Forest typology and expected climatic changes in different bioclimatic zones

European forests are extremely variable with regard to their ecological and socio-economic conditions. Therefore, 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 factsheet briefly provides details of the expected changes in the European bioclimatic zones. The maps show the bioclimatic zones and provide an indication of the distribution of the main forest types in Europe.

Forest typology

Forest ecosystem sensitivity and the inherent adaptive of capacity of forest ecosystems to respond to climate change are related to forest ecological characteristics. Accordingly, a forest typology classification reflecting this ecological variability is needed to facilitate the assessment of climate change impacts. The European Forest Type scheme consisting of 14 main categories of European forests recently presented by the EEA (2006) was used as a reference. A simplified classification was derived from the EEA classification. The original 14 categories were organized into seven classes, reflecting the major forest types found in the boreal, temperate oceanic, temperate continental, Mediterranean, and montane bioclimatic zones. The individual points show the distribution of ICP Forests (International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests) level I plots classified by major forest types. The Level I plots include 6000 observation plots on a systematic transnational grid of 16×16 km throughout Europe.

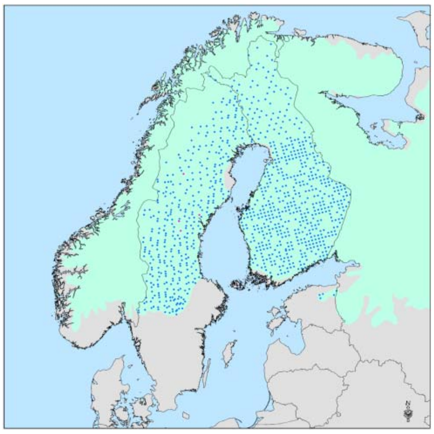
Major Forest Types:

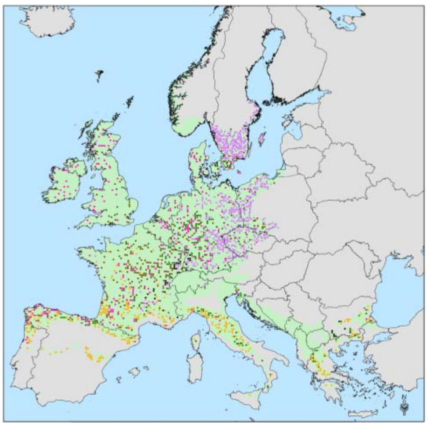
- I Boreal forest
- II Hemiboreal forest and nemoral coniferous and mixed broadleaved-coniferous forest
- III Alpine coniferous forest
- IV Acidophylous oakwoods and mesophytic deciduous forest
- V Beech forest
- VI Thermophilous deciduous, broadleaved evergreen and xerophytic coniferous forests
- VII Plantation and self-sown exotic

Boreal (Finland, Sweden)

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.

Boreal bioclimatic region (Forest Types: I, VII)





Temperate oceanic (Belgium, Czech Republic, Denmark, France, Germany, Ireland, Luxembourg, Netherlands, 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 oceanic bioclimatic zone (Forest Types: II, III, IV, V, VI, VII)

Temperate continental (Austria, Bulgaria, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, 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%).

Temperate continental bioclimatic zone (Forest Types: II, IV, V, VI, VII)

Mediterranean (Cyprus, Greece, Italy, Malta, Portugal, Slovenia, 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 and heavy precipitation events, and fewer cold days.

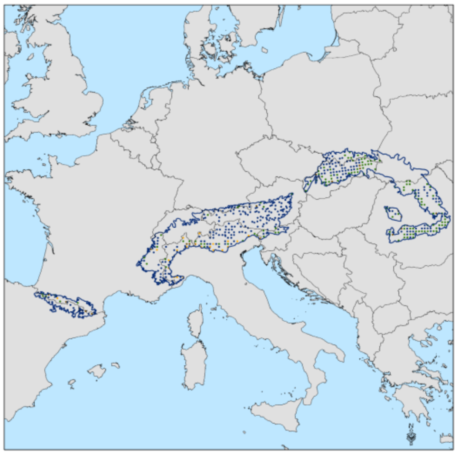
Mediterranean bioclimatic zone (Forest Types: VI, VII)

Specific changes in mountain regions (Alps, Pyrenees, Carpathians)

Alps: During the 20th Century temperatures increased in the Alps by 1.5°C or about twice the global average. 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°C in autumn, winter and spring, and 3°C in summer in the Swiss Alps. Run-off is also expected to increase. In addition, the duration of snow cover is expected to decrease by several weeks for each °C increase of temperature in the Alps.

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

Main European Mountain regions (Forest Types: III, IV, V, VI)



Full details can be found in section 2 of the report - Impacts of climate change on European forests and options for adaptation. Service Contract with DG Agriculture and Rural Development No. 30-CE-0163547/00-01. The report was compiled by the European Forest Institute (EFI) and its project partners BOKU, INRA and AISF.

Impact Factors –Atmospheric CO_2 increase

Forest Carbon Cycle

Forests use CO_2 and water as substrates for the process of photosynthesis, and produce biomass and oxygen as products of the process. Forests are also a source of CO_2 through the processes of respiration, decomposition of organic matter, and when there are forest fires and other disturbances (Figure 1).

About 44% of the land area of Europe is covered by forests, and these forests are growing (in terms of forest area and in terms of the amount of biomass in the forest and forest soils) and are a sink for atmospheric carbon dioxide (CO_2). Whether forests are a net source or sink of CO_2 depends on a number of factors including: age of forest, disturbance regime, and current and previous land use.

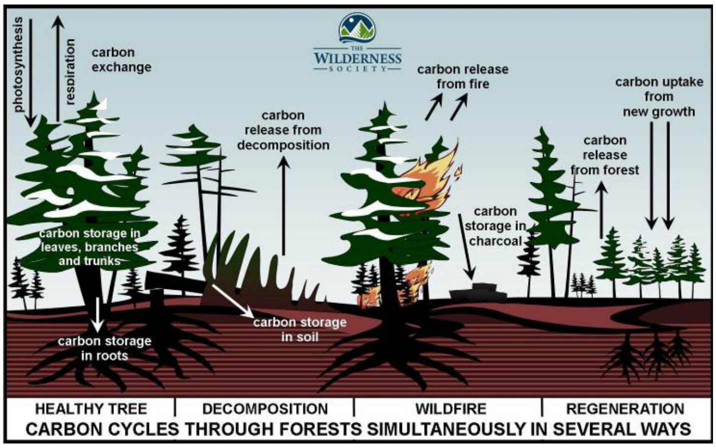


Figure 1. Forest carbon cycle. (Graphic prepared by Cecilia Claver, The Wilderness Society. http://www.wilderness.org/)

Climate change will affect many elements of the forest carbon cycle. Whether European forests continue to be a sink for atmospheric CO_2 will in part depend on how the forests react to rising CO_2 levels and climate change.

CO_2 increases rates of photosynthesis

Rising concentrations of CO_2 in the atmosphere are believed to act as a fertilizer and increase the rate of photosynthesis for some species. Rates of photosynthesis are affected by the ratio of atmospheric CO_2 and O_2. Increase of the CO_2:O_2 ratio within the plant tissues results in suppression of respiration and enhancement of photosynthesis, consequently increasing net photosynthesis. However, increases in the rates of photosynthesis vary according to the duration of the period of interest, the plant N status, and species.

A meta-analytical review of free-air CO_2 enrichment experiments found that trees were more responsive than other plant types to elevated CO_2. In a review of short-term CO_2-enriched experiments (less than one season), photosynthesis of broadleaved species was more sensitive to elevated CO_2 than that of conifers. 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 broadleaved trees, ranging from 50–60%.

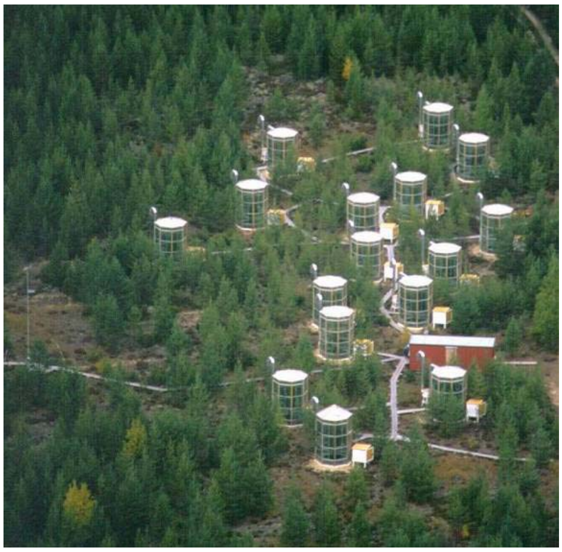


Figure 2. Closed chamber experiment studying tree response to elevated CO_2, Mekrijärvi, Finland. Photo: Mekrijärvi Research Station.

