Chapter 3
Climate Change, Impacts, Adaptation and Risk Management

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Abstract Under the moderate future greenhouse gas emissions scenario (RCP4.5), climate model simulations project that the annual mean temperature will increase in Europe by up to 2–3 °C by the middle of this century, compared to the end of the nineteenth century. The temperature increase is projected to be larger in Northern Europe than in Central and Southern Europe. The annual precipitation is projected to decrease in Southern Europe and increase in Northern and Central Europe. The projected changes in temperature and precipitation are expected to be higher in the winter than in the summer months. In Northern Europe, forest growth is generally projected to increase due to warmer and longer growing seasons. In southern Europe in particular, warmer and dryer summers are projected to decrease forest growth. Climate change is expected also to expose forests and forestry to multiple abiotic and biotic risks throughout Europe. The greatest abiotic risks to forests are caused by windstorms, drought, forest fires and extreme snow loading on trees. The warmer climate will also increase biotic risks to forests, such as damage caused by European spruce bark beetle (*Ips typographus*) outbreaks in Norway spruce (*Picea abies*) forests and wood decay by *Heterobasidion* spp. root rot in Norway spruce and Scots pine (*Pinus sylvestris*) forests. Different adaptation and risk management actions may be needed, depending on geographical region and time span, in order to maintain forest resilience, which is also important for climate change mitigation.

Keywords Adaptive management · European forests · Forest resilience · Global greenhouse gas emission scenarios · Impacts of climate change · Natural disturbances

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3.1 Global Climate Change

3.1.1 Global Climate Change in the Past

During the four billion years of planet Earth's existence, global climate has fluctuated greatly. Basically, these variations have been controlled by the heat balance of the planet. Virtually all the energy that drives the climate system originates from the sun. Approximately 70% of the total incoming solar radiation is absorbed by the earth, whilst the remaining 30% is reflected back into space. The energy input from solar radiation is balanced by the emission of thermal infrared radiation into space. A major part of the thermal radiation emitted by the surface is absorbed and then re-emitted by the atmosphere before ending up in space. This phenomenon is known as the greenhouse effect. The effectiveness of the phenomenon depends on the concentrations of various gases in the atmosphere. The most important greenhouse gases are water vapour and carbon dioxide (CO_2). Methane, ozone, nitrous oxide and several other gases likewise have some importance. In the absence of the greenhouse effect, the average surface temperature on Earth would be about −18 °C, whereas the actual current global mean is +14 °C; that is, more than 30 °C higher than without the greenhouse effect.

Natural climate changes in the history of the earth have been caused by multiple factors. These include long-term variations in the solar radiance, changes in the composition of the atmosphere, continental drifts and volcanic eruptions. During the past few million years, the climate has mainly been relatively cool, and ice ages with milder interglacial periods have followed one another on time scales of 10,000–100,000 years. Such glacial–interglacial variations are primarily induced by changes in Earth's orbit and axis of rotation. In addition, such variations are amplified by synchronous shifts in atmospheric CO_2 concentrations.

Since the pre-industrial era (i.e. from the nineteenth century), the global mean temperature has increased by about 1 °C. Accordingly, over the last few centurieis and decades, global climate has changed very rapidly compared to the trends typically experienced over millions of years in the past. This is due to the large increase in human-induced emissions of greenhouse gases — especially CO_2 — into the atmosphere. The major source of anthropogenic CO_2 emissions is the combustion of fossil fuels, the use of which has increased tremendously in tandem with global energy consumption. Deforestation and other changes in land use have also contributed to such emissions, albeit to a lesser extent. During the 1980s, climate change became recognised as a serious challenge to humankind. In order to respond to this challenge, the United Nations (UN) endorsed the establishment of an Intergovernmental Panel on Climate Change (IPCC) in 1988 (Box 3.1).

Box 3.1 Intergovernmental Panel on Climate Change (IPCC)
The United Nations (UN) endorsed the establishment of IPCC during its General Assembly in 1988. The IPCC was set up under the UN Environment Programme (UNEP) and the World Meteorological Organization (WMO). The IPCC is an organisation of the governments that are members of the UN, with the number of members currently being 195. The objective of the IPCC is to provide state-of-the-art scientific information about climate change. Besides climate change as a phenomenon, the IPCC produces comprehensive reviews and recommendations about the social and economic impacts of such change, along with potential response strategies. Consequently, the IPCC plays a fundamental role in the international conventions on climate. Since 1988, the IPCC has published five comprehensive assessment reports concerning climate change. The Fifth Assessment Report (AR5), finalised in 2013–2014, provided the scientific input for the Paris Agreement. Further the Sixth Assessment cycle has provided three Special Reports, a Methodology Report and the Sixth Assessment Report. The first Special Report — '*Global warming of 1.5 °C*' — was requested by world governments under the Paris Agreement, and was published in October 2018. The '*Special Report on Climate Change and Land*' (SRCCL) was published in August 2019, and the '*Special Report on the Ocean and Cryosphere in a Changing Climate*' (SROCC) in September 2019.

