadily decrease in forestry employment over the last decades in many places might limit the practical feasibility of such diverse management strategies. If species diversity is to be enhanced, adapted and genetically diverse reproductive material is crucial and might cause a bottleneck to large scale efforts.

In mountain forests in particular forest operations are complicated by steep terrain, rendering the density of the road network a very important factor. Accessibility is the prerequisite for small scale, structural management measures. Thus from the current perspective feasibility will depend strongly on local conditions and can be assessed as medium in general.

- ***Reliability***

At a small scale level the reliability of this adaptation measure can be estimated to be medium to high, due to the long lasting efficacy of proposed measures. In general, small scale structured management is replicating natural ecosystem dynamics e.g. in mountain areas. Thus there are no major environmental obstacles towards an implementation of such management regimes.

For larger scale measures, at the level of e.g. regions, the time lags before the measures can unfold their effects may be considerable and therefore the overall reliability is decreasing with scale. Furthermore, the substantial share of non industrialized private forest owners, with diverse management objectives, might complicate the implementation of large scale adaptation policies.

- ***Cost-effectiveness***

The economic investments can be expected as medium to high with regard to increasing species diversity and as medium for the promotion of structural diversity. Overall, diversity can lead to even positive economic effects due to reduced losses from biotic and abiotic disturbances, higher market flexibility, and under certain circumstances also through higher productivity and larger crop tree dimensions. The effectiveness with regard to the adaptation goals is estimated to be medium to high.

## 8.4 Increase management intensity

- ***Description***

Especially in regions which will suffer from decreasing water availability and drought risk it is necessary to adapt the growing stock to the local conditions of water availability. In general, higher levels of growing stock result in higher leaf areas and consequently water demand but also in higher risks towards an array of disturbances. In Mediterranean drought prone regions the maintenance of low density (savanna-like) forest stands combined with run-off harvesting techniques (to intercept runoff and redirect water to single trees) can significantly improve water use efficiency and nutrient supply within the stand, thus increasing forest productivity.

Wide initial spacing is suggested in artificial regeneration for sites susceptible to drought. In regeneration, weed control is a crucial factor to minimize adverse effects from competition for water. In later forest development stages a higher thinning intensity is proposed, inter alia increasing drought resistance and resulting in an increased share of large dimensioned timber on the total harvest volume. Such management activities can also augment the stability against a number of disturbances. Shorter rotation periods are suggested especially for commercial forestry, to counteract increasing drought stress on respective sites and to reduce the duration and abundance of highly vulnerable stand development stages. Conversely, an intensified management regime might have detrimental effects in erosion prone environments of the Mediterranean region, where an increase of rotation length, especially in coppices, is recommended (cf. 7.4).

In the Boreal region and many alpine areas a changing climate is likely to increase growth. Intensified forest management should counteract higher levels of standing stocks, which could favour drought stress and increase disturbance risks. This is especially relevant for stands with important protective functions in higher elevations where growth and regeneration currently are temperature-limited.

- ***Feasibility***

The feasibility for intensified tending and thinning is high in areas with respective forest infrastructure. In higher altitudes the road network is less dense and the accessibility influences the costs of silvicultural measures, which might hamper frequent tending or thinning. Particularly in protective forests tending and thinning efforts have to be carried out carefully, with positive effects of weak but frequent harvests. However, the feasibility of this adaptation strategy is high since it does not require major structural changes in management and has also the potential to enhance short- to midterm economic performance.

- ***Reliability***

Adaptation effects of altered management intensities might come into effect already on short to mid terms. However, increasing thinning intensities can lower stand stability for short time periods following the interventions. Therefore the reliability has to be regarded as medium. On larger scales the reliability of this measure will be heavily influenced by small scale forest owners (i.e. non industrial private forest owners), representing a substantial share within the forest owners e.g. in the Alps. Their numerous management objectives might limit the implementation of coherent adaptation policies.

- ***Cost-effectiveness***

Compared to the latter two adaptation options increasing management intensities are associated with low costs or even positive economic effects. However, the adaptive potential of such measures is also strongly limited. I.e. altered management intensities might not be possible to prevent adverse effects of climate change in stands of an increasingly maladapted species. Thus the overall effectiveness is estimated to be medium to low. When combined with the introduction of site-adapted species, the expected effectiveness would be increased simultaneously with higher costs.

## 8.5 Landscape level management measures

- ***Description***

Similar to the rich variety of management approaches in present day forestry in Europe, there is also a suite of adaptation measures available to adapt forests to climate change. However, at the stand level many of these measures are mutually exclusive. Examples for feasible combinations of adaptation measures at the stand level include, for instance, enrichment planting using genotypes which are better adapted to potential future environmental conditions, and increased structural diversity. Mixing tree species at stand level is constraint by the competitive relationship and social behaviour of species. At the landscape level, however, it is possible to diversify management strategies. Close to nature management with longer regeneration periods has many positive impacts particularly in the context of changing environmental conditions, because it enhances within-stand structural diversity and the inherent adaptive capacity of forests. But also intensive management systems with short rotation cycles serve specific forest functions in providing wood and biomass for various products and energy, as well as other goods and services. While the complexity of close-to-nature forestry brings about increased stability and resilience, short rotation forestry increases flexibility by increased turnover rates. Applying both systems in different places in the landscape can have additional benefits, as planting of new genotypes in the intensive management system can speed up the gene flow to enhance adaptive capacity also in the surrounding close-to-nature management areas.

The future climate conditions are always going to be associated with uncertainties. Consequently it will not be possible to precisely forecast how individual species will perform decades after stand establishment. Biotic disturbance regimes will directly be affected by a changing climate and via the mutual relationship with forest management; they will further increase uncertainties in this context. Diversifying species and provenance selection at the landscape level is a suitable measure to reduce risks of adverse effects and increase resilience of forestry to climate change.

Landscape level management strategies can also help to reduce susceptibility to abiotic disturbance risks. The placement of cuttings should avoid wind exposure of tall forest edges to reduce wind damage risk and planting barriers of fire resistant species between more flammable species to reduce the risks of large fires.

For the design of landscape level management strategies decision support systems are urgently needed. Diversification of management strategies at the landscape scale may implicitly or explicitly result in the (partial) segregation of forest functions. Diverse management strategies applied to different stands allows enhancing the total regional output of goods and services from forests while at the same time reducing the risk of major losses through a changing climate.

- ***Feasibility***

The feasibility of landscape level management strategies is high as they may build on existing diversity of forest stands in the landscape and require no major structural changes in management. Diversity of forest ownership supports this measure. However, small scale ownership may also be seen negatively due to huge difficulties in planning across ownerships. In large uniform forest landscapes there is more time needed to develop diversity at the landscape level.

- ***Reliability***

Diverse landscape level management strategies are especially targeted to reduce risks associated with focusing on only a limited number of management strategies. By distributing risks, large scale adverse impacts become less likely. It should be noted that under favourable climate development or if the climate change closely follows the expected trends, diversification of management strategies may in some cases lead to less favourable outputs compared to more narrow response strategies. But due to the large uncertainties associated with climate change and its impacts on forests, the reliability of more diverse management strategies is seen as rather high.

- ***Cost-effectiveness***

Cost-effectiveness depends on the selected individual adaptation measures and on the unpredictable development of future climatic conditions. Where landscape level diversity of management is already high, the costs of applying this strategy are lower compared to situations, where large uniform forest landscapes need to be diversified. Positive economic effects are possible through reduced disturbance risks. The adaptive potential of landscape level measures is high, because overall diversity increases and different adaptation processes are combined with each other.

## 8.6 Improvement of road density and infrastructure

- ***Description***

Road network optimization and road density are key issues for forest management in general. Road networks are integral part of timber harvesting systems. As such road networks are planned and optimized depending on the available and/or appropriate hauling and transport means as well as in dependence of the prevailing silvicultural system. In productive forests road network optimization has been a priority issue in recent years and major areas are well accessible already now. If in response to climate change silvicultural systems should be altered towards smaller-scale operations (cf. chapter 7.2) current road networks may need to improve. However, the bigger impact on road networks will occur in mountain protection forests. In general hand in hand with increasing relevance of protective functions forest productivity is decreasing due to steep slopes, rocky and shallow soils and environmental harshness. As a consequence, the investments in high road densities have been much lower in such forests. If disturbance frequencies and intensities in mountain forests will increase under climate change, the need for improved accessibility as prerequisite to sanitation fellings and pro-active forest protection measures will increase, too, calling for improvement of road networks and infrastructure. In addition, for wind throw mitigation the preparation of wet storage facilities should have high priority to avoid major distortions of the timber market due to abruptly increasing supply.

- ***Feasibility***

The feasibility of road construction is very dependent on the local geomorphology. Therefore it can be assumed that the feasibility is smaller in mountainous terrain than in other regions with more gentle geomorphic features. However, the highest need for new road construction will occur in mountain forests. In the past nature conservationists argued strongly against dense road networks in mountain forest regions to protect habitat for rare wildlife species as well as biodiversity in general.

- ***Reliability***

The improvement of the road density has to be seen in connection with other measures for climate change adaptation to assess the reliability. In many cases adaptation measures depend on a proper road network (see forest regeneration). The fact that the construction of roads has a practically immediate effect on forest management options is beneficial for subsequent adaptation measures which may need a certain time span to unfold their effects. But forest road construction might also pose some threats with regard to forest health in a changing environment by altering the water-drainage on slopes. Therefore the reliability is estimated to be high for disturbance management (i.e., impact management), medium for adapting species mixtures via adapted regeneration processes.

- ***Cost-effectiveness***

The costs for the improvement of road density are difficult to estimate. Costs are mainly driven by local geomorphology (20-70 Euro/running meter on average) and from a forest owner perspective can additionally be strongly influenced by subsidies. Therefore the costs are estimated to be in a range from low to high. The effectiveness of an increase in road density is dependent on the local initial state. The effectiveness will be greatest for forests with low road densities like e.g. in protective forests in mountainous regions, whereas in regions with an already high road density, e.g. commercial forests in pre-alpine areas the effectiveness will be low. In general the effectiveness might be judged as medium.

Overall, accounting for the local biophysical and socio-economic conditions a combination of selected measures from these general management options might be valuable to achieve high feasibility, reliability and cost-effectiveness simultaneously on both short and long time frames.

# 9 EXISTING AND PLANNED ADAPTATION STRATEGIES IN EU 27 MEMBER STATES

## 9.1 Status of planning for adaptation

Several countries have already developed national or regional strategies to adapt to climate change. A review searching for reports on the internet has revealed the situation documented in Table 23.