Most experiments have shown that elevated CO_2 concentration directly enhance growth of young trees or seedlings regardless of growth conditions, providing strong evidence to support the direct CO_2 fertilization effect. When exposed for longer time periods, photosynthesis and biomass accumulation could be lower than predicted from the initial growth response because trees might adjust to development under elevated CO_2. Moreover, tree growth rate might not increase proportionally with increases in the rates of photosynthesis because other limiting factors (such as nutrient availability) may become more important. For example, nitrogen is required in relatively large quantities in connection with all growth processes in plants; therefore, nutrient availability will limit the ability of trees to increase their growth rates in response to further increases in CO_2 concentration.

CO_2 and water-use

Increased atmospheric CO_2 also 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 increases. In addition, increased allocation of biomass to root growth in plants exposed to enriched CO_2 may enable plants to exploit soil water in a deeper and larger range of soil.

This effect is very important in water-limited areas like Mediterranean regions and continental Europe, which already suffer droughts. On the other hand increased water-use efficiency becomes less important in northern latitudes where precipitation is normally not limiting.

CO_2 concentration in the atmosphere will continue to increase for at least several decades. However, predicting the response to increasing CO_2 remains difficult as reactions of trees to CO_2 are variable, might diminish over time, and may be much more influenced by plant-soil interactions than is currently understood.

Full details can be found in section 4.1.1 of the report - Impacts of climate change on European forests and options for adaptation. Service Contract with DG Agriculture and Rural Development No. 30-CE-0163547/00-01. The report was compiled by the European Forest Institute (EFI) and its project partners BOKU, INRA and AISF.

Impact Factors – Changes in Temperature and Precipitation

The different bioclimatic zones have different limitations for forest production. The predicted climatic changes may have either a positive or negative effect on forest growth depending on the area studied and the main limiting factors in the area. At northern latitudes low temperatures limit plant growth for a large part of the year. In more southern latitudes and continental zones, availability of water is a more important factor influencing growth.

In Eastern Europe climate change projections suggest that the warming will be greatest in winter, and in western and southern Europe that warming will be greatest 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 in precipitation further south. The expected change in seasonal precipitation varies substantially from season to season and across regions.

Temperature

Figure 1. In temperature limited systems like the Forest–Tundra, climate change is expected to enhance tree growth. Photo: Niels van Kampenhout. http://www.flickr.com/photos/nielsvk/45798993/

Forest productivity in the northern boreal zone is mainly limited by low temperature, and often also by low nutrient availability. In boreal conditions, higher air temperature will prolong the growing season and thereby increase production.

An increase in temperature is also beneficial for tree growth on temperate sites as long as water supply is sufficient

In the Alpine zone production is water limited at low altitudes, but is temperature limited at higher altitudes where precipitation is significantly higher. Under the predicted change, production will increase mainly because of the prolonged growing season.

In the Mediterranean areas, where production is limited by low water availability, it is predicted that the growth and yield under climate change will decrease. In these areas heat is often a stress factor. The optimum temperature for photosynthesis rarely exceeds 30°C. At high temperatures photorespiration is stimulated and photosynthesis is inhibited.

Precipitation and related factors

Rising temperatures without an increase in precipitation or with decreasing precipitation can lead to drought, especially in Mediterranean and temperate continental conditions. Drought conditions reduce forest growth in sensitive species, such as beech (*Fagus sylvatica*), whereas other species such as sessile oak (*Quercus petraea*) are more tolerant of dry conditions. These influences will effect the species composition of forests.

High temperatures and dry conditions can negatively influence nutrient availability in soils and lead to enhanced loss in nitrogen via accelerated nitrification. These conditions also lead to aggravated competition of tree seedlings with other vegetation.

Changes in cloud cover alter the amount of incoming radiation at a site. These influences are currently not predictable, but may affect how different species compete for resources at a particular site.

Figure 2. In the dry Mediterranean region, temperature increase and reduced precipitation will intensify drought and negatively affect tree growth. Mediterranean evergreen forest, Sicily, Italy. Photo: A.Barbati.

Effects on species distribution

Climate change is expected to affect tree species distributions. Bioclimatic envelopes (i.e. conditions, under which species grow well) will shift northwards and higher up in elevation. Competitiveness between species can change due to alterations in temperature, moisture regime, CO_2 and radiation as has been found for beech (*Fagus sylvatica*) and ash (*Fraxinus excelsior*) seedlings. Changes in competitive relationships between species will be important in mixed stands and natural ecosystems and they will influence tree migration in the long term. However, in the short term, the physiological limits of tree growth at the warm and dry distribution limit are most important as they determine species extirpation (i.e. local extinction). The range of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) might retreat from the south and west while beech and other temperate broadleaved species spread to the north. Conifer forests subject to continuing disturbance show a more rapid shift to dominance by beech and other temperate broadleaves. The treeline is expected to move further north and upwards in the mountain regions.

In the Mediterranean, socio-economic developments, drought and altered fire regimes may lead to more shrub-dominated landscapes. In the Alps, the suitability of Norway spruce as a crop species may diminish at lower altitudes, and deciduous species may become more competitive than Norway spruce also at higher altitudes.

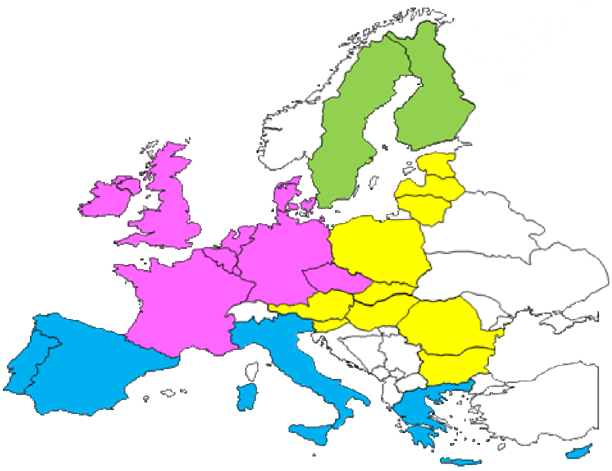


Figure 3. Summary map of the impacts of temperature and precipitation changes in Europe.

- Boreal
  + temperature
  + tree growth
- Temperate oceanic
  + temperature
  ± tree growth
- Temperate continental
  + temperature
  ± precipitation
  ± tree growth
- Mediterranean
  – precipitation
  – tree growth
  + fire risk

Climate variability and extreme events

Interannual climate variability, extreme climatic events and increased disturbance risks may cause adverse impacts even on boreal and temperate sites which otherwise benefit from increased temperature and higher CO_2 concentration. In central European regions the drought risk increases from west to east. In the Mediterranean regions productivity is expected to decline due to strongly increased droughts.

Temperature increase and changes in water regimes will also affect forests indirectly through changes in disturbance regimes as both biotic factors (pests and pathogens, natural enemies of pests) and abiotic factors (e.g. fire damage) are directly influenced by the changing climate.

Full details can be found in section 4.1.2 of the report - Impacts of climate change on European forests and options for adaptation. Service Contract with DG Agriculture and Rural Development No. 30-CE-0163547/00-01. The report was compiled by the European Forest Institute (EFI) and its project partners BOKU, INRA and AISF.

Impact Factors – Abiotic disturbances

Among the known impacts of climate change are changes in damage caused by natural disturbances (fire, storms, flooding). 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%. 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 central, western and northern Europe, may more frequently result in an imbalance in the long-term planning of harvests.

Climate change and fire risk

Forest fires are burning approximately half a million ha of forests each year in the Mediterranean region (Spain, Italy, Portugal, Greece, and France). The majority of fires are human induced, mostly due to deliberate lighting of forest fires and negligence. Natural causes represent only a small percentage of all fires in the Mediterranean. Fire damage is particularly high in hot and dry years (e.g. 2003, 2005, and 2007). While improved fire protection has significantly reduced the average fire size since the beginning of the 1990s, extremely hot years result in much larger fires. For example, the long-term average size of forest fires in Greece was 30 ha in the period 1980–2007, but in the summer of 2007 the average fire size was 113 ha. Also in Portugal, the average fire size tripled under the extreme conditions in 2003.

Figure 1. Fighting forest fires, France. Photo: © grivelphoto - Fotolia.com

Fire danger is expected to increase throughout Europe, especially in the already dry and fire-prone Mediterranean, but also in the boreal and central European regions. Recently, the impact of fire on soils has become of greater concern. Low- to moderate-intensity fires have little or no negative impacts, but 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.

Climate change and wind and snow damage

Windthrow and storm damage are most relevant in central, 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. The economic value of the damage is in the order of hundreds of millions of Euros each year. 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.

Figure 2. Storm damage November 2004, Slovakia. The storm affected 330,000 ha of forests and the total volume of damaged timber was 5.4 million m^3. Photo: State Forests of TANAP.