The concentration of atmospheric CO_2 has increased from a pre-industrial level of 280 ppm (parts per million by volume) to about 410 ppm in 2019. Simultaneously, the concentration of methane has more than doubled. On the other hand, a concurrent increase in the amount of sulphates and other aerosol particles originating from anthropogenic emissions has partially compensated for the warming effect from the increasing greenhouse gas concentrations. Aerosol-induced cooling results from the increased reflectance of solar radiation back into space. Nevertheless, greenhouse gas concentrations will eventually overwhelm this phenomenon because they continue to accumulate in the atmosphere, whereas aerosol particles are continuously being washed out from the atmosphere. Current emissions of CO_2 will be influencing the atmospheric composition for several millennia.

3.1.2 Assessment of Future Global Climate Change

Projections of future climates are derived from simulations performed using global climate models (GCMs). These models simulate the behaviour of the climate system by means of the application of physical laws. Climate models include discrete components for the atmosphere, oceans, soil, vegetation and cryosphere, and also consider interactions among these subsystems. In assessing future climate, such models are forced using different atmospheric greenhouse gas concentration scenarios (Box 3.2). Climate models require large computational resources, and thus they need to be run on supercomputers. Even so, the available computational capacity does not allow the models to simulate all the processes of the climate system in full detail. Hence, simplifying approximations are necessary, and these simplifications are implemented in different ways in the various models. Consequently, simulated future climatic changes diverge among the models. To obtain the most realistic picture of anticipated future changes and their uncertainties, it is recommended to use a wide array of climate models rather than rely on only one or a few.

Figure 3.1 illustrates the global emissions and atmospheric concentrations of CO_2, as well as the modelled evolution of mean global warming, under three RCP scenarios (for further information about the RCP scenarios, see the Box 3.2). The changes in temperature are given relative to the temporal mean of the period 1971–2000. Prior to this period, the global mean temperature had already risen by about 0.5 °C. Under the RCP8.5 scenario, global warming would continue throughout the current century, and the global mean temperature would increase by almost 4 °C within 100 years. Under RCP4.5, the corresponding increase would be about 2 °C, whilst under RCP2.6, it would be slightly more than 1 °C. Considering the global warming already taking place before the baseline period of 1971–2000, the last scenario corresponds to a temperature increase of slightly less than 2 °C compared to the pre-industrial level. Regardless of future reductions in emissions, global warming will continue during the next few decades.

Compared to other regions on Earth, very intense warming has been simulated for northern polar areas in winter as a result of the partial disappearance of sea-ice cover. Conversely, in the northern Atlantic Ocean south of Iceland, warming will be modest because a weakening of the warm ocean current (the Gulf Stream) will

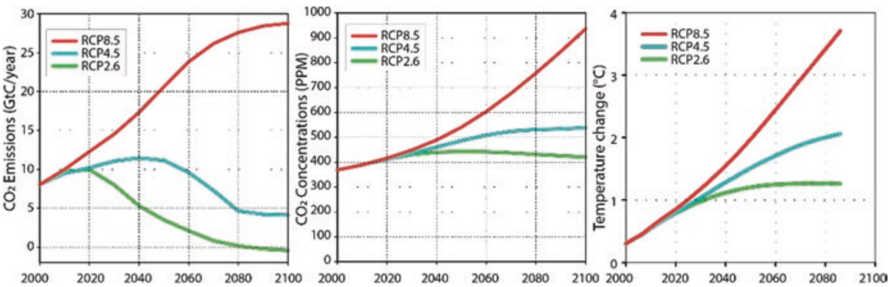

Fig. 3.1 Temporal evolution of global emissions in gigatonnes of carbon per year (left panel), atmospheric concentrations in parts per million by volume of CO_2 (central panel), and projected changes in global mean annual temperature in degrees Centigrade (right panel) for the period 2000–2085 under the RCP2.6, RCP4.5 and RCP8.5 scenarios. Temperature change is expressed relative to 1971–2000 and corresponds to the mean of simulations made using 28 different climate models (Ruosteenoja et al. 2016a; Venäläinen et al. 2020)

partially cancel the influence of global warming. Precipitation is projected to increase in equatorial areas. In addition, winter precipitation will increase at high latitudes. Decreasing precipitation totals are expected in multiple subtropical areas.

Globally, climate change will have multiple serious implications. In particular, the RCP8.5 scenario would lead to very severe climate change, with the consequences for many underdeveloped countries being catastrophic because agricultural production would suffer immensely from high temperatures and water shortages. This could lead to massive migrations from the developing world into wealthier countries. The rates of thermal expansion in ocean waters and the melting of continental glaciers and polar ice sheets would increase. The resulting sea-level rise would threaten numerous large coastal settlements and, consequently, a large proportion of Earth's population. In addition, the rapid environmental change would also threaten to drive a substantial share of the planet's plant and animal species to extinction.

Box 3.2 Representative Concentration Pathways (RCPs)

Future emissions, and the resulting atmospheric concentrations of the various greenhouse gases, cannot be known in advance, and therefore several alternative greenhouse gas scenarios have been developed. The emissions depend on the growth of the world population, energy consumption, energy production technologies, land use, etc. Since the IPCC's Fifth Assessment Report (AR5), future greenhouse gas scenarios called Representative Concentration Pathways (RCPs) have been used. The RCP2.6 scenario represents very low emissions, whilst RCP4.5 and RCP8.5 involve moderate and very high emissions, respectively. The number after the acronym refers to radiative forcing; that is, the imbalance between the solar radiation absorbed and the thermal infrared radiation emitted by the earth. For example, if the RCP4.5 scenario is realised, the positive (= warming) globally averaged radiative forcing at the end of the twenty-first century will be 4.5 Wm^{-2}. The RCP scenarios take account of the future emissions and atmospheric concentrations of several other greenhouse gases besides CO_2, as well as the aerosol particles. According to the RCP8.5 scenario, emissions would continue to increase throughout the twenty-first century, ultimately reaching three times the amount in 2000. The concentration of CO_2 would then approach 1000 ppm by 2100 (Fig. 3.1). In the RCP4.5 scenario, the CO_2 concentration would stabilise at close to 540 ppm. This level is about double that of the pre-industrial era. Under the most environmentally friendly RCP2.6 scenario, the concentrations would start to decrease slowly after the middle of this century. The RCP2.6 scenario would roughly meet the targets of the Paris Agreement. More information about the RCP scenarios is available in van Vuuren et al. (2011).