**Table 23.** Adaptation strategies in EU27 Member states

| Zone; State | Title of the strategy or report | Year of publishing |
|---|---|---|
| **Boreal** | | |
| Finland | Finland's National Strategy for Adaptation to Climate Change | 2005 |
| Sweden | Svenskt skogsbruk möter klimatförändringar | 2007 |
| **Temperate Oceanic** | | |
| Belgium | n.a | |
| Czech Republic | Climate Protection Policy in the Czech Republic (includes both mitigation and adaptation strategy) | 2008 |
| Denmark | n.a | |
| France | Préparer les forêts françaises au changement climatique | 2007 |
| Germany | ▪ Climate Change in Germany Vulnerability and Adaptation Strategies of Climate-Sensitive Sectors<br>▪ Regional strategy: Klimawandel in Nordrhein-Westfalen - Wege zu einer Anpassungsstrategie | 2005<br>2007 |
| Ireland | Ireland National Climate Change Strategy 2007-2012 (very generally about forestry and adaptation) | 2007 |
| Luxemburg | n.a | |
| Netherlands | Climate Change Scientific Assessment and Policy Analysis, Climate adaptation in the Netherlands | 2006 |
| United Kingdom | ▪ Adaptation policy framework<br>▪ Report of impacts of climate change on forestry in Wales | 2008 |
| **Temperate Continental** | | |
| Austria | Has recently (summer 2008) started a participatory process to develop a "Climate Change Adaptation Strategy" | |
| Bulgaria | The Second National Action Plan on Climate Change for the period 2005 – 2008 | 2004 |
| Estonia | n.a | |
| Hungary | National Strategy on Climate Change | 2008 |
| Latvia | n.a | |
| Lithuania | n.a | |
| Poland | n.a | |
| Romania | National Strategy on Climate Change of Romania 2005 - 2007 | 2005 |
| Slovakia | n.a | |
| Slovenia | Slovenia's First National Communication under The UN Framework Convention on Climate Change | 2002 |

Table 23 continues

| Mediterranean | | |
|---|---|---|
| Cyprus | Sustainable Development Strategy (includes forests) | 2007 |
| Greece | National Strategy for Sustainable Development (includes forests) | 2002 |
| Italy | Climate Change Impacts and Adaptation Strategies In Italy. An Economic Assessment | 2008 |
| Malta | n.a. | |
| Portugal | n.a. | |
| Spain | The National Plan for the Adaptation to Climate Change (PNACC) | 2006 |

Source: information provided by country respondents or search from internet.
"n.a." means that no information has been reported or this has not be found

It was beyond the scope of this report to analyse these national reports in detail. Instead, a detailed questionnaire was designed to collect the information from the different countries in a standardized way as documented in the next sections of this chapter.

## 9.2 Consultation of Member States - Analysis of survey results

A survey was carried out to compile existing and planned national strategies for adapting forestry to climate change in the EU 27 Member states. The questionnaire was distributed to the highest level forestry administrations in 26 countries, which take part in the EU Standing Forestry Committee. Additionally, the questionnaire was also sent to 66 research institutes in Europe that are associated members of EFI.

In many countries answers to the questionnaire were prepared by each organization autonomously, but in some countries ministries and research institutes co-operated. Consequently, the number of responses per country varies. We received answers from 20 EU countries until the first of September, 2008. The number of responses per country is documented in Annex 6.

For different bioclimatic zones we got answers as follows:

| | |
|---|---|
| Boreal | 2 |
| Temperate Oceanic | 11 |
| Temperate Continental | 10 |
| Mediterranean | 3 |

The total number of answers is very low for the Boreal and the Mediterranean zones. The number of answers is higher for the Temperate zones. However, the answers do not always cover all adaptation measures, because the countries are very diverse in their forests and forestry practices. Anyway, the answers reveal specific characteristics of the zones and provide an overview of the status of implementation of adaptation measures.

The importance of climate change impacts and the development of adaptation measures for the forest sector were reported to be significant. All the respondents expect that there will be many or some impacts of climate change on forestry in their country (Fig. 21).

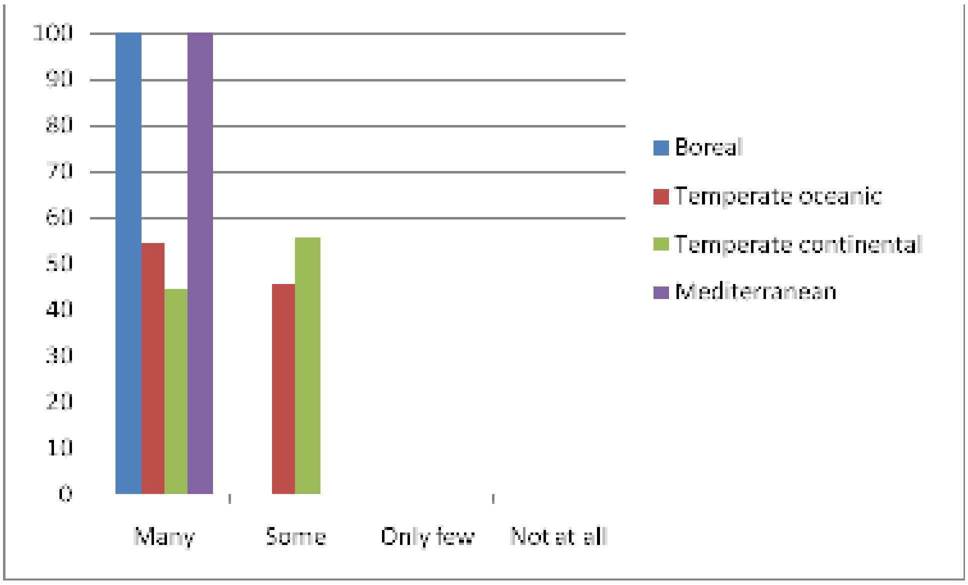


**Figure 21.** Expected impacts of climate change on forestry. Relative share of answers in different categories. Total numbers of answers are by regions: Boreal (2), Temperate Oceanic (11), Temperate Continental (9) and Mediterranean (3).

In all regions respondents believe that investing resources on adaptation is important (Fig. 22). Only in some answers from the Temperate region a more relaxed opinion was expressed (some measures or only few measures are necessary). All respondents from Boreal and the Mediterranean zone suppose that investing resources on adaptation is important. This is understandable because some impacts of climate change are most apparent in these zones. Warm winters and short snow cover time are experienced in the northern part of the Boreal zone. In the Mediterranean area the average annual number of forest fires was in the end of 1990's twice as many as during the 1970's. This increase has many reasons, but drought periods due to climate change is one main reason.

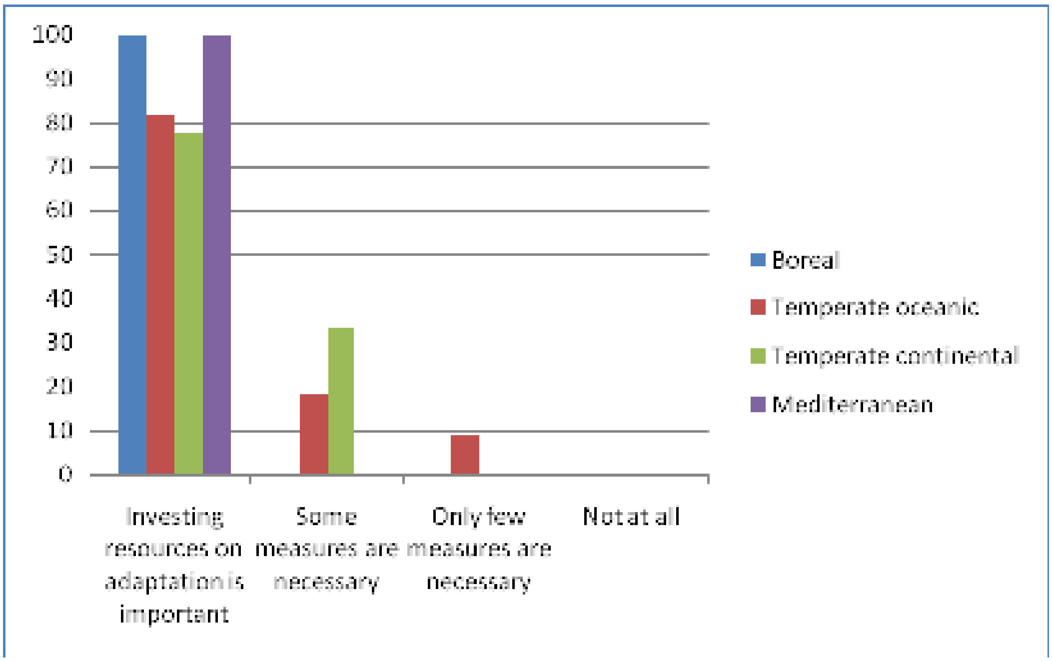


**Figure 22.** How necessary it is to have adaptation strategies to cope with climate change impacts on forests and forestry? Relative share of answers in different options. The total numbers of answers by region are Boreal (2), Temperate Oceanic (11), Temperate Continental (9) and Mediterranean (3). In some cases respondents provided multiple answers.

As a conclusion climate change is expected to have many effects in all regions. Investing resources on adaptation is important in all regions. A minority of responses from the Temperate zones saw a smaller need for adaptation strategies.

## *9.3 Forest adaptation strategies in EU Member states*

### 9.3.1 Approach for analysis of national adaptation measures

In the second part of the questionnaire the countries were asked to list on-going and planned adaptation measures related to sixteen different topics of forestry.

All together a total of 1097 adaptation measures have been identified in the responses to the questionnaire. Per country, the number of reported adaptation measures was on average 55 measures (min: 29, max: 163). Some of the measures have been listed several times, for example both as on-going and planned or new adaptation measure within one country. In such cases we could not judge whether the measures were identical or different. In the sums listed above multiple listing of measures was possible. More detailed information about number of measures is documented in Annex 7 and answers by country in Annex 9.

Two approaches were used to analyze all responses. In the first one, similar measures were recognized and grouped together. There is a lot of information to analyse, and therefore some filtering of information was required. Several adaptation measures were mentioned more than once (as on-going, planned and new ideas) and similar measures proposed by different respondents may mean the same or address the same targets. The excess of information and differences in the level of elaboration of the answers by respondents made the analysis complicated and arduous.

- Measures were combined into only one remaining measure, in cases where the difference in content was small (i.e. measures addressing the same target but using different words).
- In some cases measures given by one of the answers is included in another measure with a broader scope. This was reflected by introducing intermediate levels into the classification
- Measures were kept in different categories when they are addressing different targets.

**Table 24.** Number of measures in different action level

| Level of action | Adaptation actions | Number of measures |
|---|---|---|
| Stand level | Forest regeneration | 22 |
| | Tending and thinning of stands | 9 |
| | Harvesting | 17 |
| Forest management | Management planning | 20 |
| | Forest protection | 14 |
| Policy level | Infrastructure and transport | 14 |
| | Nurseries and forest tree breeding | 16 |
| | Further adaptation integration in risk management and policy | 71 |
| Total number of measures | | 183 |

Following this procedure, the initial list of 1097 adaptation measures was reduced to 183 measures that we consider as distinct options for adaptation (Table 24). The detailed list of measures is presented in Annex 9.