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. Market distortions of large amounts of salvaged timber can further aggravate the economic losses. Furthermore, broken and uprooted trees left in forest can lead to detrimental insect attacks on the remaining undamaged trees because of an increase in the amount of available breeding material for the insect pests.

wind and snow damage (cont). In Finland, significant amounts of timber are also damaged by snow every year. The risk of wind and snow damage is higher where there are sudden changes in wind loading to which the trees are not acclimated – e.g. in stands thinned intensively or stands adjacent to recently clear-felled areas. Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) are much more susceptible to wind and snow damage than birch (*Betula* spp.).

Figure 3. Heavy snow load, Norway spruce (*Picea abies*) forest, Finland. Photo: N.Verkerk.

Under climate change, the risk of snow and wind damage may increase at northern latitudes because of the potential decrease in soil freezing. This will lead to a decline in anchorage of trees so that uprooting could become a more common type of snow damage. Heavy snowfalls might be more common in the interior and northern parts of the boreal zone of Europe.

In the temperate oceanic region, more precipitation is projected to fall in intensive rain events, leading to higher water saturation in the soils. Waterlogged soils increase susceptibility to windthrow especially for the shallow rooting Norway spruce, which has already been affected to a greater degree by wind damage than other species in recent storm events.

Abiotic-Biotic interactions

In windthrow gaps or areas, the forest ecosystem is destabilised and there are major changes in the abiotic conditions, and for many significant pests the amount of suitable breeding material is increased.

Coniferous stands are more often affected by windthrow and more sensitive to pest outbreaks. Sun-exposed deadwood in gaps and along forest edges offer attractive micro-habitats for several species of bark beetles (Scolytidae) and longhorn beetles (Cerambycidae).

Storm events not only increase the incidence of pest outbreaks, but also result in a higher probability of tree wounds that allow the entry of pathogen organisms. However, there is a lack of knowledge concerning the specific climatic parameters involved in pathogen development triggered by windthrow.

Climate change and flooding risk

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 predicted to decrease, but the number of days with heavy rain events is predicted to increase. This change is leading to more summer droughts as well as more extreme flooding events during summer. 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.

Adaptive management options targeted to reduce disturbance risks under climate change are discussed in the Factsheet on “Adaptive capacities of European forests”.

Full details can be found in section 4.1.4 of the report - Impacts of climate change on European forests and options for adaptation. Service Contract with DG Agriculture and Rural Development No. 30-CE-0163547/00-01. The report was compiled by the European Forest Institute (EFI) and its project partners BOKU, INRA and AISF.

Impact Factors – Biotic disturbances

Climate change already has direct and indirect impacts on the temporal and spatial dynamics of pest and pathogen species. The direct impacts include influencing the frequency and intensity of outbreaks as well as their spatial patterns, size and geographical range. The indirect impacts include the influence of climate change on plant nutritional quality and plant resistance, and on community interactions with natural enemies.

Temperature increase – direct effects on pests and pathogens

- *Changes in life-cycles*

Changes may be induced in life-cycle duration (rate of development), population density and size, genetic composition and extent of host plant exploitation of insects. An increase in temperature towards an optimum for an insect pest species will usually accelerate egg and larval development, reducing development times most susceptible to predation and parasitism and thus, increase chances of survival. High temperatures during heat waves above the optimum for pest will have negative effects on insect populations, leading to decreased growth rates and reduced fecundity and survival.

In the boreal forest zone, the shift to warmer springs and winters will increase the incidence and duration of insect outbreaks. As an example, periods of mild winters and particularly warm summers have led to large outbreak areas of bark beetles.

- *Range shifts, range expansions or contractions*

Range extension of species may be promoted by increases in mean annual, summer and winter temperature (the degree of frost resistance of winter stages commonly defines the northern boundary of a species range). The size and location of species ranges is influenced by the interaction of available habitats with suitable climate. As the geographic distribution of many forest insects is more limited than their host distribution, insect distribution could change very rapidly.

Figure 1. Gypsy moth (*Lymantria dispar*). Outbreaks are predicted to become more common in the north and at higher altitudes. Photo: John H. Ghent, USDA Forest Service, Bugwood.org.

Outbreak areas of pest species are likely to shift in latitudinal range. Populations may expand their ranges to higher latitudes and elevations as a response to increased overwinter survival, higher population growth rates due to increased summer temperature, and a longer growing season. The southern boundary of the present geographical distribution may become too warm, which will result in a northward shift or even range contraction.

Increased winter temperature may affect insect development both positively and negatively. Depending on the species, higher temperatures may promote increased growth rates, lead to reduced winter mortality, but may also influence the initiation and onset of periods of dormancy.

The occurrence of exotic species not previously present in Europe has already been observed and invasive species are expected to be a major threat under climatic change.

- *Phenological coincidence between pests and their hosts*

Host-specific insect pests often require close synchrony with host phenology (e.g. timing of larval development and bud burst) in order to successfully complete their (mostly annual) life-cycle. Under climate change scenarios there is likely to be increased asynchrony between host plants and insect pests, with obvious adverse consequences (starvation).

Climate change (especially increases in summer temperature) also influences the intensity of background herbivory (endemic insect damage) and in this way may accelerate changes in forest structure and community development.

Temperature increase – indirect effects through changes in plant nutritional quality and resistance

Increasing global temperatures can affect the developmental race between poikilotherm pests and the plant host if the temperature sensitivity of the herbivore differs from that of the host. There is a need for further studies regarding the effects of temperature changes on plant allocation patterns or resistance to herbivory.

Temperature increase – indirect effects through community interactions

The population dynamics of insect pests will depend not only on the responses of the pests, but also on the presence and abundance of predators and parasites. Temperature increase could have both effects, increasing the effectiveness of certain natural enemy species by bringing parasitoids more in synchrony with their host pest and allowing pest populations to better escape natural enemy regulation.

Changed precipitation patterns – direct effects on pests and pathogens

Generally, there is only limited knowledge on direct effects of changing precipitation patterns on insects. A decrease of overwinter survival of insects hibernating in the forest litter and usually insulated by snow cover was observed in case of reduced snowfall. Low snow pack years or extreme droughts also have negative effects on certain butterfly species, leading to local population extinctions and northward and upward shifts in distribution.

Reduced precipitation in terms of snowfall and shorter periods of snow cover lower the risk of damage by pathogens benefiting from insulation by snow, such as snow blight.

Consequences of climate change – general aspects

Changes in climatic variability may be as important, or even more important for some pests and pathogens, as changes in the average climate. For many species, it is expected that performance and survivorship will be affected more by the frequency or nature of catastrophic events than by slight, progressive changes in average climatic conditions.

Plant nutritional quality and resistance. The physiological condition of the trees plays a major role in determining the pathogenicity (i.e. the potential of the organisms to cause damage) of pests and pathogens. Climate change will affect decomposition processes and consequently the nutrient supply of plants. The availability of nitrogen may be particularly important, as nitrogen-limited host tissue is likely to decline in quality for pests, while a good nitrogen supply and the reduction of secondary metabolites at the same time may enhance food quality.

The damage caused by pest insects will also be affected by how climate change affects the ecology of natural enemies (parasitoid insects and predators) and diseases (viruses, entomopathogenic fungi, etc.). Specific community interactions may influence population cycles of pests. As an example, intensity and extent of damage by defoliators may vary with the composition and activity of the natural enemy community, host stand composition and stand stress.

Increased frequency and intensity of storm events – direct effects on pests and pathogens

There is a significant interaction between the occurrence of abiotic damage and the occurrence of biotic damage (see factsheet on abiotic damage).

Increase of CO_2 – indirect effects through changes in plant nutritional quality and resistance

Interactions of increased levels of CO_2, temperature and light, and nutrient availability

The main 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 pests. 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 the level of atmospheric CO_2, temperature, precipitation, nutrient availability, plant quality, insect performance, and range expansion make predictions of future pest problems difficult.

Factors such as atmospheric CO_2 increase, changes in temperature, changes in precipitation, and changes in abiotic disturbances will have a major influence on biotic disturbance agents. However, the interactions between the various factors and the combined effects on pests and pathogens, and consequently forest health, are far from being fully understood.

Full details can be found in section 4.1.5 of the report - Impacts of climate change on European forests and options for adaptation. Service Contract with DG Agriculture and Rural Development No. 30-CE-0163547/00-01. The report was compiled by the European Forest Institute (EFI) and its project partners BOKU, INRA and AISF.

Forest ecosystem sensitivity and potential impacts – Boreal Region

Climate characteristics

The region has a cool-temperate, moist climate, varying from sub-oceanic in the west to sub-continental in the interior and the east. The most significant climatic factor for forest productivity is the length of the growing season (ranging from ca. 100 days in the north to 200 days in the south). Annual precipitation varies between 500 and 800 mm per year, with extremes of 300 and 1200 mm. Average annual temperatures are generally low: less than 4.8°C in the boreal subcontinental zone and less than 3.8°C in the continental one.

