Food and Agriculture Organization of the United Nations

UNECE

THE OUTLOOK FOR THE UNECE FOREST SECTOR IN A CHANGING CLIMATE

A CONTRIBUTION TO THE FOREST SECTOR OUTLOOK STUDY 2020-2040

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The Outlook for the Unece Forest Sector in a Changing Climate A Contribution to the Forest Sector Outlook Study 2020-2040

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ABSTRACT

This Discussion Paper is a background document to the Forest Sector Outlook Study 2020-2040 (FSOS) for the UNECE region (ECE/TIM/SP/51). It provides the details that are summarized in chapter 4 of the main study. This Discussion Paper provides a comprehensive overview of how forests might be affected in the UNECE region and its five different subregions, how forests might help climate mitigation, and how forest management may need to adapt to changing conditions. Climate change impacts on forests will be profound: extended, warmer growing seasons and higher levels of atmospheric CO_2, might enhance productivity, but more frequent and severe events, such as drought or storms could increase the likelihood of fire, outbreaks of pests, and disease. The study applies the Global Forest Products Model to projects the effects of climate change and higher levels of greenhouse gases on forest stocks in the UNECE region and globally, as well as the potential impacts on global roundwood prices, production, and the consumption and trade of wood products. It analyses how carbon stocks may evolve under different assumptions of economic growth, population growth, and climate change and covers the years 2020-2040, starting with 2017 as the base year for projections

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This Discussion Paper and the *Forest Sector Outlook Study 2020-2040* are the result of a cooperative effort involving a network of authors, reviewers, editors, the UNECE/FAO Team of Specialists on Forest Sector Outlook, and the Joint UNECE/FAO Forestry and Timber Section in Geneva as well as FAO in Rome. In combination, this network provided an unrivalled source of expertise and knowledge, which is the hallmark of the *Outlook Study*, including this Discussion Paper. The UNECE/FAO Forestry and Timber Section would like to express its gratitude to the individuals and organizations who contributed their time, expertise, and resources to this Discussion Paper and the *Forest Sector Outlook Study 2020-2040*.

Douglas Clark edited the Discussion Paper.

The study was managed by the UNECE/FAO Forestry and Timber Section and reviewed by the FAO.

This manuscript was completed on 12 November 2021.

EXPLANATORY NOTES

This Discussion Paper presents the detailed research, analysis and findings that were used to develop chapter 4 of the UNECE/FAO *Forest Sector Outlook Study 2020-2040*

For ease of reading, the publication mostly provides value data in United States dollars (indicated by the sign "$" or as "dollars").

See list of countries in the annex for a breakdown of the UNECE region into its subregions. When "Europe" or "EU" is mentioned in connection with a reference, i.e., not as part of the modelling analysis, then it refers to the group of countries as defined by the reference. The term Eastern Europe, Caucasus and Central Asia (EECCA) is used for reasons of geographic proximity and similarities in economic structure and refers collectively to 12 countries: Armenia, Azerbaijan, Belarus, Georgia, Kazakhstan, Kyrgyzstan, Republic of Moldova, Tajikistan, Turkmenistan, Ukraine and Uzbekistan. It is used solely for the reader's convenience. The Russian Federation, normally included in the country group of the EECCA, is referred to separately due to the model setup and importance of the Russian Federation in the global context.

The term industrial roundwood is used interchangeably with logs.

All references to tonnes in this text represent the metric unit of 1,000 kilograms unless otherwise indicated.

A billion refers to a thousand million (10^9). One trillion refers to one million million, or 10^{12}.

Nonwood forest products are part of the broader concept of the provision of ecosystem services through forests. However, due to limitations in resources available and guidance received by member States and the necessity of focusing on the six questions identified at the beginning of the process. The study was not able to assess the impact of future trends on important services and products such as e.g., honey, medicinal plants, nuts, fruits, mushrooms, pollination, erosion prevention, etc. In some regions of the UNECE, these goods and services may exceed the social and economic value of wood and wood products from forests.