In a second approach, keywords were identified and counted in the answers. A total number of 75 keywords occurred in the answers between 1 to 190 times. The most often occurred keywords were grouped into four main categories:

1) Research and awareness,
2) Selection of species, provenances and genotypes,
3) Methods of tending and thinning and
4) Protection against biotic and abiotic disturbances.

In the following chapters these categories are used to present the measures which are on-going or planned in different bioclimatic zones in Europe.

### 9.3.2 Boreal

In the questionnaire responses, among the main recognized aspects of climate change impacts in the Boreal zone were effects on abiotic and biotic damages (Fig. 23) and measures against these risks were the main focus of on-going and planned measures (cf. Table 25). Reduced access for winter logging is also important and some measures for this were listed, like development of new technical equipments and better planning of transportation. Effects of climate change on wildlife habitats and productivity of trees are also expected, but hardly any measures are on-going or planned for these aspects. Several climate change impact concerns were added by respondents. For instance, social forest values could be reduced when climate change modifies the recreational values of forests (spruce forests will be denser and darker).

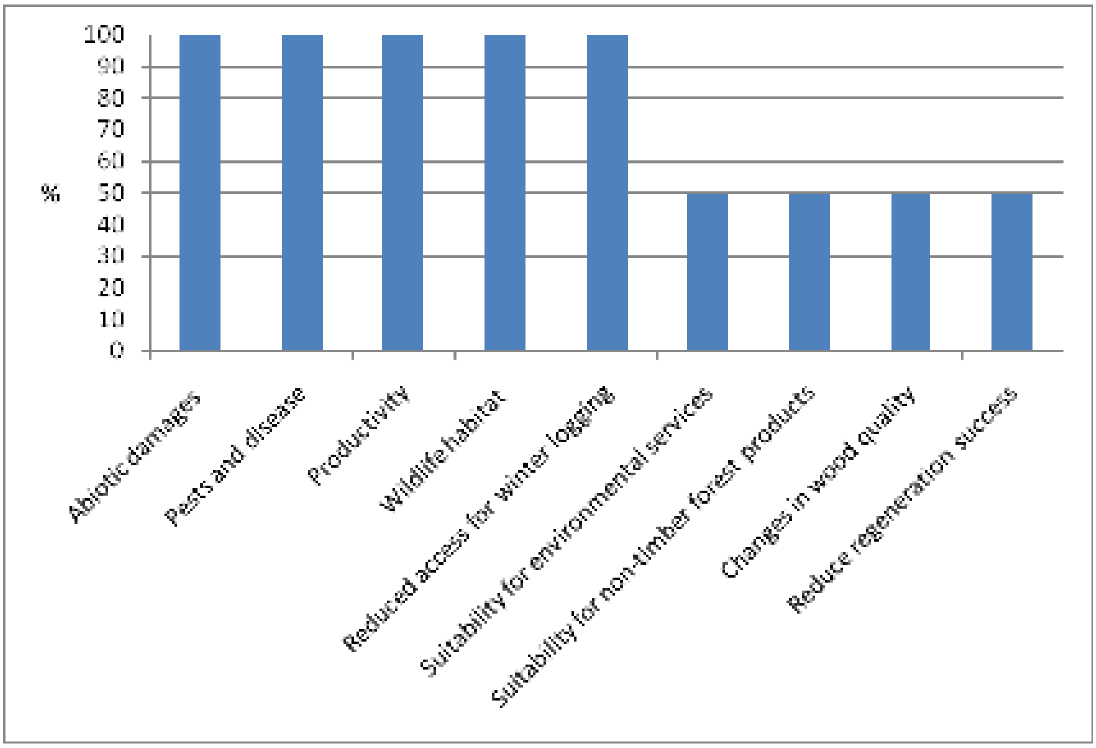


**Figure 23.** Relative share of important aspects of climate change in the Boreal zone. Total number of answers was 2. Respondents could provide multiple answers.

**Table 25.** On-going and planned measures in the Boreal zone in main categories of measures.

| **ON-GOING** | | **PLANNED** | |
|---|---|---|---|
| **More research on…** | | | |
| Tree breeding of different sites | | Strategies for protection | |
| Regeneration techniques | | Changes in selection of species, provenances and genotypes | |
| Modification of thinning | | | |
| Harvesting techniques on non-frozen soils | | | |
| **Selection of adaptable species, provenances and genotypes…** | | | |
| Which perform well across sites | | Considering abiotic factors | |
| **Change tending and thinning** | | | |
| Target of measure | What for | Target of measure | What for |
| Silvicultural systems | Decrease Abiotic risk | Thinning schedule | Decrease risk of wind throws |
| | | Thinning intensity | Decrease risk of wind throws |
| **Reducing biotic and abiotic disturbance risk** | | | |
| Target of measure | Risk | Target of measure | Risk |
| | | Stand structure | Wind throws |
| | | Monitoring | Pest outbreaks |

In the questionnaire it was also asked, which stakeholders will be most affected by climate change. All the answers were categorised to twelve groups. In the Boreal zone the most important group was forest owners (Fig. 24).

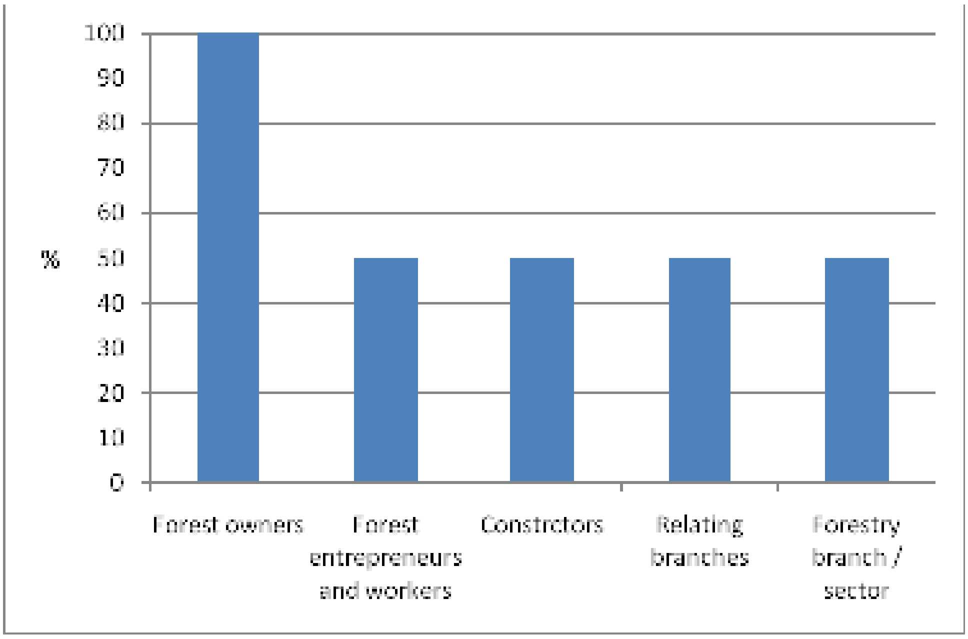


**Figure 24.** Relative share of stakeholders, who are the most affected by climate change in Boreal zone according to the answers of questionnaire. Total number of answers was 2. Respondents could provide multiple answers.

### 9.3.3 Temperate Oceanic

The most important expected climate change impacts from the perspective of respondents in the Temperate Oceanic zone were disturbance impacts and effects on productivity (Fig. 25).

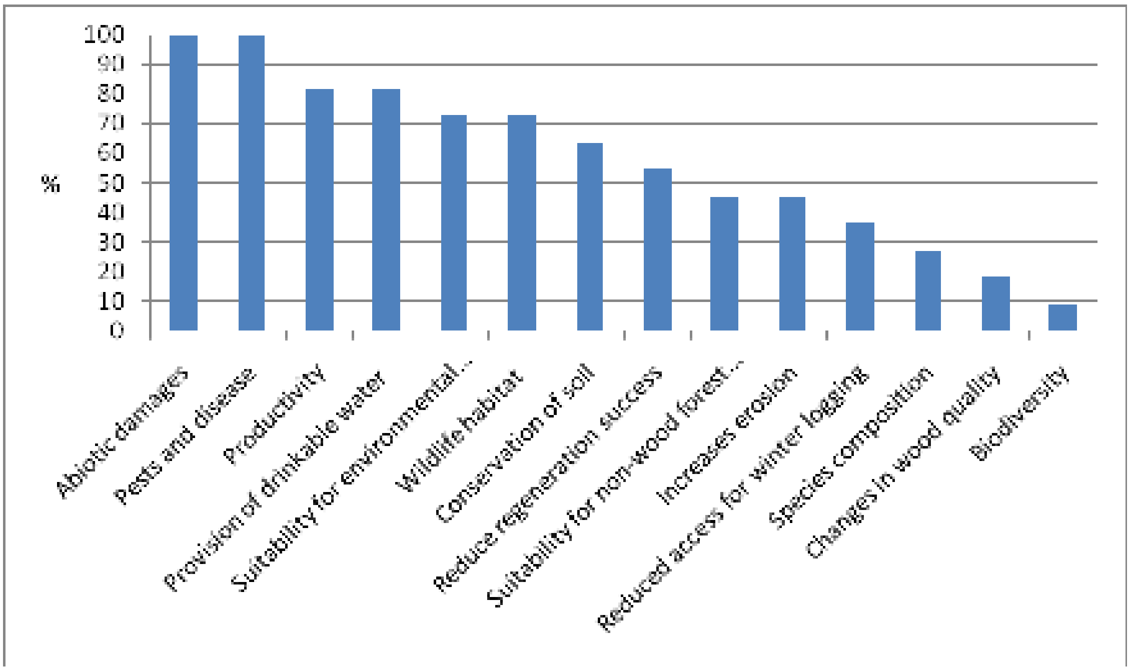


**Figure 25.** Relative share of important aspects of climate change in Temperate Oceanic zone according to answers of questionnaire. Total number of answers was eleven (11). Respondents could provide multiple answers.

The answers to the questionnaire document the need for more information on well-adapted tree species and non-local provenances under future climate conditions (Table 26). Research on adaptation of species to abiotic disturbances and on pests and disease dynamics under climate change are needed as well as forest management responses in relation to them. In selection of tree species, provenances and genotypes, the resistance to abiotic disturbances was targeted, but also selection of fast-growing species is planned. The selection of species and provenances has been listed both with a focus on native and non-native species/provenances. Management operations within stands are aspired to decrease risks of abiotic and biotic disturbances. As a planned measure they are also aiming to increase biomass supply for energy.