Key climate change trends

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.

Figure 1. Boreal pine forest with birch and spruce understorey, North Karelia, Finland. Photo: M.Kolström.

Sensitivity to climatic change

Higher air temperature (T) will lead to earlier and more rapid recovery of photosynthetic capacity in spring and a prolonged photosynthetic active season in autumn, resulting in increased growth and timber yields of boreal forests. A moderate increase in T will likely enhance carbon sequestration in forests, while a more pronounced T increase could mean that forests turn from carbon sinks into carbon sources.

Precipitation (P) 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 P – can be expected when moving from colder high latitudes to warmer southern boreal forests, where there could be increases in the demand for water. This is the case in southeastern Sweden, and could also be the case in southern Finland under climate change. Thus, the potential increase in productivity due to higher T could be reduced or offset because of insufficient water availability. Norway spruce (*Picea abies*) is more susceptible to dry periods than Scots pine (*Pinus sylvestris*) and silver birch (*Betula pendula*) due to higher retention of water in the crown and lower availability of water for the roots.

Enhanced atmospheric [CO_2] could partially mitigate drought by enhanced water-use efficiency of plants.

Changes in T and P will lead to changes in **species distributions**. Woody boreal vegetation is expected to spread into tundra at higher latitudes and higher elevations. Broadleaved deciduous trees could migrate to boreal forests under climate change.

Abiotic risks. Increased soil waterlogging and winter floods could also increase the susceptibility to windthrow, because waterlogged soils give less support to the roots. Forest damage by wind and snow are projected to increase under climate change. Climate change will shorten the period with frozen soils and snow cover, thereby negatively affecting forest management operations e.g. by limiting the accessibility of forest on wet organic soils or decreasing the possibilities to use heavy machinery on hill slopes.

Biotic disturbances. A rise in minimum winter T in the boreal zone is likely to promote outbreaks of defoliating insects due to increased rates of egg survival. Consequently, a change in northern distributional limits and the probability of mass outbreaks is to be expected for the European pine sawfly (*Neodiprion sertifer*), one of the major defoliators in boreal forests of Scots pine, or for the autumnal moth (*Epirrita autumnata*) in boreal birch forests. Outbreaks of gypsy moth (*Lymantria dispar*) and nun moth (*Lymantria monacha*) in northern deciduous forests will become more likely, as climate change may trigger northward expansions of the species by 500–700 km. The higher probability of forest defoliation will be an advantage for secondary pest insects depending on weakened host trees, such as the common pine shoot beetle (*Tomicus piniperda*). Norway spruce forests will be increasingly prone to large-scale infestation by the European spruce bark beetle (*Ips typographus*), as rising winter and summer T speed up beetle development and may allow for a switch from univoltine populations to populations that are able to produce more than one generation per year.

Biotic disturbances (cont.).The pathogenic fungus *Gremmeniella abietina* causes disease in pine forests in southern Finland, in plantations of introduced lodgepole pine (*Pinus contorta*) in high elevation areas of northern Sweden, and recently also in stands of Scots pine (*P. sylvestris*). Epidemics are usually initiated by cold and rainy growing seasons and often concentrated on sites of high humidity and cold air. While warm summers with T above the average might slow down the spread of the disease, mild winters combined with summers of high P probably will increase the risk of *G. abietina* outbreaks in northern Sweden. Longer growing seasons associated with higher T may increase the incidence of root and butt rot in Norway spruce caused by *Heterobasidion parviporum* and *H. annosum*. The border of the "high risk area" regarding root and butt rot is likely to shift to higher elevations and latitudes of Fennoscandia.

Assessment of potential impacts on forest goods and services

Wood production. Gradual increases in T and P with a concurrent elevation in CO_2 will enhance tree growth and timber yield. Recent regional studies for a forest unit in central Finland projected an increase in stand growth by 22–26% (depending on the climate scenario) resulting in an average increase of 12–13% in timber yield. Incomes from wood production are likely to increase. Differences between scenarios are due to the varying degrees of water stress caused to the trees.

Another study for Nordic countries concluded that elevated T increased growth in coniferous stands; the increase was less for Scots pine growing in a maritime climate (Norway) than for Scots pine growing in a continental climate (central Sweden and eastern Finland).

Non-wood forest products. There are still knowledge gaps regarding the effect of climate change on different non-wood forest products (e.g. mushrooms, berries, nuts). A recent study has indicated that the autumn fruiting of mushrooms has been delayed in Norway, and that the delay coincides with the extension of growing season caused by climate change. Other non-wood forest products are also likely to be affected by climate change.

Carbon sequestration. In parallel to increased growth and productivity, carbon sequestration rates will increase in boreal forest ecosystems under scenarios where there is moderate increase in T. However, for some of the projections predicting the highest increases in T, the studies predict a decrease in total C stocks (i.e. the areas become a source rather than a sink for C). This is due to the reduction of C in the soil because higher T enhances the decomposition of soil organic matter. Possible increases in forest disturbance may also have an effect.

Biodiversity. Broadleaved deciduous trees may expand their potential distribution ranges into the boreal forests. This could increase the tree species diversity and functional diversity. In addition, woody boreal vegetation is expected to spread into tundra at higher latitudes and higher elevations. Consequently, species adapted to open conditions will have to migrate north or to higher elevations. As natural migration rates differ between species, new species compositions may develop and some species adapted to tundra conditions may go extinct.

Vulnerability and uncertainty

The response of tree species and provenances to T increases at the southern distribution limits is not well understood. Models differ in the projected impacts of climate change in the southern Boreal region. In particular, the response of Norway spruce to climate change in this region is uncertain.

Vulnerability to climate change is small compared to other socio-economic pressures on the forest sector. Reduced availability of timber due to inaccessibility of forest resources on wet soils outside the frost period will pose a threat to the industry. Alternative technical harvesting and transport solutions will need to be found. Improved forest productivity, particularly in the northern part of the Boreal region will create opportunities for increased utilisation of forest resources in the mid- to long-term.

Figure 2. Harvester on unfrozen soil, eastern Finland. Photo: North Karelia College, Valtimo.

Full details can be found in sections 4.2.1 and 6.1 of the report - Impacts of climate change on European forests and options for adaptation. Service Contract with DG Agriculture and Rural Development No. 30-CE-0163547/00-01. The report was compiled by the European Forest Institute (EFI) and its project partners BOKU, INRA and AISF.

Forest ecosystem sensitivity and potential impacts – Temperate Oceanic Region

Climate characteristics

The region is characterized by relatively high rainfall and high winter temperatures. Difference between mean temperature of the warmest and of the coldest month is less than 21°C. There is no marked seasonal variation in rainfall pattern; annual precipitation varies between 580 and 2000 mm per year in the lowlands, and goes up to 3000 mm in the uplands of Scotland and western Scandinavia.

Key climate change trends

Annual mean temperature increases will be 2.5–3.5°C (for the UK and Ireland with 2–3°C). Summers are likely to be drier and hotter (up to 4°C increase). Extreme events (storms and floods) are projected to become more frequent due to warmer temperatures and higher volumes and intensities of precipitation, in particular in winter.

Figure 1. Beech (*Fagus sylvatica*) stand rich in structural diversity of tree size and age. Photo: © Uwe Wittbrock - Fotolia.com.

Sensitivity to climatic change

Higher air temperature (T) 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).

Precipitation (P) is expected to increase in winter but summers are likely to be drier and hotter. In the southern parts of the Temperate Oceanic zone summer P is the main factor limiting forest growth and productivity.

T increase may have strong impacts on forest productivity and the competitive relationships between different tree species. Simulation studies with a variety of climate change scenarios have indicated that positive growth responses could occur in temperate forests if increasing P balances the increased evaporative demand under elevated T. Negative impacts can be expected where climate warming changes the water balance, leading to increased drought stress.

Enhanced atmospheric [CO_2] could partially mitigate drought by enhanced water-use efficiency of plants.

Changes in T and P will lead to changes in **species distributions**. In large areas of western and central Europe, T increase may lead to the replacement of natural conifers with the more competitive broadleaved trees. Recent studies predict a reduction in the numbers of species in the Temperate Oceanic region, and occasionally gains in functional diversity.

Abiotic risks. The most important effects of climate change on temperate forests will probably be mediated through changes in disturbance regimes such as storms and windthrow, which may gain in importance under climate change.