If the RCP2.6 scenario is realised, the consequences of the change will be far less severe than those resulting from RCP8.5. However, this target would require efficient reductions in global emissions starting right now, in the 2020s. This seems to be a huge challenge at present. Apart from the reduction in emissions, land-use changes, such as increasing or decreasing the share of forests, can impact greenhouse gas concentrations either adversely or favourably. Growing forests effectively absorbs CO_2 from the atmosphere. However, they also impact surface albedo, i.e. increasing albedo cooling the climate and decreasing albedo adding to the warming, respectively.

3.1.3 Projected Climate Change in Europe

In Europe, by the middle of this century, under RCP4.5, climate model simulations have projected the largest annual mean temperature increase — about 3 °C relative to the end of the nineteenth century — for the north-eastern part of the continent (Fig. 3.2). In Western Europe and along the coasts of the Mediterranean Sea, the projected warming is close to 2 °C. During the winter months, the warming in Northern Europe will be stronger than during the summer. Annual precipitation is projected to decrease in Southern Europe and increase in Northern and Central Europe. The maximum local annual changes would be around ±10%. The increase in precipitation in Northern Europe is projected to be the greatest in winter, whilst the decrease in precipitation will be the greatest in Southern Europe during summer.

The annual amount of solar radiation will increase across most of Europe. The largest increase — about 6% — is projected for Central Europe. Relative humidity is projected to decrease by 1–3 percentages. Temporal fluctuations in temperature will attenuate in the cold season, whereas fluctuations in precipitation will be amplified. Changes in their variability are expected to be strongest in the northern and north-eastern parts of the continent.

Under RCP4.5, the thermal growing season (defined as the period when daily mean temperatures are above 5 °C) is projected to lengthen by 10–15 days, both in the spring and autumn, from 1971–2000 to 2040—2069. Moreover, the temperature sum of the growing season is projected to increase by several hundreds of degree days. For example, around 2050, the average sum of growing degree days (GDDs, with base temperature of 5 °C) in southern Fennoscandia would be approximately the same as in northern Central Europe in the late twentieth century (Fig. 3.3).

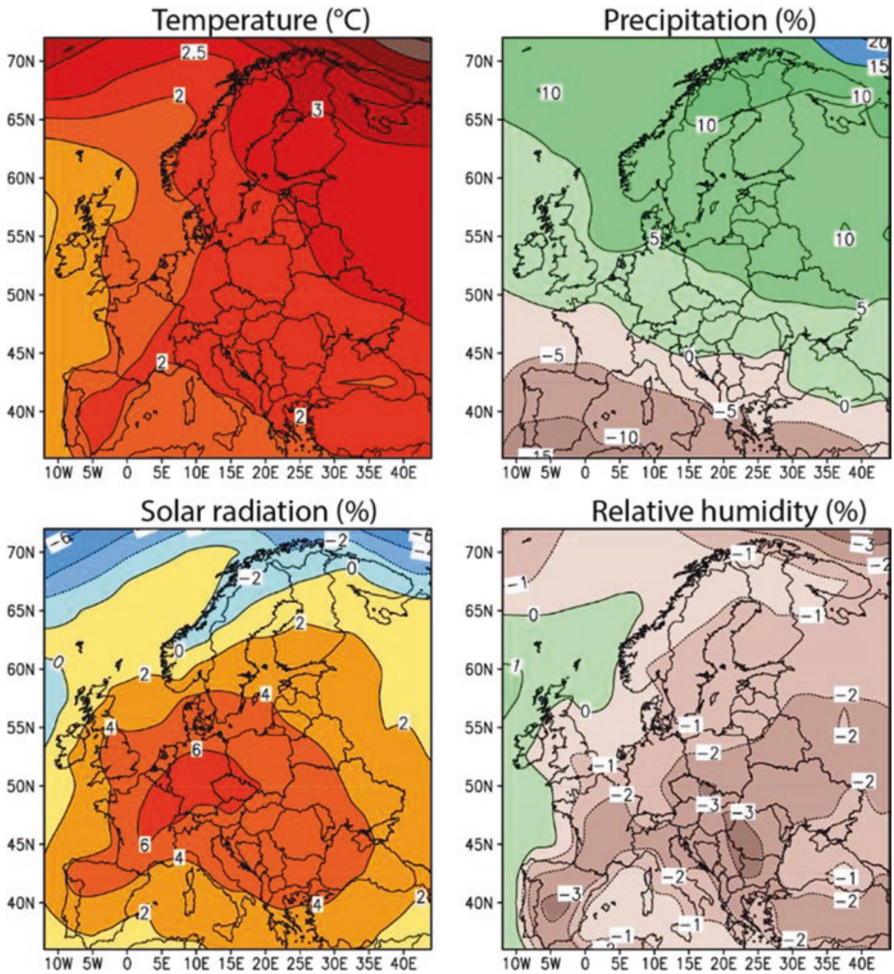

Fig. 3.2 Projected changes in annual mean temperature (°C), precipitation (%), incident solar radiation (%) and relative humidity (in percentage points) in Europe from the period 1971–2000 to 2040–2069 under RCP4.5 (Venäläinen et al. 2019)