**Table 26.** On-going and planned measures in the Temperate Oceanic zone in main categories of measures.

| ON-GOING | | PLANNED | |
|---|---|---|---|
| **More research on…** | | | |
| Adaptable tree species | | Fire risk areas and protection of them | |
| Non-local provenances | | Classification of wind throw hazard | |
| Protective function of forests | | Plasticity of tree species and populations | |
| Forest management in relation of wind hazards | | Basic growth and yield | |
| Resistance of species to drought | | Combining mitigation and adaptation | |
| Invasive new pests and diseases | | | |
| **Selection of adaptable species, provenances and genotypes…** | | | |
| Which are resistant to hard winds | | Which are fast-growing | |
| Which are resistant to drought | | For future weather circumstances (drought, rain events) | |
| | | And mixing them from different climatic zones | |
| | | From local indigenous, native species | |
| | | Which are resistant to fire | |
| | | Which are resistant to frost | |
| **Change tending and thinning** | | | |
| Target of measure | What for | Target of measure | What for |
| Thinning intensity | Decrease risk of wind throws | Thinning intensity | Decrease risk of wind throws |
| Enhance thinning | Decrease fire risk | Thinning schedule | Decrease risk of wind throws |
| | | Thinning schedule | Biomass for energy |
| | | Selective thinning | More diverse stands |
| | | Specific management for the forest edges | Decrease risk of wind throws |
| | | Specific management for the forest edges | Biomass fuel |
| | | More open stands | Decrease risk of fungi |
| **Reducing biotic and abiotic disturbance risk** | | | |
| Target of measure | Risk | Target of measure | Risk |
| Thinning methods | Fire | Intensity and frequency of thinning | Wind throws |
| Co-operation, control | Fire | Monitoring | Wind throws |
| Small clear cut areas | Wind throws | Shorter rotation | Many disturbances |
| | | Mechanical protection | Pests |
| | | Intensity of thinning | Fire |
| | | Zone recreational areas | Fire |
| | | More open stands | Pathogens, water stress |

Forest owners are the most affected by climate change in Temperate Oceanic zone (Fig. 26). Other significant stakeholders are forest entrepreneurs, forest workers and forest administrations.

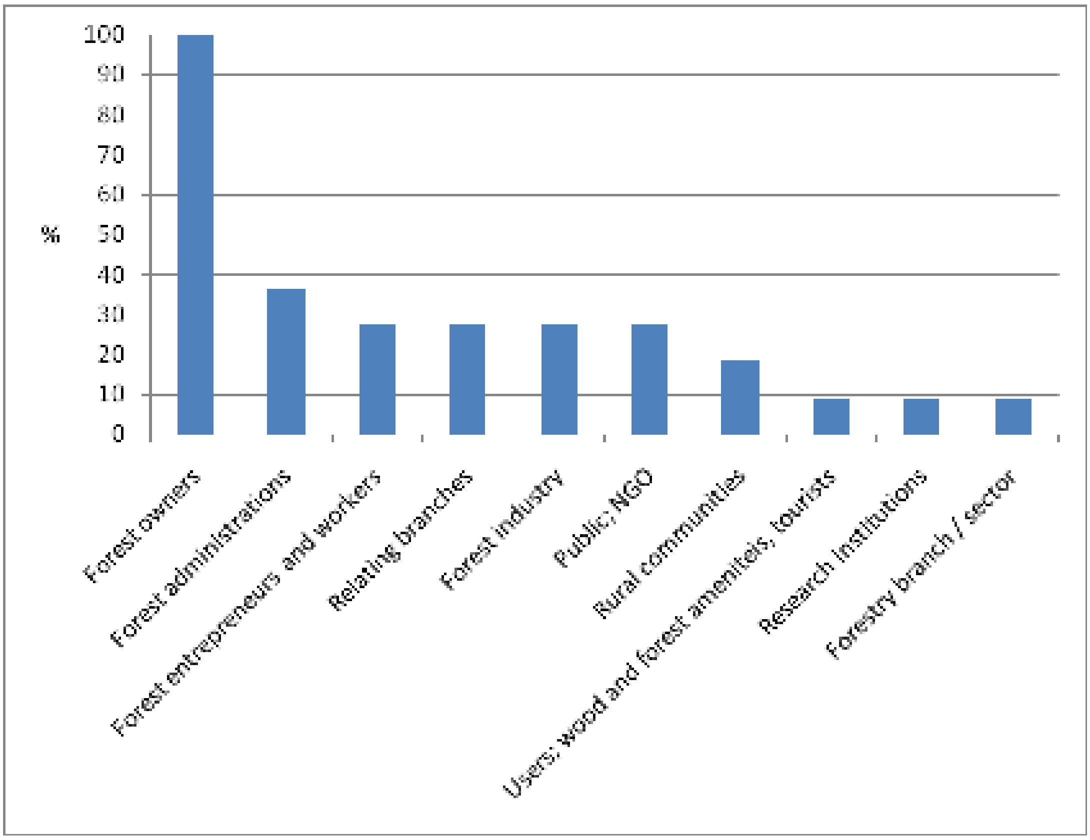


**Figure 26.** Relative share of stakeholders most affected by climate change in Temperate Oceanic zone according to answers of questionnaire. Total number of answers was eleven (11). Respondents could provide multiple answers.

### 9.3.4 Temperate Continental

The most important effect of climate change from the perspective of respondents in the Temperate Continental zone is on abiotic damages (Fig. 27). Effects on pests and diseases and on wildlife habitats are also important. In this zone other products are highlighted, like provision of drinkable water, because of drought, and suitability for non-timber forest products.

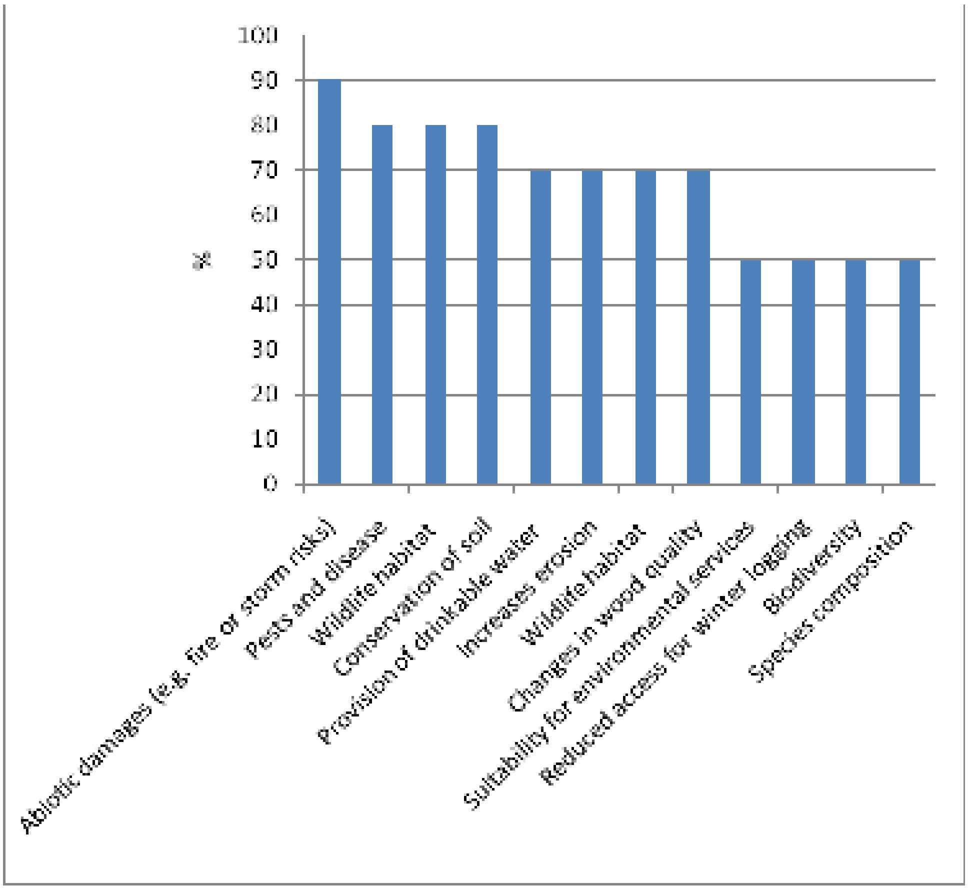


**Figure 27.** Relative share of important aspects of climate change in Temperate Continental zone according to answers of questionnaire. Total number of answers was ten (10). Respondents could provide multiple answers.

Adaptation measures in the Temperate Continental zone are very versatile (Table 27). On-going and planned research concerns adapted seedlings, biotic and abiotic damages, biodiversity, especially genetic diversity, silvicultural treatments, protection functions of forests and also effects of climate change on society. Measures at stand level are aimed at decreasing risks of abiotic disturbances, i.e. fire, wind, drought, as well as biotic disturbances, i.e. pests and pathogens. Building stable diversified forests is an on-going measure and it is planned to improve stand stability by the selection of suitable species, provenances and genotypes.

**Table 27.** On-going and planned measures in the Temperate Continental zone

| **ON-GOING** | | **PLANNED** | |
|---|---|---|---|
| **More research on…** | | | |
| Better adapted species or varieties | | Afforestation facing new difficulties | |
| Valuable habitats and species from biodiversity point of view | | Adapted seedling material | |
| Silvicultural treatments (long-term experiments) | | Site classification, soil-tree interactions | |
| Invasive pests and pathogens | | Protection functions of forests | |
| Avalanche danger | | Fire risk | |
| Genetic diversity | | Risk of pests and diseases | |
| Protective function (soil, erosion) | | Genetic diversity | |
| | | Prognostic technique | |
| | | Adaptation measures | |
| | | Also society level (not only ecological orientated) | |
| | | Tending of stand in critical areas | |
| | | Flexible silviculture | |
| | | Realistic scenarios | |
| **Selection of adaptable species, provenances and genotypes…** | | | |
| Which are less sensitive to changing environmental conditions | | Which manage on extremely dry or wet habitats | |
| Which perform well across sites | | Which are more resistant to drought | |
| To build stable diversified forests | | With preference of native species | |
| Which are resistant to drought | | More resistant to temperature extremes | |
| Which are resistant to hard winds | | For optimal stand stability | |
| From native indigenous | | Which are more resistant to biotic factors | |
| To plant suitable trees at critical areas (e.g. erosion, avalanches, landslides) | | For afforestation according existing soil types | |
| To prevent fuel accumulation in forests on areas with high fire risk | | | |
| **Change tending and thinning** | | | |
| Target of measure | What for | Target of measure | What for |
| Forbidding thinning | Special conditions | Silvicultural measures | More diverse stand structure |
| Thinning intensity | Decrease risk of wind throws | Management of stands | More stable stand structure |
| Management | Close to nature | Intensity of tending and thinning | More open stands |
| Thinning methods | Mixed and multistory forests | Close to nature management | Decrease risks of wind throws, and outbreaks |
| Silvicultural system | Special conditions | | |
| Limited thinning | Erosion sensitive areas | | |
| Tending measures | Protective role of forests | | |

Table 27 continues

| **Reducing biotic and abiotic disturbance risk** | | | |
|---|---|---|---|
| Target of measure | Risk | Target of measure | Risk |
| Control | Pests and pathogens | Harvesting procedure | Additional damages |
| Protection methods | Fire | Early warning system | Pests and pathogens |
| Restoration | Abiotic damages | Monitoring network | Pests and pathogens |
| Biodiversity of forests | Pests and diseases | Stand structure | Biotic and abiotic damages |
| Monitoring | Pests and diseases | Forecasting | Fire |
| | | Prevention network | Fire |

As in the Boreal and the Temperate Oceanic zones, forest owners are the main group of stakeholders most affected by climate change (Fig. 28). Other groups of stakeholders listed as important are communities and forestry administrations.