This publication refers to the publication UNECE/FAO (2011) *The European Forest Sector Outlook Study II: 2010 – 2030* as "the Outlook" or "this Outlook".

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List of Acronyms and Abbreviations

(Infrequently used abbreviations spelled out in the text may not be listed here)

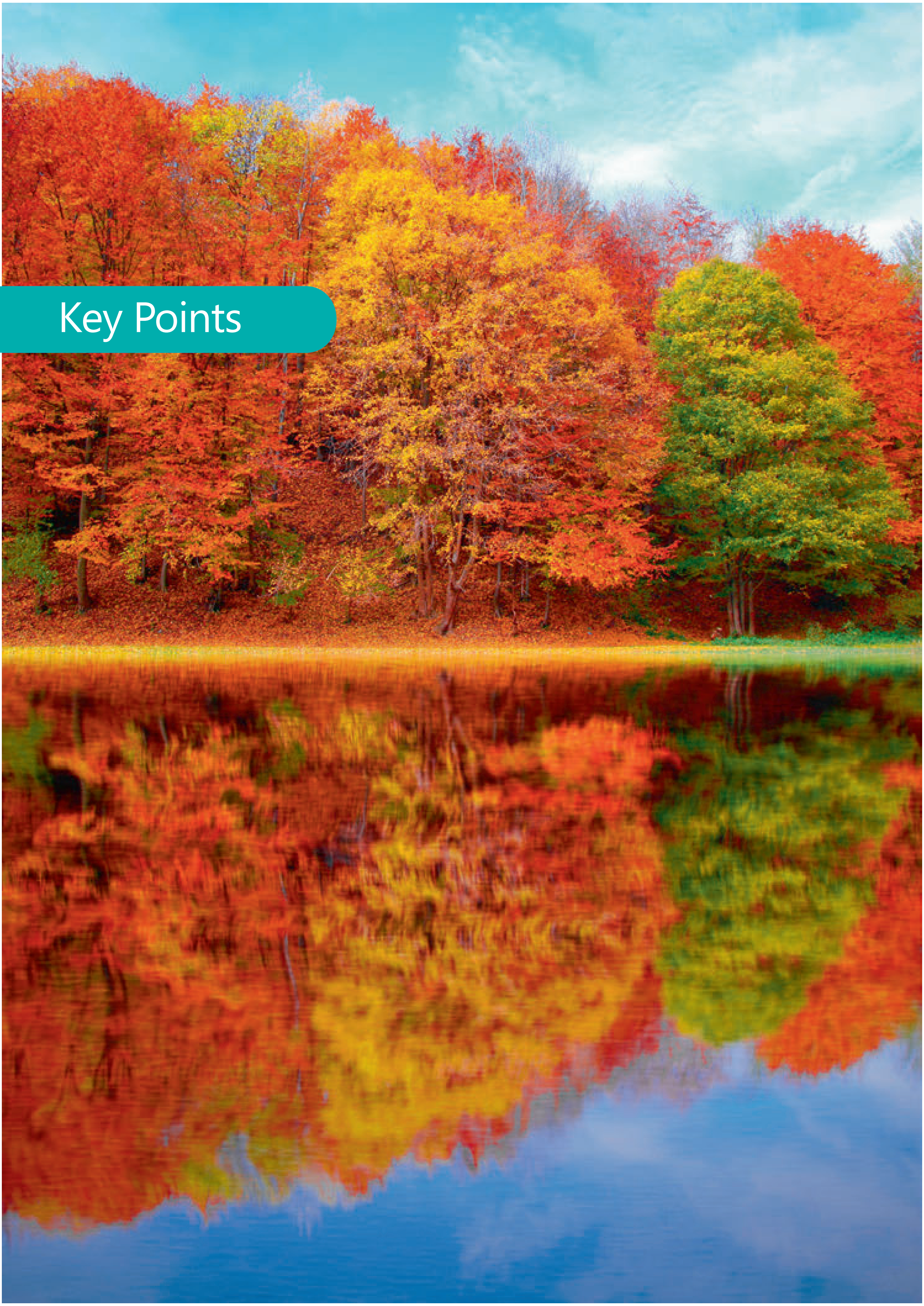
$	United States dollar(s) unless otherwise specified
°C	degrees Celcius
China-HWC	China-High Wood Consumption
CLT	Cross Laminated Timber
CO_2	Carbon dioxide
CSF	Climate-Smart Forestry
EECCA	Eastern Europe, Caucasus and Central Asia
EFSOS	European Forest Sector Outlook Study
EU	European Union
Europe-HWC	Europe-High Wood Consumption
FAO	Food and Agriculture Organization of the United Nations
FRA	Global Forest Resources Assessment
GDP	Gross Domestic Product
GFPM	Global Forest Products Model
GHG	Greenhouse Gas
ha	hectare(s)
HFA	High Forest Area Scenario
HWC	High Wood Consumption
HWFC	High Wood Fibre Consumption
HWP	Harvested Wood Products
IPCC	Intergovernmental Panel on Climate Change
IUCN	International Union for Conservation of Nature
Kg	kilogram
LVL	Laminated Veneer Lumber
m^2	square metre(s)
m^3	cubic metre(s)
n.a.	Not Applicable
NPP	Net Primary Productivity
NYDF	New York Declaration on Forests
OECD	Organization for Economic Co-operation and Development
RCP	Representative Concentration Pathways
RED	Renewable Energy Directive
SSP	Shared Socioeconomic Pathways
tC	metric tonnes of carbon
tCO_2e	metric tonnes of carbon dioxide equivalent
Textile-HFWC	The Textile-High Wood Fibre Consumption
UN	United Nations
UNECE	United Nations Economic Commission for Europe
UNFCCC	United Nations Framework Convention on Climate Change
US	United States of America
USDA	United States Department of Agriculture