Figure 2. After Storm Kyrill, Germany, 2007. Photo: Bendus. http://www.flickr.com/photos/bendus/422074713/

Biotic disturbances. Prolonged and warmer vegetation periods will especially enhance the development of several species of bark beetles, allowing for the establishment of additional generations and multiplying population densities. As an example, the European spruce bark beetle (*Ips typographus*), which is commonly univoltine in southern Sweden, will develop a second generation in this area already at an annual mean T increase of 2-3°C. Increasing incidence of storm events and drought periods also render pine forests of the Temperate Oceanic zone more susceptible to infestation by other bark beetles (e.g. *Tomicus piniperda*, *I. sexdentatus*, *I. acuminatus*). Range expansion and both, altitudinal and latitudinal range shifts are to be expected for several moth species, such as gypsy and nun moth (*Lymantria dispar* and *L. monacha*), and pine and oak processionary moth (*Thaumetopoea pityocampa*, *T. processionaea*). The latter species may affect the recreational value of pine and oak forests due to the urticating hair of the moth larvae.

Biotic disturbances (cont.). T increase associated with drought will be a main factor predisposing forests to diverse fungal diseases. In the future, the expansion and northward shift of highly thermophilic, Mediterranean pathogen species is to be expected, for instance in the southern parts of the Temperate Oceanic zone. Fungal diseases already present in a latent form will probably become pathogenic in drought-stressed trees. Drought is also a main trigger of infections by root diseases, such as *Armillaria* spp. in conifers, and plays a significant role in the complex of oak decline. The relationship between drought, fungus attack, tree decline and death has been found for the soil pathogen *Phytophthora cinnamomi* in wide parts of the Mediterranean area, Switzerland, UK, Slovakia and Romania. The disease will be promoted by an increase in summer T, although in the northern parts of the Temperate Oceanic zone (e.g. northwestern Germany) winter survival will still remain limited by low T.

Assessment of potential impacts on forest goods 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 water is a more limiting factor.

For example, in France, forest productivity in the north is expected to be enhanced by climate change, increasingly from west to east, whereas in the southwestern Temperate Oceanic region, productivity will be reduced by climate change to an increasing degree from west to east.

Non-wood forest products. A recent study analysed autumnal fruiting patterns of macro-fungi over 56 years in southern England 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.

There are gaps in the information about the impacts of climate change on productivity of mushrooms and other non-wood forest products in this region. However, NWFPs are of smaller importance compared to the Boreal and Mediterranean regions.

Carbon sequestration. Impacts on carbon sequestration are strongly affected by management interactions. Most of the Temperate Oceanic region is benefiting from increased tree growth and productivity and consequently carbon sequestration rates are increasing as well. The carbon balance may be negatively impacted by more frequent disturbances.

Biodiversity. Most existing studies rely on environmental envelope approaches which suggest that there will be a shift in the natural species composition from coniferous dominated forests towards broadleaved species. However, as the majority of European forest is intensively managed, management effects will strongly influence the transition by either maintaining economically important species outside their natural range (e.g. Norway spruce) or by supporting the regeneration of new target species. 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.

Vulnerability and uncertainty

Extreme events such as storms, droughts, flooding, and heat waves are probably the most important threats in this region. Increased winter rainfall and high wind speeds in combination may lead to large storm damages. Several biotic disturbance agents may impose significant threats, particularly in warm and dry years. Conservation of rare species may be threatened because fragmentation of valuable habitats will present an obstacle to migration to new suitable habitats.

Full details can be found in sections 4.2.2 and 6.2 of the report - Impacts of climate change on European forests and options for adaptation. Service Contract with DG Agriculture and Rural Development No. 30-CE-0163547/00-01. The report was compiled by the European Forest Institute (EFI) and its project partners BOKU, INRA and AISF.

Forest ecosystem sensitivity and potential impacts – Temperate Continental Region

Climate characteristics

The region is characterized by hot summers, cold winters and low rainfall. Difference between mean temperature of the warmest and of the coldest month is greater than 21°C. Average annual temperatures range from 6°C to 12°C; compared to the Temperate Oceanic zone precipitation is lower and decreases eastwards; it typically ranges from 380 mm to 635 mm in lowlands; in the mountain areas, rainfall is higher than 1400 mm, and locally may reach values up to 3000 mm.

Key climate change trends

Annual mean temperature will increase around 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. Mean annual precipitation will increase by up to 10% mainly in winter, while reductions are expected in summer precipitation in several areas (up to –10%).

Figure 1. Thermophilous deciduous forest, Italy. Photo: A.Barbati.

Sensitivity to climatic change

Higher air temperature (T) The effect of climate change on individual species can be either positive or negative, depending on the site conditions and regional climate changes. There will be a detrimental impact in productivity where the elevated T leads to increased evapotranspiration and the demand of water increases. On the other hand milder winters may reduce winter hardening in trees, increasing their vulnerability to frost.

Precipitation (P). Summer P is the main constraint factor of forest growth and productivity through their role in determining the frequency of droughts. Currently, the demand of water during the growing season is normally larger than the amount of rainfall. Therefore, production decreases at sites vulnerable to water stress and increases in sites where the increased evaporative demand under the elevated T is balanced by an increase in P.

Changes in T and P in continental and central Europe will lead to a decrease in growth of conifers due to water limitations by the end of the century. Beech (*Fagus sylvatica*) is projected to face severe problems when T increases and could be replaced by oaks (*Quercus* spp.) due to the lower sensitivity to water stress.

Enhanced atmospheric [CO_2]. An experimental field study indicated that mature trees may react to increasing CO_2 concentrations with possible differences between species. Beech showed a significant growth enhancement especially under drought conditions, whereas sessile oak (*Quercus petraea*) and hornbeam (*Carpinus betulus*) did not respond to increased CO_2.

Changes in T and P will lead to changes in **species distributions** especially if the number of years with water stress increases.

Abiotic risks. The most important effects of climate change on temperate forests will probably be mediated through changes in disturbance regimes (e.g. fires). Fire danger is likely to increase.

Biotic disturbances. Altitudinal shifts and an increase of areas suitable for outbreaks of some pest species may occur; for example, the gypsy moth (*Lymantria dispar*) in Slovakia. The gypsy moth is likely to profit even from a high increase in average T (up to 5.8°C). At the same time, climate change may induce a shift from the main host species *Quercus* spp. to alternative tree species, such as beech. Defoliation by gypsy moth will also raise the probability of attack by secondary pathogens and pest insects, and is one of the factors (together with drought stress of the trees) involved in the “complex disease” oak decline.

Biotic disturbances (cont.). Rising average T and increases in disturbance events, such as windthrow or extreme weather conditions will bring forward outbreaks of the spruce bark beetles *Ips typographus* and *Pityogenes chalcographus*. The possibility of a completed third beetle generation will become probable in certain regions of the Temperate Continental zone.

Reductions in summer precipitation resulting in drought-stress of forests will predispose host trees to root diseases (e.g. caused by *Armillaria* spp.). Tree dieback due to *Armillaria* spp. is also reported in association with oak decline, together with an assortment of other fungal pathogens (e.g. *Phytophthora quercina*), periods of soil water deficits and climatic conditions unfavourable for tree vitality. High T and xeric conditions seem to favour the incidence of root rot caused by *Heterobasidion* spp.; however, the risk of infection by the root rot is reported to be very low under extremely dry climatic conditions. Given an increase of precipitation in spring, the future risk of severe outbreaks of fungal pathogens that reproduce best during warm and moist periods might be high.

Figure 2. Red rot of heartwood caused by Heterobasidion annosum. Photo: Andrej Kunca, National Forest Centre - Slovakia, Bugwood.org.

Assessment of potential impacts on forest goods 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 northeastern German lowlands suggested that wood production could decline by about 10%. In addition, results from Austria suggest that beyond a T increase of approximately 1^{o}C (with no changes in precipitation) impacts may become widespread and severe. The study also suggests that at low-elevation sites Norway spruce (*Picea abies*) would become unsuitable as a crop species.

Non-wood forest product. There is a lack of information available about impacts on non-wood forest products in this region. These are, however, of smaller importance compared to the Boreal and Mediterranean regions.

Carbon sequestration. The carbon balance may be negatively impacted by more frequent disturbances.

Biodiversity. Climate change and 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. Another effect is that beech could be replaced by oaks if the number of years with water stress increases.

Vulnerability and uncertainty

Climate change impacts will strongly depend on the future amount and distribution of precipitation. Extreme events may be crucial for forests health and productivity, but their frequency and intensity under climate change is still largely unknown.

Drought risk is an important threat especially under water limited conditions. Extreme events and connected disturbances due to storm, flooding, and fire are also important. Biotic disturbance agents may impose significant threats as well.

Full details can be found in sections 4.2.3 and 6.3 of the report - Impacts of climate change on European forests and options for adaptation. Service Contract with DG Agriculture and Rural Development No. 30-CE-0163547/00-01. The report was compiled by the European Forest Institute (EFI) and its project partners BOKU, INRA and AISF.