3.2 Climate Change Impacts on Forests and Forestry

3.2.1 Forest Growth and Dynamics

Climate change is already having both direct and indirect effects on forests and forestry in different European regions. The direct effects include changes in the growing conditions of the forests due to changing temperatures, precipitation and atmospheric CO_2 concentrations. Indirect effects consist of various abiotic and biotic disturbances. In addition, land-use policy aimed at mitigating climate change

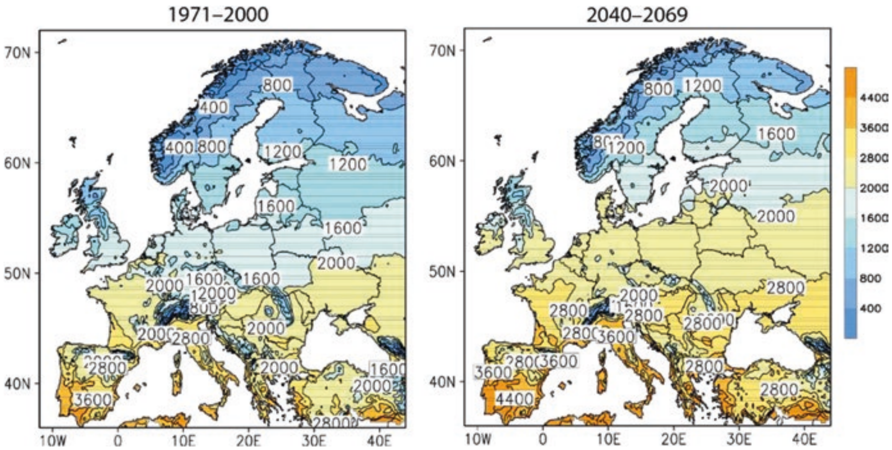

Fig. 3.3 Average sum of growing degree days (GDDs, with base temperature of 5 °C) for the period 1971–2000 and projection for the years 2040–2069 under RCP4.5 (redrawn from Ruosteenoja et al. 2016b)

can affect forests. As well as climate change and its severity, the future growth and dynamics of forests will be affected by the forest structure (i.e. the proportions and ages of tree species) and the intensity of forest management and harvesting (e.g. Heinonen et al. 2018). Climate change may have both positive and negative impacts on forest growth, such impacts depending on the geographical region and forest zone (European Environment Agency 2017).

In Northern Europe, longer and warmer growing seasons in general will promote more optimal forest growing conditions, especially in boreal forests at high latitudes and altitudes. This is because boreal forest growth is currently primarily limited by relatively short summers and low summer temperatures (Hyvönen et al. 2007). In addition, the increase in atmospheric CO_2 concentrations will favour forest growth (e.g. Hyvönen et al. 2007). In Southern Europe, but also to some extent in Central and Northern Europe, the growing conditions may become suboptimal for some tree species (Allen et al. 2010; Reyer et al. 2014). This is related to too high temperatures and too low soil water availability during the growing seasons. As a result, the growth of some tree species may slow down and mortality may increase. The differences in the responses among various tree species may be expected to increase in tandem with the severity of the climate change. In addition, the expected increase in many abiotic and biotic disturbances may counteract the positive effects of climate change on forest productivity, at least partially (Jactel et al. 2011; Reyer et al. 2017; Seidl et al. 2017).

3.2.2 Abiotic Disturbances

3.2.2.1 Wind and Snow Damage

During the last few decades, the major causes of widespread forest damage in Europe have been windstorms and forest fires (Schelhaas et al. 2003; Senf and Seidl 2021). In the period 1986–2016, storms were a major disturbance agent in Western and Central Europe, accounting locally for >50% of all disturbances (Senf and Seidl 2021). However, storm-related disturbances have also occurred in south-eastern and Eastern Europe. Fires have been a major disturbance agent in Southern and South-eastern Europe, but they have also occurred in Eastern and Northern Europe.

Strong winds have destroyed a significant amount of timber, causing substantial economic losses for forestry, especially in Central and Northern Europe. The increased amount of wind damage in the last few decades can be explained, at least partly, by an increasing volume of growing stock and changes in forest structures (Schelhaas et al. 2003). In Northern Europe, wind damage is likely to increase in the future because climate warming will shorten the duration of soil frost, which currently provides additional anchorage for trees during the windiest season of the year, from late autumn to early spring (Lehtonen et al. 2019). In addition, soil moisture is projected to increase in late autumn, likewise making forests more vulnerable to windfall.

According to multi-model-derived projections for European wind climate, climate change will not significantly alter the wind speeds in Northern Europe (Ruosteenoja et al. 2019). There is no robust signal of increasing or decreasing storminess in other European regions, either (e.g. Kjellström et al. 2018; Ruosteenoja et al. 2019). However, the projections for future trends in storminess diverge among the climate models (e.g. Feser et al. 2015). Accordingly, possible regional increases in the intensity of strong storms, changes in storm tracks, increasing growing stock and changes in forest structures (age and tree species composition) may affect the wind damage risks to forests.