Note to the reader about this "Forest Sector Outlook Study 2020-2040" Discussion Paper

This Discussion Paper presents the detailed analysis and findings on the outlook for the UNECE forest sector in a changing climate based on analysis modelling conducted for the preparation of the "Forest Sector Outlook Study 2020-2040" (UNECE/FAO, 2021). Chapter 4 of the "Forest Sector Outlook Study 2020-2040" was drafted based on the analysis and findings presented in this Discussion Paper.

The detailed methodology for the Forest Sector Outlook Study, including the methodology used in this Discussion Paper, is presented in the companion publication "Detailed Methodology for the Preparation of the Forest Sector Outlook Study 2020-2040" (UNECE/FAO, 2022a). A detailed analysis of structural changes in the forest sector and their long-term consequences for the forest sector is presented in another companion publication, "Structural Changes in the Forest Sector and their Long-Term Consequences for the Forest Sector" (UNECE/FAO, 2022b).

Key Points



Key Points

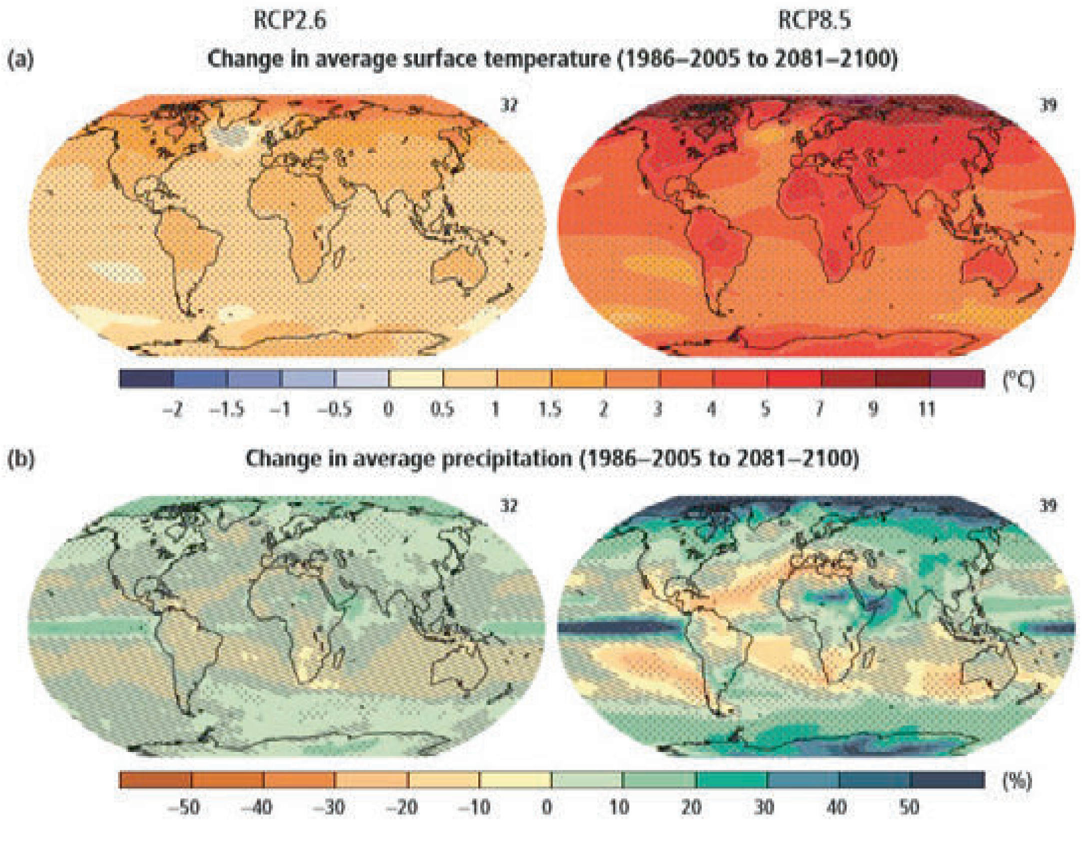
- Climate change impacts on forests will be profound: extended, warmer growing seasons and higher levels of atmospheric CO_2, might enhance productivity, but more frequent and severe events, such as drought or storms could increase the likelihood of fire, outbreaks of pests, and disease.
- The GFPM model projects the effects of climate change and higher levels of greenhouse gases on forest stocks in the UNECE region and globally, as well as the potential impacts on global roundwood prices, production, and the consumption and trade of wood products.
- Forests help to mitigate climate change and the study projects rising carbon storage, with forests being net carbon sinks.