Forest ecosystem sensitivity and potential impacts – Mediterranean Region

Climate characteristics

The region is characterized by hot and dry summers (two months of summer droughts, at least) and winters mild to cool and rainy. There is a variety of climatic regions owing to the complex configuration of seas and mountainous peninsulas in the Mediterranean zone. Annual precipitation typically amounts to 500–600 mm, up to 800–900 mm in more humid zones.

Key climate change trends

Yearly rainfall is expected to drop by up to –20% (up to –50% in summer) but increases in winter. Temperature increases 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, heavy precipitations events, and fewer cold days.

Figure 1. Xerophytic coniferous forest, Italy. Photo: A.Barbati.

Sensitivity to climatic change

Higher air temperature (T) without increase in precipitation or with decreasing rainfall will lead to increased occurrence of drought which is the most important impact factor in this region.

Precipitation (P) is expected to decrease; this, in combination with increased T will lead to more droughts which will reduce plant growth and primary productivity. Moreover other detrimental effects will be reduction of nutrient availability, loss in nitrogen via accelerated nitrification, and altered plant recruitment.

From a network of beech dendrochronological records it was found that **drought** has a great impact on beech at the lower elevations. Drought-tolerant tree species and shrubby plants (e.g. *Phyllirea latifolia*, *Erica* spp.) could be favoured at the expense of more mesic ones (e.g. *Quercus ilex*), with consequent changes in dominance and species distribution.

Enhanced atmospheric [CO2] could increase water use efficiency of trees, 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.

Figure 2. Forest fire, France. Photo: © Olivier Tuffé - Fotolia.com

Abiotic risks. The most important abiotic risk is the fire which is expected to increase due to climate change. The total burned area in Spain has increased by 600% between 1960 and 1990, principally because of the daytime T increases and the relative moisture decrease which have affected vegetation growth, fuel structure and combustibility.

Climate change is expected to increase the number of years with fire risk, especially in northern parts of the Mediterranean region (North Spain, North Italy) 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.

Biotic disturbances. The higher incidence of extreme weather events, increasing T and severe droughts will strongly affect biotic disturbances. It is highly probable that T increase will lead to distributional shifts of insect populations. In cases where altitudinal expansion or dislocation of the range of the host tree species is possible, or where pest species are able to switch hosts, the pest species (e.g. the pine processionary moth, *Thaumetopoea pityocampa*) are likely to profit from the changes in climate. However, T may also rise above the optimal development conditions for certain species, leading to restrictions at the southern edge of distribution, for instance of gypsy (*Lymantria dispa*) and nun moth (*L. monacha*).

Biotic disturbances (cont.). Highly thermophilic pathogen species are likely to become more serious in southern Europe. Typical components of the endophytic microflora inhabiting Mediterranean tree species 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 may pose a considerable future threat to southern forests. T increase and summer droughts will promote outbreaks of various pathogenic fungi, for instance of *Heterobasidion abietinum* in southern Italian stands of silver fir (*Abies alba*), together with the root disease *Armillaria* spp.

Changing patterns of P have been leading to an increasing incidence of oak decline in the Iberian Peninsula. The highly pathogenic fungus *Phytophthora cinnamomi* is especially active under warm climate and requires wet soil conditions to infect roots. Recently, long periods of high T interspersed with short intervals of heavy P have become more common and predispose oaks (*Quercus* spp.) to infection.

Figure 3. Cork oak (*Quercus suber*) affected by oak decline, Algarve, Portugal. Photo: Moreira, A.C.

Assessment of potential impacts on forest goods and services

Wood production. Wood production may decline significantly under the projected climate change scenarios. Prolonged droughts will increase mortality, and increased forest fire risk will cause further losses in wood production.

Non-wood forest products. There is little specific information available on climate change impacts on cork production or on mushroom production. Both are important non-wood forest products in the Mediterranean region. However, a clear relationship between mushroom production and rainfall has been reported, suggesting that declining P may negatively affect mushroom production.

Carbon sequestration. Negative impacts of drought on forest growth and productivity will also negatively affect carbon sequestration rates. The net carbon balance will be strongly affected by disturbances, especially by projected increases in frequency and intensity of forest fires.

Biodiversity. The distribution of a number of typical tree species is likely to decrease in the Mediterranean. The projected increase in fire disturbances will also affect species diversity, favouring disturbance tolerant species and negatively affecting species that are less adapted to fire disturbance regimes. A study using bioclimatic niche models to assess invasion risk of alien plant species concluded that most of the southwestern part of Europe is potentially suitable for invasion by South African species.

Protective functions. The impact of fire on soils has important secondary effects on carbon cycling and water relations. In addition, fire together with increased flooding is likely to lead to increased erosion risk due to reduced plant regeneration after frequent fires, potentially contributing to an acceleration of desertification.

Vulnerability and uncertainty

Climate change impacts will strongly depend on the future amount and distribution of precipitation. The degree to which increasing water limitations may be partly compensated by increased water use efficiency under increasing CO_2 concentrations in the atmosphere is uncertain. Frequency, intensity and duration of heat waves under climate change are still not well known.

The extreme forest fire risk is the largest threat in the Mediterranean region. Increasing drought limitations are threatening the survival of many forest species. Both productive and social forest functions and services may decline, at least in parts of the region.

Full details can be found in sections 4.2.4 and 6.4 of the report - Impacts of climate change on European forests and options for adaptation. Service Contract with DG Agriculture and Rural Development No. 30-CE-0163547/00-01. The report was compiled by the European Forest Institute (EFI) and its project partners BOKU, INRA and AISF.

Forest ecosystem sensitivity and potential impacts – Mountain Regions (Alps, Carpathians, Pyrenees)

Mountainous regions are characterized by steep elevation gradients, resulting in a large diversity of ecotones and complex climatic patterns. Therefore, the uncertainties of climate projections are higher in mountain regions compared to areas with more uniform geomorphology. In mountainous regions warming is likely to exceed the average continental trend. This has already been observed for the second half of the 20th century in the Alps where the temperature increase has been twice the European average. The duration of snow cover is expected to decrease by several weeks for each °C of temperature increase in the Alps.

Mountain dwelling societies are demanding multiple forest services beyond just timber production; this can be a challenge for forest management in times of climate change.

Figure 1. Mountain forest, Alto Adige, Val Gardena, near Colfosco, Dolomites, Italy. FAO Forestry Photos database. http://www.fao.org/forestry/29361/en/

Sensitivity to climatic change

Higher air temperature (T). As processes at high altitudes (subalpine, alpine and nival vegetation zones) are limited by T, an increase in T has the potential to extend the growing season and enhance tree growth in these areas. As an example, recent reports show a strong stimulation of diameter growth for Norway spruce (*Picea abies*) in a subalpine environment and for Swiss stone pine (*Pinus cembra*) growing at the tree line.

Changes in the competitiveness of particular species under changing conditions will lead to changes in the aut- and synecological potential species composition. The number of tree species able to survive at higher elevations will increase due to increased competitiveness of broadleaved species under warmer conditions. It is also expected that the tree line will move upwards as a response to the projected warming, where suitable microsites are available. A limitation to a warming-related relaxation of current environmental harshness in high mountains is that an earlier initiation of root and shoot growth could make trees more vulnerable to sudden drops in T in early summer.

Precipitation (P) is frequently a limiting factor for forest productivity in the foothills of mountain ranges as well as in inner alpine dry valleys. Changes in the P regime (amount, and also the seasonal distribution) in combination with increasing T may have a detrimental effect on forest growth and subsequently cause tree mortality. Growth of Scots pine (*Pinus sylvestris*), downy oak (*Quercus pubescens)* and Norway spruce in the Alps, beech (*Fagus sylvatica*) in the lowlands of the Pyrenees, and Norway spruce in the lowlands of the Carpathians are already negatively affected by drought stress.

Abiotic risks. Mortality from forest fires could gain importance as well as windstorms might increase in the European Alps under future climate conditions. All climatic scenarios indicate increased drought and this affects the fire risk. Forest fires will be of particular importance in the Pyrenees.

Figure 2. *Ips typographus* damage, Switzerland. Photo: Beat Forster, Swiss Federal Institute for Forest, Snow and Landscape Research, Bugwood.org.

Biotic disturbances. Mountain forests are particularly sensitive to changes in climatic conditions and coniferous forests at higher elevations may suffer in the future from dramatically increased biotic damage. Over the last 15 years, an increase in bark beetle infestations (*Ips typographus, Pityogenes chalcographus*) of Norway spruce stands in Switzerland and Austria has already taken place, triggered by storm damage events and favoured by the increasing T of the recent decade. Secondary spruce forests in the foothills of the Alps, often not well adapted to the site conditions, are also particularly susceptible to bark beetle damage.