Compared to the damage caused by windstorms, snow-induced damage in European forests is typically far less severe (Schelhaas et al. 2003). Snow-induced damage occurs most frequently in Northern Europe and at high altitudes (Nykänen et al. 1997). For most of Europe, climate model projections for the mid-twenty-first century indicate slightly decreasing probabilities for heavy snow loading. In northern Fennoscandia (e.g. northern and eastern Finland and north-western Russia), however, the probability of heavy snow loads may increase slightly (Groenemeijer et al. 2016; Lehtonen et al. 2016a). Excessive snow loads typically result in stem breakage and the bending or leaning of tree stems. In particular, young Scots pines (*Pinus sylvestris*) and broadleaf trees with a large height-to-stem-diameter ratio are susceptible to snow damage (Nykänen et al. 1997). With unfrozen soil, trees can be uprooted. The increase in duration of frost-free periods is expected to increase such damage under the warming climate.

In addition to climatic factors, the severity of wind and snow damage risk is affected by the tree and stand characteristics (tree species, height and diameter, rooting characteristics, and stand density) and the forest configuration (e.g. the distance from the upwind edge of a new clearcut). For example, in high-risk areas of the boreal zone, an increase in the cultivation of the shallow-rooted Norway spruce (*Picea abies*) at the cost of Scots pine will increase the future wind damage risk (Ikonen et al. 2020). Conversely, an increase in the cultivation of pine and broadleaf trees will increase the future snow damage risk (Nykänen et al. 1997). Trees damaged by wind or snow may also bend over or lean on power lines, and thus may disrupt the availability of electricity to society.

3.2.2.2 Drought and Forest Fires

Global climate change is expected to increase the occurrence of summer drought everywhere in Europe, most severely in the south, but to some extent in the north as well. This increasing drought will be caused by an intensification in potential evaporation, which will outweigh the impact of changes in precipitation. In Northern Europe, the average moisture in the soil surface layer will decrease, especially in spring and early summer, whereas in Southern Europe, the loss will be most pronounced in late summer (Fig. 3.4). Consequently, anomalously dry conditions are projected to become increasingly frequent in European forests (Ruosteenoja et al. 2018). Accordingly, at sites with water shortages, in particular, forest growth is

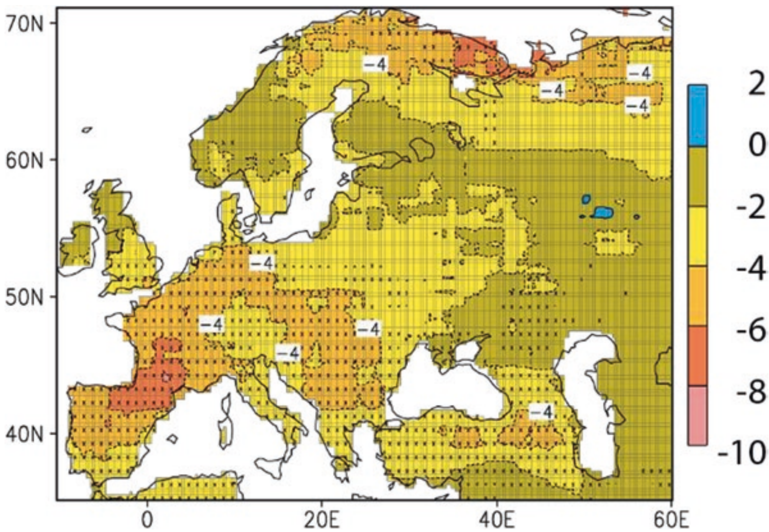

Fig. 3.4 Projected changes in time-mean near-surface soil moisture (in percentage points) in Europe in June–August under RCP4.5 for the period 2040–2069. The change was averaged over 26 GCMs and is expressed relative to the period 1971–2000. Areas where at least 23 models agreed on the sign of change are stippled (Ruosteenoja et al. 2018)

expected to decline and mortality to increase under a warmer climate (Allen et al. 2010).

High temperatures and an increase in the frequency and severity of summer drought periods will act to increase the risk of forest fires. This phenomenon has already been observed, particularly in South-eastern Europe (Venäläinen et al. 2014). The widespread, devastating fires in Sweden in the summers of 2014 and 2018 showed that large-scale forest fires are possible in the Nordic countries as well. For example, a single fire in Sweden in 2014 burned 14,000 ha of forest (Joint Research Centre 2015).

In the southern parts of Europe, the meteorological fire danger is projected to increase significantly by the middle of this century (e.g. Groenemeijer et al. 2016). It is likely that the fire danger will likewise increase in Northern Europe (Lehtonen et al. 2016b). In semi-arid areas, such as the Mediterranean region, low vegetation productivity may limit these fires, and therefore the actual occurrence of fires may increase less drastically than what is predicted by the changing weather conditions alone. However, even when considering ecosystem functioning, the area burned is still likely to increase, especially in the Mediterranean Basin, the Balkan region and Eastern Europe (Migliavacca et al. 2013; Turco et al. 2018). Under a warmer and dryer climate, there may be an increasing risk for mega-scale forest fires in European forests, such as those that have recently occurred in Canada and Siberia (e.g. Hanes et al. 2019; Walker et al. 2019). Such disturbances could release huge amounts of stored carbon into the atmosphere, thus nullifying the potential positive impact on climate change on carbon sequestration in forests.