- This average carbon sink is projected to be 1.5 billion tCO2e per year over the period of this study. Increasing global forest area by 10% by 2040 would sequester an additional 1.43 billion tCO_2e per year in the UNECE region.
- Increased wood removals to substitute fossil-based alternatives in textile manufacture and wood construction were projected to be nearly carbon neutral.
- The benefits of substitution would be enhanced by replacing the most carbon-intensive materials with wood products, and by improving manufacturing efficiency.
- Adaptive management of forests will be crucial to maintain the broad range of ecosystem services that forests provide.
- Climate change impacts might also present windows of opportunity for adaptation by diversifying forest structure and species mix.

1 Introduction

Our planet's climate has changed appreciably since the beginning of the industrial age. Atmospheric levels of carbon dioxide (CO_2) have risen significantly. Surface temperatures over much of the Northern Hemisphere increased by more than 1°C between 1901 and 2012, and by more than 2°C in large parts of Canada and the Russian Federation (IPCC, 2014). Boreal forests have experienced the largest temperature increases, in comparison to other forest biomes (Gauthier et al., 2015). These warming trends are projected to continue, though the size of the increase will vary according to which projected emission pathway, also called Representative Concentration Pathway (RCP), is followed. Under the low emission pathway RCP2.6, average land surface temperatures by 2081-2100, would be 2°C-3°C higher almost everywhere in the UNECE region, compared with 1986-2005 levels. Under the most emissions-intensive pathway RCP8.5, the rise could be more than 4°C-5°C in most of the region's continental areas (FIGURE 1.1a).