Biotic disturbances (cont.). The severity of fungal diseases in mountainous regions is strongly affected by changes in T and P, especially the amount of snowfall and duration of snow cover. Snow blight (*Phacidium infestans*) and the black snow mould (*Herpotrichia juniperi*) both require deep snow cover for development and infection of the host trees. The longer the snow cover, the longer the fungi are able to develop under beneficial moisture conditions. T increase, reduced summer P, and a shift from snowfall to more rain might consequently reduce the future risk of canker (e.g. Scleroderris canker, *Gremmeniella abietina*) attack and snow mould and thus decrease stress of trees growing close to the tree line.

Assessment of potential impacts on forest goods and services

Wood production. The projected climatic changes will lead to changes in productivity. At higher elevations growth of current forests will increase as a result of the extended growing season, as long as the sites are not limited in water availability. Secondary coniferous forests at low elevation sites in drought prone areas will suffer from decreased productivity and some conifer species may become unsuitable as a crop species. At higher elevations the set of suitable tree species and therefore the silvicultural decision space will increase due to increased competitiveness of broadleaved species under warmer climates.

Non-wood forest products. There is a lack of information available about impacts of climate change on non-wood forest products in mountain regions. However, a pilot study in the Pyrenees showed a positive correlation between fungal fruiting and the rainfall just before and during the autumn fruiting period.

Carbon sequestration. Due to enhanced productivity the forests in the European mountains are expected to maintain their function as a carbon sink – at least for the first half of the 21st century. For the second half, increasing respiration rates and more frequent disturbances are projected, and therefore the sink function will decrease, and forests may become a carbon source. Socio-economic conditions (demand for forest biomass, market prices) will also determine whether mountain forests remain a carbon sink or become a carbon source.

Biodiversity. Impacts of projected climatic changes on biodiversity are not yet studied sufficiently. In addition, actual species and habitat diversity will be strongly determined by changing disturbance regimes and management activities. Species-rich broadleaved forest communities will increase their potential area in the Alps and Carpathians. 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.

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 T may lead to leaching of nitrate.

Recreational use of forests. Not much targeted research has been devoted to the inter-relationships of forest composition and structure and the perception by tourists in a landscape context. Large-scale disturbances with increased tree mortality may negatively impact the recreation function of forests.

Protective function against natural hazards*.* Regarding the different natural hazards which play a major role in alpine environments, such as avalanches, debris flows, flooding, landslides and rock fall, different aspects influence the protective function. Because of this complexity and the fact that the hazardous processes themselves are also climate sensitive, it is difficult to directly address the impacts of climate change on the protective function of mountain forests. In general one might state that an increase in forest cover in alpine and subalpine zones enhances protective functions, due to prevention of erosion, runoff dampening, reduction of avalanche, etc. However, large-scale disturbances like fire and wind will make management of protection forests under climate change a challenge and will exert strong negative influences on protection functions.

Vulnerability and uncertainty

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. 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.

Full details can be found in section 4.2.5 of the report - Impacts of climate change on European forests and options for adaptation. Service Contract with DG Agriculture and Rural Development No. 30-CE-0163547/00-01. The report was compiled by the European Forest Institute (EFI) and its project partners BOKU, INRA and AISF.

Adaptive capacities of European forestry

The concept of adaptive capacity was introduced in the Third Assessment Report of the Intergovernmental Panel on Climate Change. The two components of adaptive capacity studied in the current project are: (i) the **inherent adaptive capacity** of trees and forest ecosystems; and (ii) the **socio-economic factors** determining the ability to implement planned adaptation measures.

Inherent adaptive capacity of forests

Inherent adaptive capacity is the evolutionary mechanisms and processes that enable species to adjust to new environmental conditions. A large body of results obtained mostly in provenance tests demonstrate that tree populations were substantially differentiated during the last 10,000 years. For example, specific populations are better suited for warmer and drier conditions than other populations of the same species. However, rather little is known about the pace of the evolutionary processes.

Bioclimatic envelopes of tree species are predicted to shift northwards and eastwards by about 100–500 km depending on the climatic scenarios and species. The sessile oak (*Quercus petraea)* example illustrates these predictions, and shows that in 2080 the climate in France may no longer be suitable for sessile oak (Figures 1 and 2). These predictions are based on the premise that there are no changes of the climatic requirements of the species, and no changes of the extant interactions among species. Despite their limitations and uncertainty, these figures allow identification of the evolutionary constraints that species will face due to new biotic and abiotic conditions. Exposed to climate change, populations have different response options, depending on the location of the population across the distribution range: local maintenance, dispersion, extirpation (i.e. local extinction) or extinction of the species. Modelling studies (e.g. bioclimatic envelopes) suggesting drastic shifts in the distribution of the species may be overly simplistic, as we anticipate that populations will undergo evolutionary changes enabling species to cope with environmental change. We identify different evolutionary mechanisms acting in different parts of the distribution.

Figure 1. Sessile oak (*Quercus petraea*). Photo: Yann Vitasse.

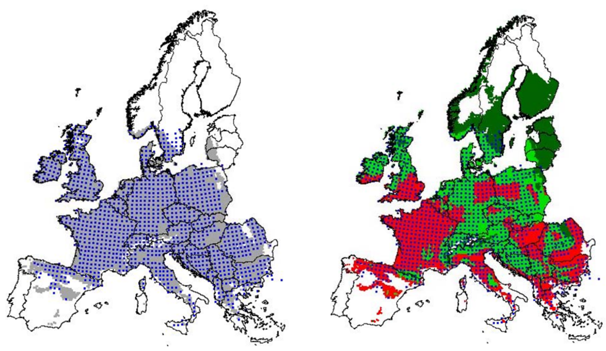


Figure 2. Observed and predicted species climatic envelope – example for sessile oak (*Quercus petraea*).
The map on the left shows the current distribution pf sessile oak, the map on the right shows the climatic envelope by 2080 under Climate model - HadCM3, Greenhouse gas emissions model - A1FI. Thuiller et al. 2005, Proceedings of the National Academy of Sciences 102:8245–8250.

- leading edge (gain of envelope)
- central range
- rear edge (loss of envelope)

Evolutionary mechanisms at the leading edge: Dispersion

Dispersion is the main mechanism by which species may colonize new suitable sites "offered" by global change. Rates of dispersion can be inferred from past migration velocities estimated from fossil records. For instance, beech (*Fagus sylvatica*) or oaks (*Quercus* spp.) would be able to shift their range from 10 to 70 km at maximum during the next hundred years, not taking into account that land fragmentation and agriculture may actually present obstacles to migration. Hence, natural dispersion would need to be assisted by artificial seed transfer to cope with the shifting bioclimatic envelopes.

Evolutionary mechanisms in the central range: Short-term adaptation

Results of translocation experiments in trees (provenances tests), i.e. experiments where populations were transplanted in different environments, indicate large genetic variations among populations, and that local adaptation occurs. Historically documented transfers during the past 2–3 centuries indicate that evolutionary change leading to adaptation can be rapid as a result of natural selection or individual tree plasticity (documented e.g. for Q. *robur* and *Q. petraea* in Europe). Long-distance pollen flow importing genes from southern latitudes may enhance and accelerate local adaptation in the central range of the species.

Inherent adaptive capacity of forests (cont.)

Evolutionary mechanisms at the rear edge: Short-term adaptation and plasticity
To avoid extirpation under southern latitudes where constraints will be most severe, tree species may exploit their large genetic or epigenetic diversity to respond to required shifts of fitness. Individual plasticity, although largely unknown or unexplored, will offer an immediate response to cope with these shifts. Lastly, migration at higher altitudes will allow species to stay at similar latitudes as observed for beech in the Pyrenees Mountains.

In conclusion, current knowledge demonstrates the importance of considering existing genetic variation among populations for recommending seed transfers into forest management planning. The opposite clines that were observed among species in provenance tests suggest that transfer recommendations have to be done on a species basis. High inherent adaptive capacities could allow tree populations to cope with currently projected climate change.

Socio-economic adaptive capacity

The socio-economic adaptive capacity is the ability of specified sectors, e.g. the forestry sector, to implement planned adaptation measures. Relative to the huge contrast between developed and less developed countries at the global scale, socio-economic conditions within Europe are similar. Nevertheless, there are significant differences in socio-economic conditions within the forest sector in Europe, and these will affect the adaptive capacity of the sector to respond to climate change.

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. The natural resource conditions are considerably different in large parts of southern Europe, where many forests on steep slopes have low potential for economic wood production and social values of forests are more important. The lack of economic activity in the forest sector is constraining adaptive capacity.

Forest ownership structures also influence adaptive capacity. Management traditions and decision-making structures are more variable in small privately owned forests compared to large, mainly 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. Measures to promote forest cooperation and active support from the public forest administration could help to alleviate the constraints. Without the measures, adaptive capacity is likely to be smaller in regions where the forest holdings are fragmented.

Availability or shortage of forest sector labour is another socio-economic factor that differs between the regions. Together with the education level of forest workers 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. However, when the target orientation in forest management is focusing on the potential natural vegetation of the 20th century only, this concept may constrain the adaptive capacity of the sector by excluding potentially productive species under the changing climate conditions of the 21st century.