3.2.3 Biotic Disturbances

3.2.3.1 European Spruce Bark Beetle Outbreaks

In recent decades, disturbances from bark beetles have greatly increased in Europe. The amount of timber damaged by bark beetles in spruce and pine forest has increased by nearly 70% over the last 40 years, from 2.2 million m^3 per year (1971–1980) to 14.5 million m^3 per year (2002–2010) (Seidl et al. 2014). The planting of Norway spruce outside of its natural range (and on sites with lower soil water holding capacity), an increase in growing stocks, and changes in forest age structures and compositions have made forests more prone to bark beetle outbreaks (Hlásny et al. 2019; Jandl 2020). In addition to warm and dry summer conditions, severe wind damage and drought also intensify bark beetle outbreaks (Marini et al. 2017).

The primary bark beetle species in Europe responsible for outbreaks is the widely distributed, eight-toothed European spruce bark beetle (*Ips typographus*) (e.g. Christiansen and Bakke 1988). At low population levels, it colonises only stressed and dying trees (e.g. wind-damaged Norway spruce). However, at high population levels, it can mount a mass attack on a large number of healthy trees. European spruce bark beetle particularly favours older and larger trees (e.g. aged >60 years, diameter at breast height > 20–25 cm) (Hlásny et al. 2019). European spruce bark beetle outbreaks have largely increased in recent years in Europe (Hlásny et al. 2019, 2021; Jandl 2020; Romashkin et al. 2020). For example, in Czechia in 2017, in an unforeseen, severe outbreak, the amount of damaged timber exceeded the annual demand at the country level, collapsing the timber market and prices, respectively. In Austria over the last decade, the high supply of beetle-infested timber has reduced the market price for bark beetle affected timber to 30% of the previous level (Jandl 2020). In Sweden, a European spruce bark beetle outbreak damaged an additional 4 million m^3 of timber after windstorm Gudrun, which damaged 70 million m^3 of timber in January 2005 (Lindelöw and Schroeder 2008).

The survival and reproduction of European spruce bark beetle benefit from warmer and dryer climates, and thus also from climate warming (Christiansen and Bakke 1988; Jönsson et al. 2007; Lindelöw and Schroeder 2008; Hlásny et al. 2019; Jandl 2020). Under optimal conditions, bark beetle populations can increase more than 15-fold from one generation to the next (Hlásny et al. 2019). It can also produce two generations (multivoltinism) in one summer, if swarming conditions are favourable early in the season, and the sum of GDDs exceeds approximately 1500 °C days, which is twice the GDD sum needed for the complete development of an individual, from egg to adult (625–750 GDDs) (Jönsson et al. 2007). Moreover, the number of successfully developed beetles in different sister broods of the first generation increase with an increase in GDD sum (Öhrn et al. 2014). In warm areas of the southern part of the species distribution region, a third generation may also be possible (Jakoby et al. 2019).

Lower GDDs currently partially explain the lower bark beetle outbreak risk in Northern Europe compared with more southerly areas. However, the 1500 GDD isoline that potentially allows a change from univoltine (i.e. a single generation in summer) to multivoltine population dynamics is moving northwards. For example, in European Russia, the latitudinal shift of the isoline that indicates the northern limit of 1500 GDD has moved 450 km northwards since the 1960s (Romashkin et al. 2020).

Based on Asikainen et al. (2019), the probability of exceeding the GDD sum of a 1500 °C-day threshold will increase in Northern Europe under climate change. Recent warmer and drier summers, together with unharvested wood left in forests after wind damage, have already increased the populations and attacks of bark beetles in the southern boreal zone, and even in middle boreal zone (Romashkin et al. 2020). Overall, European spruce bark beetle outbreaks are projected to increase in the future, under warmer and drier climates, from Central to Northern Europe (Jönssön et al. 2007; Seidl et al. 2014).

3.2.3.2 Other Biotic Threats to Forest Health

European spruce bark beetle is currently the most obvious biotic damage agent in European forests, outbreaks of which have markedly increased with climate warming. However, climate change also affects the reproduction, growth, behaviour and potential distribution range of other species that can cause problems with forest health. Thus, disturbances by several other major forest pathogens, pest insects and browsing mammal species are also expected to increase in European forests.

In Northern Europe, *Heterobasidion* spp. root rot is already one of the most destructive diseases in conifers (Garbelotto and Gonthier 2013). However, increasing temperatures are further increasing its spore formation and the growth rate of its mycelia. Milder winters increase the length of the period the fungus is able to spread and infect new stands (La Porta et al. 2008). Together, these intensify the amount of decay in infected trees and the spread of fungus in diseased stands.

The epiphytic, parasitic vascular plant, pine mistletoe (*Viscum album* ssp. *austriacum*), is also increasing in abundance at its current northern limit, such as in Germany and Poland, and is spreading upwards into the montane forests of Europe (Szmidla et al. 2019). This is probably the result of increasing winter temperatures in areas where pine mistletoe has previously been limited by the low freeze tolerance of its seeds. Abundant mistletoe populations reduce tree growth substantially and, in dry areas, they also increase water stress and tree mortality (Kollas et al. 2018).