Projected trends for precipitation are much more uncertain. (FIGURE 1.1b). From 1951-2020, the Mediterranean and Western Canada have become noticeably dryer, while in Norway, the Russian Federation, Sweden, and the central United States of America, precipitation has increased. Projected precipitation varies widely across the UNECE region, depending on which RCP or global climate model is considered. There is little change under RCP2.6 in 2081-2100, with only small increases in precipitation compared to 1986-2005. Under RCP8.5, there would be pronounced drying of the Mediterranean region with increased precipitation in the boreal zone.

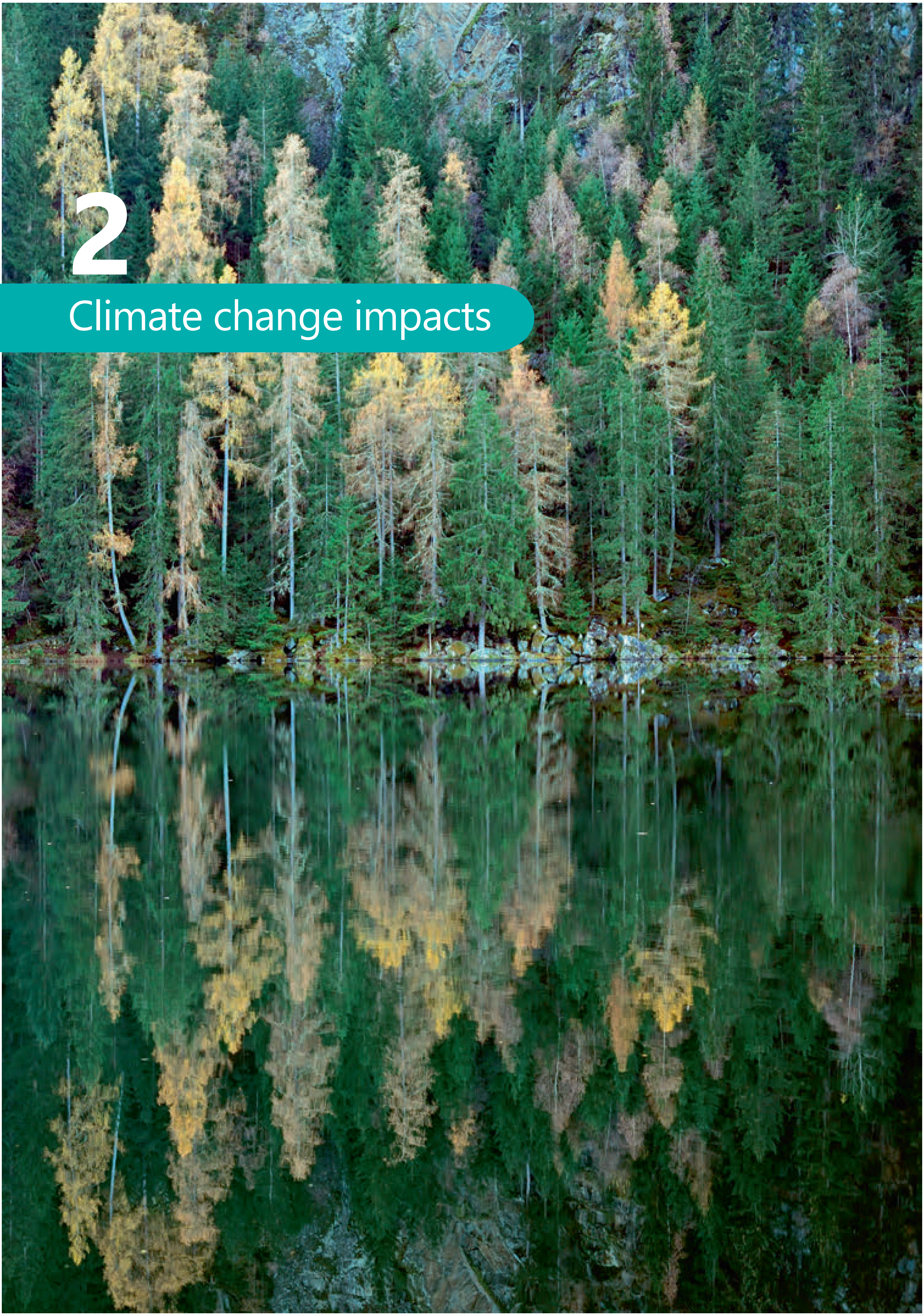
FIGURE 1.1 CHANGE IN AVERAGE SURFACE TEMPERATURE AND CHANGE IN AVERAGE PRECIPITATION