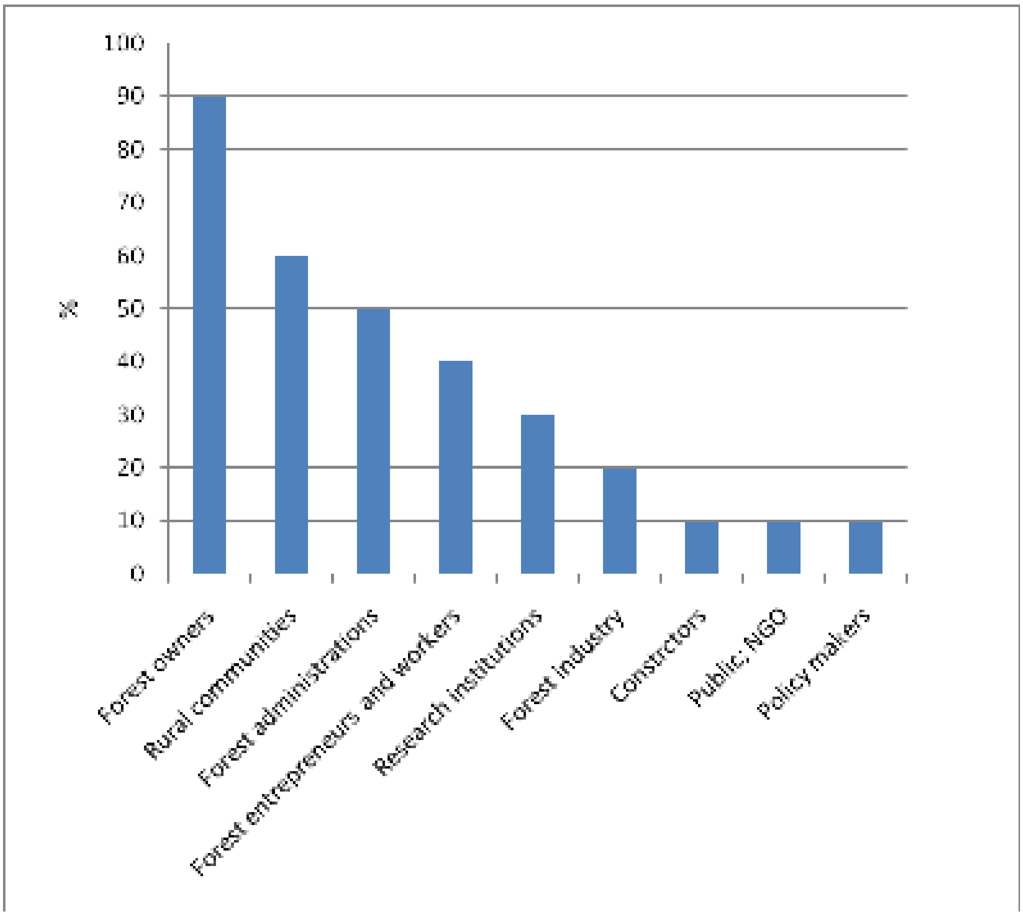


**Figure 28.** Relative share of stakeholders most affected by climate change in Temperate Continental zone according to answers of questionnaire. Total number of answers was ten (10). Respondents could provide multiple answers.

### 9.3.5 Mediterranean

Abiotic and biotic damages are perceived as import impacts of climate change in the Mediterranean zone. Because of frequent droughts, the provision of drinking water is also important. Impacts on wildlife habitat were also listed in all answers (Fig. 29). In the Mediterranean region effects on soil ecosystem sustainability and the role as carbon sink, which may change into a source, were added as important aspects. Also changes in eco-tourism and other nature-oriented functions of forests and forest landscapes were added as a possible effect of climate change.

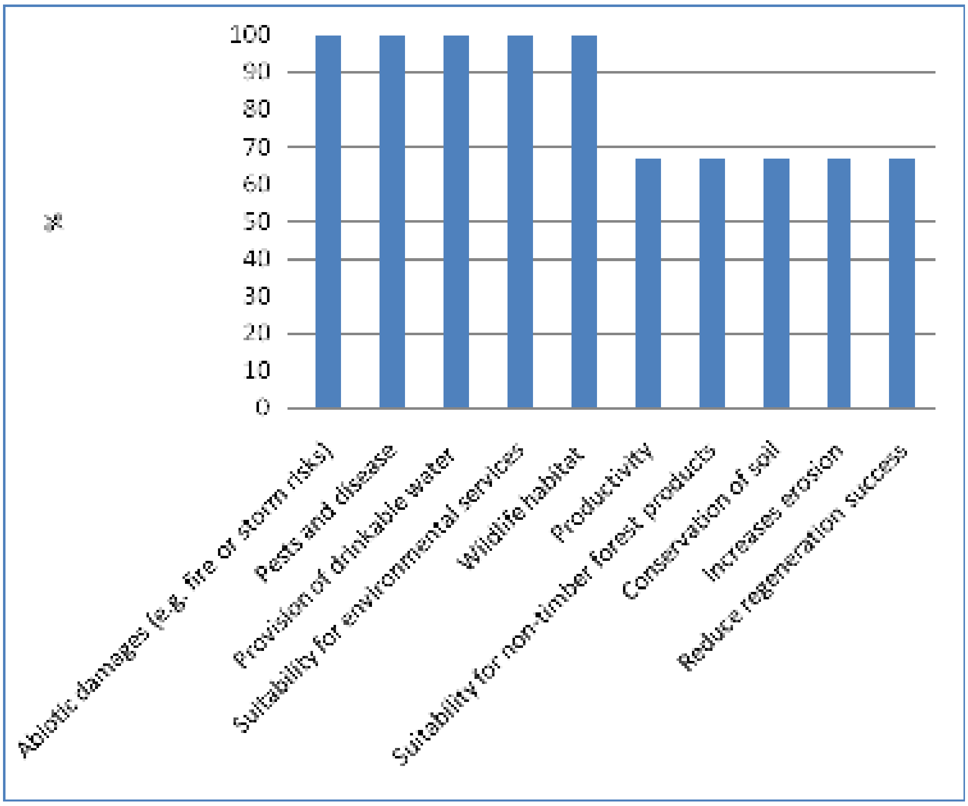


**Figure 29.** Relative share of important aspects of climate change in Mediterranean zone according to answers of questionnaire. Total number of answers was three (3). Respondents could provide multiple answers.

Most important research needs in the Mediterranean zone are provenance selection and genetic diversity (Table 28). In addition, on-going research topics are land management, pests and diseases. More research is planned to address natural resistance, tending of stands in critical areas, protective functions of forests and non-wood products. On-going and planned measures on stand level are focused on decreasing risks of drought, fire and erosion. Measures of reducing risks of biotic and abiotic disturbances include fencing sensitive areas from herbivores, using natural regeneration to avoid erosion by tourism and grazing, and controlling pests and pathogens.

**Table 28.** On-going and planned measures in the Mediterranean zone in main categories of measures.

| ON-GOING | | PLANNED | |
|---|---|---|---|
| **More research on…** | | | |
| Provenances | | Adaptive species and provenances (drought) | |
| Genetic diversity | | Biodiversity (genetic diversity) | |
| Land management | | Natural resistance | |
| Pests and diseases | | Sustainability of the protective functions of forests | |
| Sites for selective thinning | | Non-wood products | |
| **Selection of adaptable species, provenances and genotypes…** | | | |
| Which are less sensitive to changing environmental conditions | | Which are less sensitive to changing environmental conditions | |
| Which are resistant to drought | | Which are resistant to drought | |
| From native indigenous | | From native indigenous | |
| And have a mixture of them | | | |
| **Change tending and thinning** | | | |
| Target of measure | What for | Target of measure | What for |
| Silvicultural system | Special conditions | Thinning intensity | Most sensitive areas (drought, erosion) |
| Thinning methods | Less fuel in forests | | |
| Thinning methods | Soil erosion | | |
| **Reducing biotic and abiotic disturbance risk** | | | |
| Target of measure | Risk | Target of measure | Risk |
| Fencing sensitive areas | Herbivores | Natural regeneration | Tourism, grazing |
| Prevention plans | Fire | Networking | Fire |
| Networking | Fire | Increasing awareness | Fire |
| Biological insecticides | Pests | Control in nurseries | Harmful organisms |
| Thinning methods | Fire | Control | Invasive pests and pathogens |
| | | Short rotation | Drought |

In contrast to other zones, in the Mediterranean zone the most affected stakeholder group is communities (Fig. 30). Forest owners were listed as second most important group.