Higher temperatures are likely to promote distributional shifts in many native forest pest-insect species and invasive alien species towards more northerly latitudes and higher elevations (Battisti and Larsson 2015). Frequent cold winters in Northern Europe have so far limited outbreaks of many insect defoliators that overwinter as eggs. However, an increase in winter temperatures will favour their reproduction and, concurrently, may increase the risk from these in the future. Nun moth (*Lymantria monacha*), one of the most serious defoliators of coniferous forests in Central Europe (Bejer 1988), is a good example. Previously cold winters have controlled nun moth populations in Northern Europe because its eggs freeze in temperatures below −30 °C (Fält-Nardmann et al. 2018). The species has been historically absent or very rare in Finland, but since the 1990s, its populations have increased hugely, and it is now very abundant in the southern part of the country (Melin et al. 2020).

In Southern Europe, heat-tolerant and cold-sensitive species, such as the pine processionary moth (*Thaumetopoea pityocampa)* and the oak processionary moth (*Thaumetopoea processionea)* have expanded their geographical ranges beyond the Mediterranean region (Battisti et al. 2005; Godefroid et al. 2020). Processionary moths damage not only trees, but their larvae have defensive hairs (urticating setae that the larvae release when disturbed) that can cause allergic reactions in humans (Vega et al. 2011). Therefore, the processionary moth is considered to be a threat to human health when present in urban forests and parks (Rossi et al. 2016).

The warming climate is increasing problems relating to the regeneration of coniferous forests in Europe by, for example, the large pine weevil (*Hylobius* *abietis*) (Nordlander et al. 2017). This is because warmer summers and a shortening of the frozen soil period is decreasing the development time of immature weevils, increasing their feeding time and prolonging the feeding period. Browsing by high local populations of moose (*Alces alces*) is also a serious problem in young Scots pine and birch seedling stands in Northern Europe. The expected reduction in snow depth and duration may increase the severity of browsing damage (e.g. Herfindal et al. 2015).

3.3 Climate Change, Adaptation and Risk Management

Forests should provide multiple ecosystem services for society. However, climate change is inducing many abiotic and biotic damage risks in forests and forestry at different spatial and temporal scales, all of which affect the provisioning of ecosystem services. Warmer and drier summer conditions particularly increase the risk of damage by drought, forest fires and pest insects, while warmer and wetter winters increase the risk of damage by windstorms and strong winds, heavy snow loading and pathogens (Seidl et al. 2017). Such disturbances are likely to increase the most in coniferous forests in the boreal zone. They may partially counteract the positive effects of climate change on forest productivity, causing severe economic losses in forests (Hanewinkel et al. 2013; Reyer et al. 2017).

The simultaneous occurrence of multiple hazardous events can make the adverse impacts manifold (Hanewinkel et al. 2013; Venäläinen et al. 2020; Hlásny et al. 2019). Wind and snow damage in particular, but also the occurrence of drought, may increase the availability of breeding material for bark beetles, thus enhancing their outbreaks. The drought may further influence the forest fire risk through increased tree mortality (e.g. Jenkins et al. 2014). Wind and snow damage may also increase *Heterobasidion* spp. attacks through tree injuries from harvesting, which will then exacerbate the risk of wind damage due to poorer anchorage and less stem resistance in decaying-wood trees.

How vulnerable forests are to climate change and the associated increase in various abiotic and biotic disturbances depends on the exposure (e.g. the severity of the climate change, the climate variability and its extremes), sensitivity and adaptive capacity of forests. Fortunately, adaptive forest management can offer ways to increase the resilience of forests to climate change and its related disturbances. The severity of climate change will affect the necessary adaptation and risk management actions for different regions and time spans. In adaptation and risk management, the occurrence of multiple hazardous events should be considered simultaneously in order to ensure the sustainable provisioning of different ecosystem services for society. Fortunately, the same management measures may simultaneously enhance the resilience of forests against multiple abiotic and biotic disturbances (Table 3.1).

The resilience of forests against different abiotic and biotic disturbances may be increased, for example, by modifying the age structure and tree species composition at the forest landscape level through forest management. In forest regeneration, the

Table 3.1 Possible adaptive and risk management strategies

Possible management strategies for enhancing resilience
High temperature/drought • region–/site-specific species/genotype choice • natural regeneration where appropriate • mixed conifer–deciduous stands • wider spacing and heavier thinning regimes • shorter rotation periods (or lower target diameters for final harvesting)
Wind damage • region–/site-specific species choice • timely pre-commercial and commercial thinning (not too heavy) • avoidance of forest fertilisation at the same time as thinning • avoidance of heavy thinning in the upwind edges of new openings • avoidance of creating large height differences between adjacent stands in final harvesting
Snow damage • region–/site-specific species choice • timely pre-commercial and commercial thinning (not too heavy in dense stands) • avoidance of forest fertilisation on sites at high altitudes (>200 m a.s.l.)
Bark beetle outbreak • mixed conifer–deciduous stands • timely thinning to improve tree vigour (outbreak prevention) • shorter rotation periods (or lower target diameters) • harvesting of infested trees (sanitation felling and salvage logging) • removal of harvested and wind-damaged trees before beetles fly in spring/emergence of first new beetle generation • mosaic of forest stands in forest landscapes to minimise spread of beetles
***Heterobasidion* root rot** • mixed conifer–deciduous stands • shorter rotation periods (or lower target diameters for final harvesting) • harvesting of unhealthy trees
Forest fires • fragmented forest landscape to limit fire spread • timely thinning to avoid mortality (decrease in flammable material)