Full details can be found in sections 5.1 and 5.2 of the report - Impacts of climate change on European forests and options for adaptation. Service Contract with DG Agriculture and Rural Development No. 30-CE-0163547/00-01. The report was compiled by the European Forest Institute (EFI) and its project partners BOKU, INRA and AISF.

Adaptation measures

Adaptation measures refer to adjustments in forestry in response to actual or expected climatic changes or their effects. The measures can be taken to reduce the impact of a particular risk or to exploit possible beneficial opportunities.

A questionnaire concerning on-going and planned adaptation measures in the European Union was distributed to EU27 member states via members of Standing Forestry Committee, and also to EFI associate member institutions which have made a contribution to climate change studies. The results were contrasted with the results of a 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 measures for forestry in the EU27 member states were developed.

The analysis of the responses revealed similar motives for adaptation measures across the bioclimatic regions. Three groups of motives for adaptation objectives were identified: (1) Minimizing impacts of disturbances; (2) Ensuring wood production; (3) Ensuring other ecosystem services.

Some of the measures conflict with one another and cannot be applied in the same stand. However, it is possible to combine different measures at larger spatial scales. When considering how to implement the recommendations it is therefore necessary to take a broad view and consider the overall objectives of multifunctional forest management. Similar measures may be listed both as on-going and planned due to variable implementation status in different countries or because the target of the measure is modified.

Level of Action	Type of Adaptation Actions
Stand level	• forest regeneration • tending and thinning of stands • harvesting
Forest management	• management planning • forest protection
Policy level	• infrastructure and transport • nurseries and forest tree breeding • Further adaptation integration in risk management and policy

In addition to the measures, the surveys also identified areas where research would be needed. These include research into: well-adapted tree species, provenances and genotypes; plasticity of tree species and populations; regeneration techniques; silvicultural treatments; harvesting techniques on non-frozen soils; protective role of forests; carbon sinks of forests; climate change impact on forest goods and services; risk of serious pests and diseases and on causalities of biotic forest disturbance; invasive new pests and diseases.

Minimizing the impacts of disturbance

Pests and pathogens

Climate change will affect the probability of disturbance by biotic and abiotic agents in forests in all bioclimatic zones. To cope with the increasing risk of endemic and novel insect pest outbreaks and fungal diseases, the development and implementation of adaptive silvicultural strategies and measures is required. Risk assessment, protective measures and pest control have to be key components in present and future forest management planning.

On-going measures	Planned measures
• Monitoring of pests and diseases • Prophylactic measures to decrease the risk of certain pests and diseases: o Use close-to-nature management to increase stability of forest ecosystems o Increase biodiversity of forests o Select tree species and provenances adapted to given site conditions and less vulnerable to biotic disturbance	• Monitor pest outbreaks, establishing monitoring networks and use of early warning systems • Prophylactic and adaptive measures to decrease the risk of specific pests and diseases: o Select tree species, provenances and genotypes which are more resistant to relevant biotic factors o Use close-to-nature management, promote diversity in species composition, stand age and structure o Shorten rotation; old forests are the most sensitive for biotic disturbances

• Measures to control insect pests and fungal diseases: o Implementation of sanitation measures (e.g. removal of logging residues or windthrown trees) • Use of biological insecticides	• Risk assessment, development and implementation of decision support systems • Control pests and pathogens

Forests may become more susceptibile to certain types of biotic disturbance. One example of disturbance that is predicted to become more common, are outbreaks of bark beetles.

- Recommended measures to reduce the risk of bark beetle outbreaks (*Ips typographus*):
  - Aim for high proportion of broadleaved and conifer species other than *Picea abies*
  - Avoid (over)maturity of stands of *Picea abies*
  - Avoid and monitor forest locations of high solar irradiation and increased temperature conditions (e.g. gaps, stand edges)
  - Implement sanitation measures, such as removal of windthrown or already infested trees
  - Improve accessibility of forest stands
  - Monitor for developmental status of bark beetles and population density

Drought

Rising temperatures without increase in precipitation or with decreasing rainfall lead to drought, especially in the Mediterranean and temperate continental zones.

On-going measures	Planned measures
• Select drought tolerant tree species, provenances or genotypes	• Shorten rotation; final felling at younger age • Reduce stand density to reduce competition for water

Fire

Risk of fire is highest in the Mediterranean zone, but the risk will also increase in other zones because of increasing of dry periods.

On-going measures	Planned measures
• Reduce fuel accumulation with suitable thinning methods • Use prescribed burning to reduce the fuel and therefore the risk of high-intensity wildfires • Select tree species which are less sensitive to fire • Make prevention plans • More networking with a broad range of actors	• Raise awareness about fire risks

Windthrow

Strong winds could increase with climate change in the Temperate Oceanic and Boreal zones.

<table>
<tr><td>On-going measures</td><td>Planned measures</td></tr>
<tr><td>• Improve resistance of stand structure
• Reduce the size of clear cut areas</td><td>• Implement forest edge management
• Use close-to-nature management</td></tr>
<tr><td colspan="2">Other possible measures</td></tr>
<tr><td colspan="2">• Shorten rotation; old forests are the most sensitive to strong winds
• Avoid open clear cut areas
• Select wind-firm species; avoid planting species with shallow rooting on sites susceptible to high winds and waterlogging</td></tr>
</table>

Ensuring wood production

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 as young seedlings and plants are particularly sensitive to drought or other extreme climatic conditions.

On-going measures	Planned measures
• Select tree species that perform well across sites • Select tree species that can develop into stable diversified forests • Select indigenous tree species and provenances • Mix different tree species, provenances and genotypes	• Use more natural regeneration • Select tree species and provenances that are more resistant to temperature extremes • Select fast-growing tree species

Tending and thinning

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 focus on the modification of tending and thinning practices, regarding the frequency and intensity of operations.

On-going measures	Planned measures
• Change silvicultural systems and thinning intensity to reduce risks of abiotic disturbances • Forbid thinning or change silvicultural systems in special conditions (e.g. slopes >40°; or where there are erosion problems; in avalanche corridors) • Change thinning methods for mixed and multistory forests	• Change thinning schedule and intensity to decrease risks of abiotic disturbances • Change thinning schedule for biomass harvesting • Use specific management for the forest edges to avoid risks of abiotic disturbances • Change management of stand for more stable and diverse stand structure • Change thinning intensity in the most sensitive areas

Harvesting

Harvesting 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.

On-going measures	Planned measures
• Modify harvesting procedures • Improve harvest equipment and tools for wet conditions • Use small-scale cutting areas • Execute sustainable harvesting	• Prefer selective cutting

Ensuring other ecosystem services

Humankind benefits from a multitude of resources and processes that are supplied by natural ecosystems. Forest ecosystem services include watershed protection, biodiversity conservation, and carbon storage. Other services of the forest ecosystems are cultural and recreational services. Significance of ecosystem services is the highest in the Mediterranean zone and the lowest in boreal zone.

Protective role of forests

Forests play an important role in the protection of soil, water, managed natural resources, and human infrastructure. In some areas, notably mountain areas, these functions override other functions.

On-going measures	Planned measures
• Use special thinning methods to decrease the risk of erosion • Plant suitable tree species at erosion areas • Limit thinning at erosion areas • Adjust afforestation activities to ensure water protection • Recognize and promote the protection role of forests	• Encourage soil preservation through afforestation and thinning investment • Combine water retention areas with recreational use

Biodiversity conservation

The forests of Europe are an important reservoir for biodiversity. In order to achieve goals of sustainability, the biodiversity of forests must be maintained.

On-going measures	Planned measures
• Develop species rich, robust forest edges • Support ecological corridors • Maintain old and dead trees • Prevent fragmentation of forests	• Establish forest refuges for threatened forest species • Change zoning of recreational areas in forests because of forest protection and threatened species • Create large forested areas to increase resilience and connectivity • Preserve biodiversity by maintaining natural processes and structures

Carbon storage

Forests are important in the global greenhouse gas balance and contribute to mitigating increasing atmospheric CO_2 concentrations by storing large amounts of carbon.

On-going measures	Planned measures
• Monitor and study of carbon fluxes and pools	• Encourage carbon storage through afforestation • Utilize tree species that increase carbon sequestration and produce biomass for energy • Substitute fossil fuel emissions by increased use of wood products

Cultural and recreational services

More than 90% of the forests in Europe are open to public access. This has shaped the way European forests look today.

On-going measures	Planned measures
•	• Limit tourist access to more fragile areas of forest under natural regeneration

Full details can be found in section 9 of the report - Impacts of climate change on European forests and options for adaptation. Service Contract with DG Agriculture and Rural Development No. 30-CE-0163547/00-01. The report was compiled by the European Forest Institute (EFI) and its project partners BOKU, INRA and AISF.