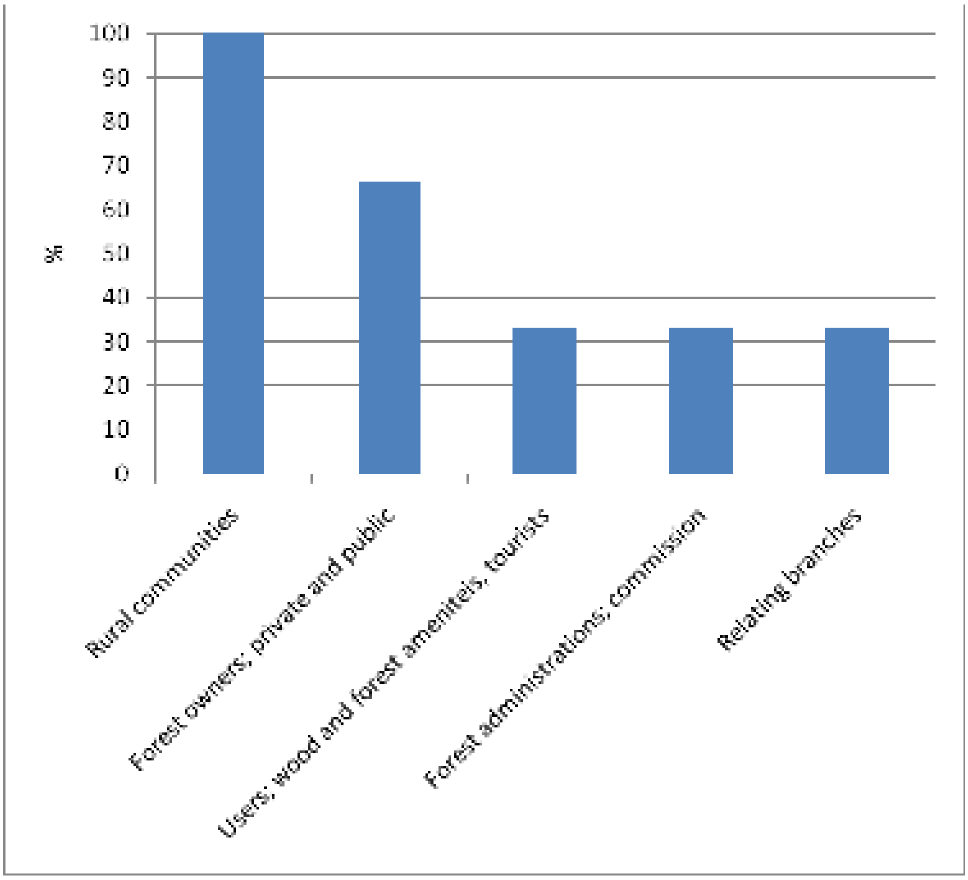


**Figure 30.** Relative share of stakeholders most affected by climate change in Mediterranean zone according to answers of questionnaire. Total number of answers was three (3). Respondents could provide multiple answers.

## 9.4 Priorities for adaptation in EU forests

### 9.4.1 Adaptation objectives and strategies in different regions

The review of on-going and planned adaptation strategies reveals that across the different bioclimatic regions there are similar motives for adaptation measures. The following three groups of adaptation objectives can be distinguished:

1. Minimize impacts of disturbances
2. Ensure wood production
3. Ensure ecosystem services.

***i) Minimize impacts of disturbances***

There are three main factors of abiotic risks against which different measures are implemented or planned; fire, storms and drought. **Fire** is already a big problem in the Mediterranean region, but the risk of it is expected to increase, also in other regions. **Storm** damages are currently most relevant in the Temperate zones, but also in the Boreal region measures are planned to respond to the expected increase of wind hazards. **Drought** risks are the focus of management measures in all zones except for the Boreal. Biotic **pests and diseases** are expected to increase in importance in all regions and measures to address them are planned in all bioclimatic zones.

**Fire risk**
In the Mediterranean zone various measures are recognized to reduce fuel accumulation with suitable thinning methods and prescribed burning and to select species that are less sensitive to fire. Furthermore at policy level prevention plans are made and networking is promoted. There are some measures also applied in the Temperate zones, whereas in the Boreal zone there are no specified measures on-going against fire risk. The planned measures in the Mediterranean zone focus on the policy level and include raising the awareness about fire risks. The planned measures in the Temperate Oceanic and Continental zones are similar to those already on-going in the Mediterranean.

**Storm/wind hazard risk**
On-going measures in the Temperate zones include stand level measures to improve resistance to wind damage. Furthermore, in management planning it is a recognized strategy in the Temperate Oceanic zone to reduce the size of clear cut areas. In the Boreal and the Mediterranean zones no specific measures are currently addressing storm risk. The planned measures are similar to existing ones in the Temperate zones, but they include some more specific adaptation measures such as implementing forest edge management. Also close-to-nature management was mentioned as a means of reducing wind hazard risk. In the Mediterranean zone no specific measures are planned.

**Drought risk**
The selection of drought tolerant species, provenances and genotypes is a recognized adaptation measure in the Mediterranean, as well as in the Temperate Oceanic and Continental zones. Planned measures include shorter rotation in the Mediterranean zone and more intensive thinnings to reduce stand density. In the Boreal zone drought is not a major problem for forestry, accordingly there are no specific measures on-going or planned in that zone.

**Pest and disease risk**
Different measures have been listed as on-going in the four bioclimatic zones. These range from monitoring pests to control of biotic disturbances, partly using biological insecticides. More research on invasive new pests and diseases is on-going in the Mediterranean and both Temperate zones. Various general and specific adaptation measures are planned in the different regions. The Temperate Oceanic and Continental zones listed notably larger number of measures, while in the Mediterranean and Boreal zones only monitoring and more general control measures have been listed.

***ii) Ensure wood production***

In the Boreal and Temperate Oceanic zones selection of species is aimed at species, which perform well across sites and in the latter zone, at species which can build stable diversified forests. In Temperate Oceanic and the Mediterranean zone measures are aimed at diverse stands. Selection of species and provenances from native indigenous origin is an on-going measure in the Temperate Continental and Mediterranean zones. In both Temperate zones more research on well-adapted tree species, provenances and genotypes is conducted. In addition, in the Temperate Continental zone research on silvicultural treatments is on-going. Forest management is very intensive in the Boreal zone and related research needs under climate change are regeneration techniques, modification of thinning regimes and harvesting techniques on non-frozen soils.

In both Temperate zones more diverse stands are target of planned silvicultural and thinning measures. In both Temperate and the Mediterranean zones species selection from native indigenous species is planned. In the Temperate Oceanic zone there is one planned measure which uses possible benefits of climate change: to extract biomass for energy due to modified thinning schedules. On the policy level all four zones have similar measures planned focusing on more research on tree species, provenances and genotypes. In addition, more research is needed in Temperate Continental zone on soil-tree interaction and in Temperate Oceanic zone on basic growth and yield of forests.

***iii) Ensure ecosystem services***

Decreasing the risk of erosion was recognized as target of on-going measure in the Mediterranean and Temperate Continental zones, but the specific measures differed: special thinning methods in the Mediterranean zone, planting suitable tree species and limiting thinning on areas susceptible to erosion in the Temperate Continental zone. More research on the protective role of forests in general is on-going in both Temperate zones. In the Boreal zone there were no on-going or planned measures listed in relation to ecosystem services.

**Conclusions**

In general it can be noticed that for many adaptation strategies, on-going measures include a relatively limited number of actions, while planned measures address additional levels of actions. For example, measures to minimize impacts of disturbances are on-going at stand level, but planned measures are also addressing the forest management and policy level. This shows that there is need to approach adaptation on different levels of action.

The number of reported measures and their extent on different levels is the highest in both Temperate zones. In the Boreal zone only relatively few measures were listed. This might be partly due to bio-geographic characteristics of the zone. The Boreal zone is more homogenous and also less sensitive to climate change impact factors like drought and fire disturbance, which explains that certain measures are not deemed necessary. The other reason might be the number of answers. One country was represented in the Boreal zone with two answers, whereas from both Temperate zones many answers were received from several countries. A larger number of answers imply that more points of view on adaptation measures can be represented.

The different sources of forest disturbance risks show some regional variation between bioclimatic regions. In the Mediterranean zone the main disturbances are related to drought and fire. In the boreal wind hazards are the main target for measures to avoid disturbances. In both Temperate zones, there are many disturbances against which there are on-going and planned adaptation measures.

Measures aimed at ensuring wood production are related to modified, more diverse and stable stand structures in the Mediterranean and both Temperate zones. In the Boreal zone measures focus on management, ranging from regeneration to harvesting, which shows that wood production has a very important role.

Protective function of forests is important in the Mediterranean and Temperate Continental zone and specific adaptation measures are needed to secure these functions.

### 9.4.2 Options for adaptation and the implementation of strategies in EU Member States

The screening and evaluation of adaptation options in chapter 7 and 8 has been made at a general level, only some measures were related to specific bioclimatic zones. Here we compare the results of the screening and the answers of the questionnaire from different bioclimatic zones. Not all adaptation options are relevant in all zones. Therefore if some measure is missing in one zone, it is possible that the measure is not relevant there. But if the measure is relevant for the zone, it could be considered to be included in future adaptation strategies in forestry.

Adaptation options at **stand level** are well in use in different bioclimatic zones. In the answers from the Boreal zone there were not so many stand level measures as in other zones. For example, natural regeneration has not been mentioned as an adaptation measure in the Boreal zone. However, it is a common practice in forestry for reasons not related to climate change adaptation. Measures which are reducing impacts of drought are not necessary in the Boreal zone and the protective function of forests is less important than in southern parts of Europe. Enrichment planting in naturally regenerated stands and establishing pioneer populations (i.e. species populations outside their current distribution range) are on-going or planned measures in the Temperate Oceanic zone, but they would be possible options also in other regions.

Adaptation options at the **forest management level** are foreseen in the Temperate Oceanic and Continental zones. Forest decision support systems (DSS) are indispensable tools for supporting adaptive forest management. In the answers of questionnaire from the Boreal zone the use of DSS has not been mentioned, but from screening the scientific literature we know that there are many systems already in use in the Boreal zone. Measures of forest protection are quite detailed in the screening of options, but most of the answers to the questionnaire were more general. Quite many detailed measures were mentioned in the answers from the Temperate and the Mediterranean zones. Specific measures identified in the screening of scientific literature but not reflected in the survey answers are:

- Avoiding afforestation on former agricultural areas and planting of *Picea abies* and *Pinus* spp. on former areas of deciduous forests where pathogens are a problem
- Measures aimed at ecosystem with highly diverse ground vegetation (because of insects)
- Avoiding heavy thinning (because of snow damages).

However, some of these measures are quite specific in addressing one disturbance agent (e.g. pathogens) while the same measure may have other merits (e.g. connecting isolated forest habitats in agriculturally dominated landscapes).

Adaptation options on **policy level** match well with the answers of questionnaire. Two adaptive measures at nurseries are to increase the storage of seeds for species with seeds that sustain longer storage without loss of viability and maintain diversity within the varieties. They are mentioned in the answers from the Temperate Oceanic zone, but these measures would be suitable for other zones too. Targeted programs and adaptation strategies will be needed in risk management and at the policy level as already proposed in some answers of respondents.

# 10 CONCLUSIONS AND RECOMMENDATIONS

Climate change is now recognised as one of the most serious challenges facing the world – its people, the environment and its economies. It is believed that most global warming we can now observe is attributable to emissions of GHGs that result from human activities, in particular land use changes such as deforestation, and the burning of fossil fuels. The changing climate is also a major challenge for EU forests and forestry. This chapter summarizes the main findings about how EU forests can be affected by global warming and how the sector and forest policies can address the challenge of adapting to projected impacts of climate change.