appropriate region- and site-specific choice of tree species (genotypes) and spacing may increase the adaptive capacity and resilience of the forest in the long term. Similarly, favouring more resilient tree species in pre-commercial (tending) and commercial thinning may increase the resilience of the forest. By favouring mixtures of conifers and broadleaf species over monocultures on suitable sites, their resilience may be further increased against many abiotic and biotic risks to forests (e.g. Pretzsh et al. 2017). For example, the wind damage risk in forests with shallow-rooting Norway spruce are well known throughout Europe (Jandl 2020). Overall, single-species forests offer pests and pathogens more opportunities for spreading than mixed stands, where tree species have different ecological niches. The latter scenario provides, for example, fewer host trees for a bark beetle outbreak and could also host larger populations of their natural enemies and competitors, etc. (Hlásny et al. 2019). The use of greater thinning intensity or wider spacing increases water availability at the tree level in a stand, which may decrease drought stress in trees, and its consequent damage.

The avoidance of fertilisation in high-altitude forest sites, especially in relation to thinning, may decrease the snow damage risk to boreal forests (e.g. Valinger and Lundqvist 1992; Nykänen et al. 1997). Furthermore, the use of shorter rotation periods or lower target diameters for final harvesting may decrease the risk of damage by windstorms and strong winds, pest insects (e.g. bark beetles) and pathogens (e.g. wood decay by *Heterobasidion*), for example, in Norway spruce, which is particularly sensitive to such damage. The increase in risk of large-scale forest fires during summer droughts (Ruosteenoja et al. 2018) must also be considered in the timing of forest harvesting operations because the sparks generated by the machinery used in such activities may result in the ignition of forest fires.

Uncertainties relating to climate change, forest disturbances and the future preferences of society call for the simultaneous use of diverse management strategies, rather than a single, one-size-fits-all management strategy (e.g. even-, uneven- and any-aged management), which might also help to increase the overall production levels of ecosystem services (Díaz-Yáñez et al. 2020). Multi-functionality in forest management may also ensure the simultaneous provisioning of different ecosystem services for society, whilst increasing the resilience of forests against abiotic and biotic disturbances. However, the frequent adjustment of forest management practices (e.g. 10–20-year frequency) to changing growing conditions is also needed in order to adapt to climate change and maintain forest resilience, which are required to sustain the provisioning of different ecosystem services. On the other hand, climate change may increase large-scale forest fire and pest insect occurrences in unmanaged, mature forests (e.g. in forest conservation areas) due to the increased tree mortality that will result from warmer and drier climates. As a result, these disturbances may also spread to managed forests. Thus, preparedness for such risks should be increased in society.

Overall, the challenge of dealing with climate change-induced disturbances in forest management and forestry is pan-European (Jandl 2020). Different adaptation and risk management actions may be needed, depending on geographical region and time span, to maintain the sustainable provisioning of different ecosystem services for society, and to increase the forest resilience. The role of forests in climate change mitigation should also be considered in adaptation and risk management. This is because forests contribute greatly to climate change mitigation through sequestering carbon from the atmosphere and storing it in forest ecosystems and wood-based products, the latter also substituting for fossil-intensive resources (Kauppi et al. 2018). The intensity of forest management practices and the severity of natural disturbances may significantly affect the carbon sequestration (and stock) in forests as a result of changes in forest structure (e.g. age and tree species composition). Consequently, changes in forest structure will indirectly affect climate regulation through changes in forest albedo and latent heat fluxes, biogenic volatile organic compounds and aerosols (e.g. Thom et al. 2017).

3.4 Research Implications

There are large uncertainties in predicting future climate and its impacts on European forests and forestry. This is due to uncertainties in global developments in future greenhouse gas emissions, which are greatly affected by the level of success of climate change mitigation. Therefore, such uncertainties should be considered in climate change impact and adaptation studies, by using several alternative climate projections in simulation-based scenario analyses. In order to define climate-smart (and adaptive) risk management strategies, there is a need for a more holistic understanding of how the prevailing climatic conditions, forest structure, forest management (strategies) and severity of climate change, together with the associated increases in natural disturbances, may affect the provisioning of multiple ecosystem services (e.g. timber, biodiversity and the recreational values of forests) and climate regulation for different geographical regions and time spans. Climate change will affect, in addition to the physiological conditions of trees and tree defence mechanisms against natural enemies, the distribution and population dynamics of those enemies, and this needs to be understood in greater detail. In the current world of uncertainty, we should seek different ways to simultaneously improve the provisioning of different ecosystem services for society, the resilience of forests and their climate benefits.

3.5 Key Messages

- There are large uncertainties in the projected climate change and its impacts on European forests and forestry for different regions and time spans, due to large uncertainties in the level of success of climate change mitigation efforts.
- In general, forest growth is projected to increase in Northern Europe, as opposed to Southern Europe.
- Climate change may induce multiple abiotic and biotic damage risks in forests and forestry throughout Europe via windstorms, drought, forest fires, bark beetle outbreaks and wood-decaying fungus diseases.
- The uncertainties relating to climate change and the increasing multiple risks to forests and forestry should be considered when adapting forest management and forestry to climate change in order to increase the resilience of forests against different abiotic and biotic disturbances.
- The necessary adaptation and risk management measures may differ, depending on geographical region and time span.

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