## 10.1. Impacts and risks of climate change on EU forests

Forest trees have long lifespans lasting decades to centuries and therefore EU forests will be widely affected by changing climatic conditions. Many of the present forest stands will have to cope with climate conditions that will prevail towards the end of this century.
Although there are important regional variations in the expected climatic conditions over the 21st Century, predicted impacts for Europe can be summarised as milder and wetter winters, hotter and drier summers and more frequent and intense extreme weather events.
Projections of future climate conditions strongly depend on the development of GHG emissions, but even for the same level of emissions, considerable uncertainties remain about the regional projections of the future climate as documented in different climate models. General trends in all models include:

(1) Warming is greatest over eastern Europe in winter and over western and southern Europe in summer.
(2) In mountainous areas warming is likely to exceed the average continental trend. This has already been observed e.g. for the European Alps in the last decades.
(3) In northern Europe the projected increase in temperature is of about equal magnitude throughout the seasons.
(4) The temperature changes are coupled with increases in mean annual precipitation in northern Europe and decreases in southern Europe.
(5) The change in seasonal precipitation varies substantially from season to season and across regions. A substantial increase is projected in the intensity of daily precipitation events even in the areas where a decrease in mean annual precipitation is forecasted.
(6) Climate is expected to become more variable with greater risk of extreme weather events, such as prolonged drought, storms and floods.

Forests will have to adapt to changes in mean climate variables but also to increased variability. Climate change will have many consequences for species' growth and productivity, susceptibility to disturbances, and distribution ranges. The impacts are expected to vary between regions and tree species and they include both risks and opportunities for EU forests.

The key findings of the study are:

- Changes in temperature and precipitation directly affect forests and forestry, but the impacts can vary depending on the current environmental conditions.
- Rising concentrations of $CO_2$ in the atmosphere have resulted in increased assimilation rates and improved water use efficiency under experimental conditions, but the magnitude and permanence of the effects in natural ecosystems is not yet clear.
- An increase solely in temperature is beneficial for boreal and temperate sites especially at higher elevations and altitudes, where water is not a limiting factor. However, interannual climate variability and increased disturbance risks may result in adverse impacts and subsequent net productivity losses.
- In central European regions, forest productivity will be strongly affected by the interaction of higher temperatures, changes in precipitation, and interannual climate variability. From west to east, the **drought** risk increases. In the Mediterranean regions productivity is expected to decline due to strongly increased droughts.
- **Fire** danger is expected to increase throughout Europe, especially in the already fire-prone Mediterranean areas, but also in the Temperate Continental and Boreal regions.
- **Wind throw** and other storm damages are most relevant in central Europe, as well as in western and northern Europe. It is uncertain, if the frequency of Atlantic storms will increase in the future. However, local storms may be more intense and damages may be larger in combination with water saturated soils which reduces stand stability.
- Global circulation models project that it is very likely that higher amounts of precipitation will occur in northern Europe, especially during winter and spring, considerably increasing the risk of **flooding** in central and northern Europe.
- Natural hazards characteristic for mountainous regions (debris flow, landslide, rock fall and avalanche) are also climate sensitive. Debris flow and landslides are interrelated to some extent with heavy rainfall events and flooding and thus likely to occur more often in future. Rock fall events will increase at high elevations in permafrost soils. Changes in the avalanche regime cannot be forecasted at present. The protective function of forests, vital for infrastructure and mountain dwellings, will strongly depend on future changes in the hazard regimes as well as in structural forest traits.
- Warming is likely to intensify the risk of pest's outbreaks.

The effects of climate change on **insect pests and pathogens** and consequently on forest health are far from being fully understood. Specific knowledge on the climatic parameters necessary for development is crucial, but in many cases lacking, in order to seriously evaluate the future relevance or performance of pest species. Predictions of forthcoming pest problems are also difficult due to the complex interactions among climatic conditions, nutrient supply, plant quality and resistance, and natural enemies and diseases. Nevertheless, there is consensus in the fact that climate change already has and will have impact on **temporal and spatial dynamics of pest species**, influencing the frequency and intensity of outbreaks as well as their spatial patterns, size and geographical range. In this context both, adverse consequences for certain forest organisms, such as impaired performance or the loss of habitat, and advantageous effects of changing environmental conditions for biotic disturbance agents are to be expected. Especially forest pest and pathogen species that directly profit from **increased temperature or altered patterns of**

**precipitation** are going to meet improved developmental conditions. This is the case for *Ips typographus*, the European spruce bark beetle, which has been benefitting from warm and dry summers as well as from storm events in recent decades in large parts of Europe. It is **quite certain that the risk of vast beetle outbreaks will still be increasing under a climate change scenario**, as multivoltine populations of high density will become more and more probable in spruce forests of high altitude and latitude.

Regions that represent northern or upper distributional limits, such as the Alps or the Boreal zone, will probably be affected most by an increase in stability and population density of certain pest species. **Insect distribution could change rapidly in response to climatic variations**, as the geographical range of many forest insects is more limited than their host distribution. As an example, the gypsy moth, *Lymantria dispar*, which is highly polyphagous and tolerant to elevated temperature, has the potential to expand its range northwards by 500-700 km. Consequently, outbreaks of gypsy moth in the boreal area will become increasingly probable in the next decades. At the same time, the present distributional range in the southern part of Europe is likely to become too warm for certain species (e.g. gypsy and nun moth, *Lymantria monacha*), which will not only result in northwards shifts, but range contractions. The probability of an establishment of exotic species, on the other hand, will increase.

In Southern Europe, highly termophilic pathogen species are likely to become more serious. Typical components of the endophytic micro flora inhabiting Mediterranean tree species may develop rapidly in trees stressed by **drought**. Such **shifts from latent to pathogenic stage may pose a considerable threat to forests under a changing climate**, as the organisms in their latent form may be present in wide areas for a long period and suddenly cause dieback in case of beneficial environmental conditions. A further challenge, especially for forestry in the western Mediterranean area, is the decline and dieback of oak forests. **Changing patterns of precipitation, especially alternating periods of drought and heavy rainfall** have been associated with an increased predisposition of trees to the pathogenic fungus *Phytophthora cinnamomi*. Generally, it is to be expected that pathogens of Mediterranean and tropical origin will expand their geographical range northwards and become a problem for instance in the southern parts of the Temperate Oceanic region.

Forests of Central and Northern Europe, will as well be increasingly predisposed to fungal diseases (e.g. *Armillaria spp*. or *Heterobasidion annosum*) that benefit from longer growing seasons associated with higher temperatures and from host trees stressed by reductions in summer precipitation. In turn, **increased amounts of precipitation during summer**, as expected for Northern Europe, have been observed to support the spread of fungal diseases, such as Scleroderris canker, *Gremmeniella abietina*.

Assessing potential impacts of climate change needs to consider general trends in climate variables, short term climate variability, and the interactions with biotic and abiotic disturbances. Especially in northern and western Europe the increasing atmospheric $CO_2$ content and warmer temperatures will result in positive effects on forest growth and wood production – at least in the short-medium term. On the other hand, increasing drought and disturbance risks will cause adverse effects. These negative impacts are very likely to outweigh positive trends in southern and eastern Europe. With more drastic changes in climate towards the end of the 21$^{st}$ century, severe and wide ranging negative climate change impacts have to be expected in most European regions.

Potential impacts and risks are best studied and understood with respect to wood production. It is clear that all other goods and services provided by European forests will also be impacted by climate change, but much less knowledge is available to quantify these impacts.

## *10.2 Adaptive capacity and vulnerability assessment*

Vulnerability of forests and forestry to climate change is a function of the potential impacts of climate change and the adaptive capacity to respond to these impacts.
**Adaptive capacity** has two components: the inherent adaptive capacity of trees and forest ecosystems and the socioeconomic factors determining the ability to implement planned adaptation measures. The **inherent adaptive capacity** encompasses the evolutionary mechanisms and processes that permit tree species to adjust to new environmental conditions. We show how evolutionary mechanisms acting at different hierarchical levels, from individuals to communities via populations and species are active in tree species, and may enhance their adaptation capacity to climatic changes. A large body of results stemming from provenance test shows that tree populations differentiated genetically during natural environmental changes that occurred during the Holocene. Examples of individual adaptation via plasticity are suggested by temporal variation of fitness related traits observed during the lifetime of trees, but are very seldom documented at this time. Past seed dispersion data obtained by fossil pollen records suggest that the speed of future natural dispersion may not be able to keep up with the shift of bioclimatic envelopes of trees species. However, maintaining or improving the genetic adaptive capacity of populations and species is important in the long term. We show how these mechanisms that were acting in the past under natural climate change will contribute in the future to the adaptation to human mediated climate change.

**Socioeconomic factors** that determine adaptive capacity to climate change include economic wealth, technology and infrastructure, information, knowledge and skills, institutions, equity and social capital. The socioeconomic adaptation capacity related to the forest sector has rarely been analysed in EU27 up to now. Adaptive capacity is generally higher in regions with active forest management. Forest ownership structures, the availability or shortage of forest sector work force, and the educational level of forest workers are other factors influencing the adaptive capacity in the forest sector.

**The adaptive capacity in the forest sector** is relatively large in the Boreal and the Temperate Oceanic regions. In the Temperate Continental region adaptive capacity in the forest sector is more strongly affected by socio-economic constraints. Adaptive capacity is strongly limited in the Mediterranean region where large forest areas are only extensively managed or unmanaged.

Very few regional **vulnerability assessments** have been made so far for European forests. **The assessment and mapping of regional vulnerability to climate change including stakeholder interests and preferences as well as quantified risks and opportunities constitute a clear research need.** Better understanding of the regional adaptive capacity in the forest sector and the knowledge about the regional vulnerability of forest goods and services to climate change are crucial to planning adaptation measures.

## *10.3 Options for adaptation in European forests and forestry*

There are many options to actively adapt to the changing climate conditions in European forests. Because of the long management cycles, forestry must anticipate adaptation to the future much earlier than other sectors. Adaptation measures at different levels have been assessed; in this section they are summarized in three groups of measures related to stand management, forest management planning and policy design.

***i) Stand measures***

**Forest regeneration** offers a direct and immediate opportunity to adapt species composition of forest stands to changing climatic conditions. In general, the range in mid- to long-term climate change signals in a region remains huge and therefore uncertainties about the degree of climate change need to be considered in tree species selection for regeneration. One strategy to cope with uncertainty in future climates is to hedge against risks from climate change by increasing species diversity at stand and higher hierarchical levels. Due to large areas in small scale ownerships, landscape level planning approaches are extremely difficult and most effective decisions will be taken at stand level. However, higher diversity usually means higher cost of management compared to mono-species stands with simpler forest structure. Whether natural or artificial, regeneration is the stage at which the species and genetic composition of the stand gets established, where diversity builds up and can be manipulated. A highly recommended option to secure the adaptive response of established regeneration is to raise the level of genetic diversity within the seedling population, either by natural or artificial mediated means. A recommended procedure would be to mix seedlings at the nursery stage coming from different seed stands of the same provenance regions. Seeds from neighbouring provenance regions could be added. Identification of seedlots to be mixed should be based on results of provenance tests. Many provenance tests have been established at a national, local or international level. They need to be analysed in a standardized way in order to recommend directions and range of seed transfer for the mixing. The enhancement of natural regeneration is highly recommended in coppice forests, too;

in this regard, silvicultural measures aimed at regulating standards density and increasing coppice rotation time might be of help in triggering natural regeneration in coppices.

More work is required to expand knowledge on the site suitability of tree species and provenances in the perspective of changing climatic conditions.

Changes in the frequency and intensity of **tending and thinning** are mostly aiming at improving stand structure to reduce susceptibility of stands to disturbances in all regions. Under adaptive silvicultural regimes, however, species mixture regulation to favour admixed species shares will be equally important. An increase in structural and species diversity is also particularly important for mountainous regions to support the protective function. Management adjustments, in terms of thinning, will also be required to account for accelerating growth rates due to more favourable growing conditions in a warmer climate particularly in mountain areas and boreal conditions.

**Harvesting** activities should take place at smaller scales and where possible according to the principles of natural regeneration, enhancing structural as well as species and genetic diversity via long regeneration periods. Increased attention should be paid to avoid increasing the susceptibility to disturbances by harvesting operations such as producing open stand edges exposed to prevailing winds and strong direct sunlight. Development of machinery is one important adaptation measure in the Boreal zone to cope with less favourable conditions for winter harvesting.

### *ii) Forest management measures*

**Forest management planning** is becoming more challenging in the perspective of climate change. New planning and decision support tools have to be developed and applied to deal with uncertainty and risk in long-term forest planning. Flexible adaptive planning, which takes into account all conceivable scenarios and allows to consider multiple options for future development, may be the best suited alternative. A prerequisite of adaptive management is the monitoring and evaluation of processes and goals which demands maintained or even extended inventories and long term research initiatives. Additionally, effective operative and strategic controlling in forest management can support the achievement of management objectives also under changing climatic conditions. Cooperation of scientists, decision makers and stakeholders will lead to a more comprehensive understanding of the complex problems involved in decision making and will provide a more realistic and reliable basis for decision support for management in future forest ecosystems. The increased use of science-based decision support systems in forest management planning could foster such activities.

Adaptation to climate change implies **forest protection** against the increasing hazards of abiotic and biotic disturbances**.** Yet, general predications are of no avail, given the heterogeneity of management goals from nature protection to intensive wood production, the multitude of forest ecosystems and potential damaging agents throughout Europe. In order to develop adequate silvicultural strategies to cope with potential risks, comprehensive knowledge on the complex causalities of forest disturbance (e.g. pest outbreaks, fungal diseases) on a regional scale is demanded. Such specific information should be incorporated in decision support systems, helping foresters to identify the parameters responsible for increased forest susceptibility to certain damaging agents and to gain awareness of opportunities for and limits of damage prevention. The concept that **specific site and stand related characteristics** influence the local or regional probability of disturbance may be a helpful approach for the development of adaptive strategies.

Adaptive measures are to be targeted not only on species composition, but on the full scale of silvicultural options from site selection to harvesting. In general, establishing and sustaining forest ecosystems with highly **diverse tree composition, age and structure** is recommended.

Since tree and stand characteristics change dynamically along with forest growth, the risk of wind damage will also change. The highest risk of wind damage is most likely to be found where sudden changes in wind loading patterns occur and when the trees are not yet accustomed to it. The risk of snow damage can be reduced by avoiding heavy thinning. Fire protection will be mainly important in Mediterranean, temperate continental and boreal forests. For stands predisposed to e.g. storm damage or bark beetle (*I. typographus*) attacks a shortening of rotation periods could significantly decrease susceptibilities. Differences in species' susceptibility to both biotic and abiotic disturbances can be exploited in adaptive management strategies.

To be effective and cost efficient species enrichment through the regeneration phase should utilize the natural regeneration potential whenever possible. Thus, any stress factor constraining natural regeneration must be reduced (e.g. extensive browsing by ungulates or livestock).

### iii) *Policy level measures*

Measures to adapt **infrastructure and transport** to climate change are aimed at restoring groundwater regimes, irrigation systems and road network. Drought stress can be reduced in susceptible areas by restoring the groundwater regime for example in floodplain forests and by building storage lakes and irrigation canals. The development of an appropriate road network is very important especially in mountain forestry to ensure the proposed small scale management activities and to provide accessibility necessary for sanitation fellings. In northern regions it is of special importance to reconstruct roads in order to minimize sediment runoff due to increased precipitation and shortened frost periods. The shortened frost periods in boreal forests pose a significant challenge for harvesting and transportation technology, especially on wet soils.

Proper forest regeneration is an important stand level measure to adapt to climate change. **Nurseries and tree breeding** facilities should produce well-adapted material for forest regeneration. In order to increase diversity of reproductive material used in artificial stand regeneration, it is suggested to mix seedlings at the nursery stage coming from different seed stands of the same provenance regions. More sophisticated methods based on biotechnology may shorten significantly these delays, once genes of adaptive significance have been identified. Research efforts are being conducted for searching candidate genes related to traits that will be responding to climate change: bud burst, bud set and water stress. The only way that breeding activities may take into account climate change requirements is to maintain diversity within the varieties produced by seed orchards at levels that would be higher than for standard utilizations.

Adaptation to climate change refers to adjustments in ecological, social, and economic systems in response to actual or expected climatic stimuli and their impacts. But there are institutional and policy barriers for responding to climate change, as an example, forest management guidelines are designed for the current climate regime. The **development and evaluation of adaptation strategies** should be a participative process involving decision-makers, stakeholders, experts, and analysts. Vulnerability assessment methods have been promoted where key system vulnerabilities are first identified, and adaptive strategies are developed and evaluated in the context of existing decision processes. A key approach in **risk management** is diversification of tree species mixtures and management approaches between neighbouring forest stands or within a forestry district to increase adaptive capacity and improve the overall resilience of forests to climate change. At larger geographical scales of management units and forest landscapes, a range of different adaptation strategies can be combined.

**Monitoring** of forest health, pests and diseases is absolutely crucial, (i) to quickly identify new pests (e.g. invasive species) and (ii) because secondary damage agents can in weakened systems quickly turn into large scale threats.

More **research** is needed to expand the knowledge base related to almost all aspects related to adaptive forest management strategies. The research needs vary between regions depending on the most important climate change risks.

A prerequisite to adaptive management is **capacity building**, i.e. ensuring a social and educational environment promoting expertise to cope with complex issues in land management. Furthermore, a coordinated policy level adaptation strategy needs to include the full **forest wood chain** since changes in the biophysical production processes and production potentials might require responses and adaptations of downstream industry partners. Moreover, adaptation options need to be harmonized with other emerging **land use** policies concerning e.g. climate change mitigation or the conservation of biodiversity.

### *10.4 Emerging recommendations*

The survey of adaptation measures revealed three similar motives for adaptation measures in EU Member States:

- minimize impacts of disturbances
- ensure wood production and
- ensure ecosystem services.

Many **adaptation options** have been identified and most of them are either in use or planned to be implemented in different parts of Europe. The most important adaptation measures identified were

- more research
- selection of species, provenances and genotypes which are either more tolerant towards expected changes (i.e. have a broader niche) or are particularly fit for specific potential future conditions
- changing tending and thinning, and
- reducing biotic and abiotic disturbance risks.

Table 29 lists adaptation options, not yet in use, but suitable to be included in different bioclimatic zones.

**Table 29.** Recommended measures in addition to on-going or planned measures for adaptation to climate change in different bioclimatic zones and action levels.

| **Level** | **Zone** | | | | **Recommended adaptation measure** |
|---|---|---|---|---|---|
| | **B** | **TO** | **TC** | **M** | |
| Stand | x | | | | ▪ Take account increasing potential risk of fire |
| | x | | x | x | ▪ Enrichment planting in naturally regenerated stands |
| Forest management | x | x | x | x | ▪ Take account a risk of pathogens in establishment of stands |
| | x | x | x | x | ▪ Take account diverse ground vegetation in forestry management |
| | x | | | | ▪ Avoid heavy thinning in snow damage risk areas |
| Policy | x | | x | x | ▪ Increase storage of seeds |
| | x | | x | x | ▪ Maintain diversity within the tree varieties at nurseries |

B = Boreal, TO = Temperate Oceanic, TC = Temperate Continental, M = the Mediterranean.

We do not have evidence from each country, to what extent on-going measures are really implemented. Respondents might have delivered, at least partly, “this is what we should do”, instead of “this is what we are doing” responses. On the other hand, it is not enough that scientists and decision makers know what should be done. It is of utmost importance to **disseminate** the knowledge on suitable adaptation measures to all affected stakeholder groups, particularly to forest owners, forest workers, and policy makers at different levels, who need to implement the measures. The phenomenon of climate change is global, but adaptation measures for it are local, so the awareness of and help to forest owners and forest workers is very important and should be raised. This clear end-user orientation requires that proposed adaptation measures are “fit for practice” and not purely academic constructs. To ensure this, serious participative and transdisciplinary efforts must be taken.

Many projected impacts and adaptation measures responding to them are based on data referring to past or current conditions. The known response strategies may be valid also under changing climate conditions, for example in the case of responses to abiotic disturbances. But uncertainties remain, for example, how tree species will respond to combined rising $CO_2$-content and warming. Without rapid and far-reaching policy measures succeeding in curbing GHG emissions, the projected climate changes will result in drastically different growth conditions for European forests in the second half of the 21$^{st}$ century. We have no experience of how tree species and provenances respond to rapidly changing climate conditions. Thus there is a need to develop new strategies for introducing **better adapted species and provenances** where the present species/genotypes will become unsuitable over the coming decades. Uncertainty about the full extent of climate change impacts and the suitability of adaptation measures creates a need for **monitoring and further research.** Intensive monitoring will be needed to quickly implement sanitary cuttings to avoid that secondary damages get out of control. Potential impacts of climate change on non-wood forest products and other services provided by European forests are less well understood and need specific attention. This is particularly important in southern Europe, where the adaptive capacity of the forest sector is smaller. Forest research on climate change adaptation needs to be interdisciplinary, covering not only ecological, but also economic and social perspectives. The assessment of regional vulnerability to climate change including quantified risks and opportunities requires more investigation and constitutes a clear research need.

While the majority of climate change impacts are likely to be negative – especially in the long-term – it should not be forgotten that management strategies should also be adapted to utilize opportunities where they arise (e.g. improved tree growth). Such benefits, even if they are only of temporary nature, could increase the adaptive capacity of the sector and support long-term adaptation and innovation to better cope with climate change.

In addition to local co-operation, international co-operation is also necessary, especially in cases, when fire or pest outbreaks spread out to more than one country. Extensive co-operation is benefitial particularly in the monitoring of impacts of climate change.

The improvement of climate change projections and their refinement at spatial scale will result in new information about likely impacts on EU forests. This information should be progressively used in policy development to improve the resilience of forests to future climate.