Note: Based on multi-model mean projections for 2081–2100 relative to 1986–2005 under the low-emission RCP2.6 (left) and high emission RCP8.5 (right) scenarios. The numbers in the upper right corners of each panel are how many models were used to calculate the multi-model mean. Stippling (dots) shows regions where the projected change is large compared to natural internal variability and where at least 90% of models agree on the sign of change. Hatching (diagonal lines) shows regions where the projected change is less than one standard deviation of the natural internal variability.
Source: IPCC, 2014 (Figure SPM 7, p.12).

Though many climate models do not result in altered patterns for seasonal temperatures and precipitation, substantial seasonality is expected, as well as increased frequency of extreme climatic events, in response to climate change. Winter temperatures are expected to rise faster than summer temperatures, with larger changes at higher latitudes. Winters are expected be wetter, with dryer summers leading to drought conditions in some regions, coinciding with high water demand by agriculture and cities (Lindner et al., 2014). There is an increasing probability of temperature extremes, with excessive summer heat. There is evidence that current climate models may systematically underestimate potential heat extremes (Lorenz et al., 2019). Warmer temperatures would increase water absorption capacity, raising the prospect of more intense precipitation events. The Intergovernmental Panel on Climate Change (IPCC) in its 5th Assessment concluded that, "...heat waves will occur more often and last longer, and extreme precipitation events will become more intense and frequent in many regions..." (IPCC, 2014).

Climate change will impact forest ecosystems in a variety of ways. This Discussion Paper provides a comprehensive overview of how forests might be affected in the UNECE region and its five different subregions, how forests might help climate mitigation, and how forest management may need to adapt to changing conditions. Annex C provides an overview of the countries of the UNECE region, and the five subregions considered in this Discussion Paper, which include 1) North America; 2) Europe-EU; 3) Europe-Other; 4) the Russian Federation; and 5) Eastern Europe, Caucasus and Central Asia (EECCA).



2 Climate change impacts

KEY QUESTION:

How will UNECE forests be affected by climate change?

Trees are long-lived. Their productivity and health reflect weather and site conditions, past site development, management history and disturbances. Consequently, understanding how climate change will affect forests is complicated. The rate of change, the occurrence of extreme events and a gradual alteration in average growing conditions add to the difficulty of quantifying how climate change might impact forests. Changing temperatures, precipitation and atmospheric CO_2 concentrations are likely to influence growth rates directly, quite often by enhancing photosynthesis and, indirectly, by changing long-term growing conditions and forest dynamics. In addition to these gradual changes, climate change is affecting the frequency and severity of natural disturbances and extreme events. All these factors will strongly influence tree species distribution as well as forest health, productivity, function and ecosystem services (FIGURE 2.1).

The first section of this chapter considers how climate-induced changes in growing conditions could affect forest productivity and tree species distribution. It also examines the incidence of extreme events and forest disturbances, and the effects of climate change on harvesting conditions.

This comprehensive overview of climate change impacts on forests sets the scene for interpreting the results from modelling completed for the Forest Sector Outlook Study 2020-2040, including this background Discussion Paper, using the Global Forest Products Model (GFPM) in subsequent sections.[1] These modelling results translate projected changes in net primary productivity into forest products' markets impacts, yet do not account for the effects of a range of other factors, such as changing disturbance regimes and changing species suitability (see Box 3 "Modelling the effects of changes in net primary productivity on global forest products and markets").

2.1 Climate change impacts on forest productivity

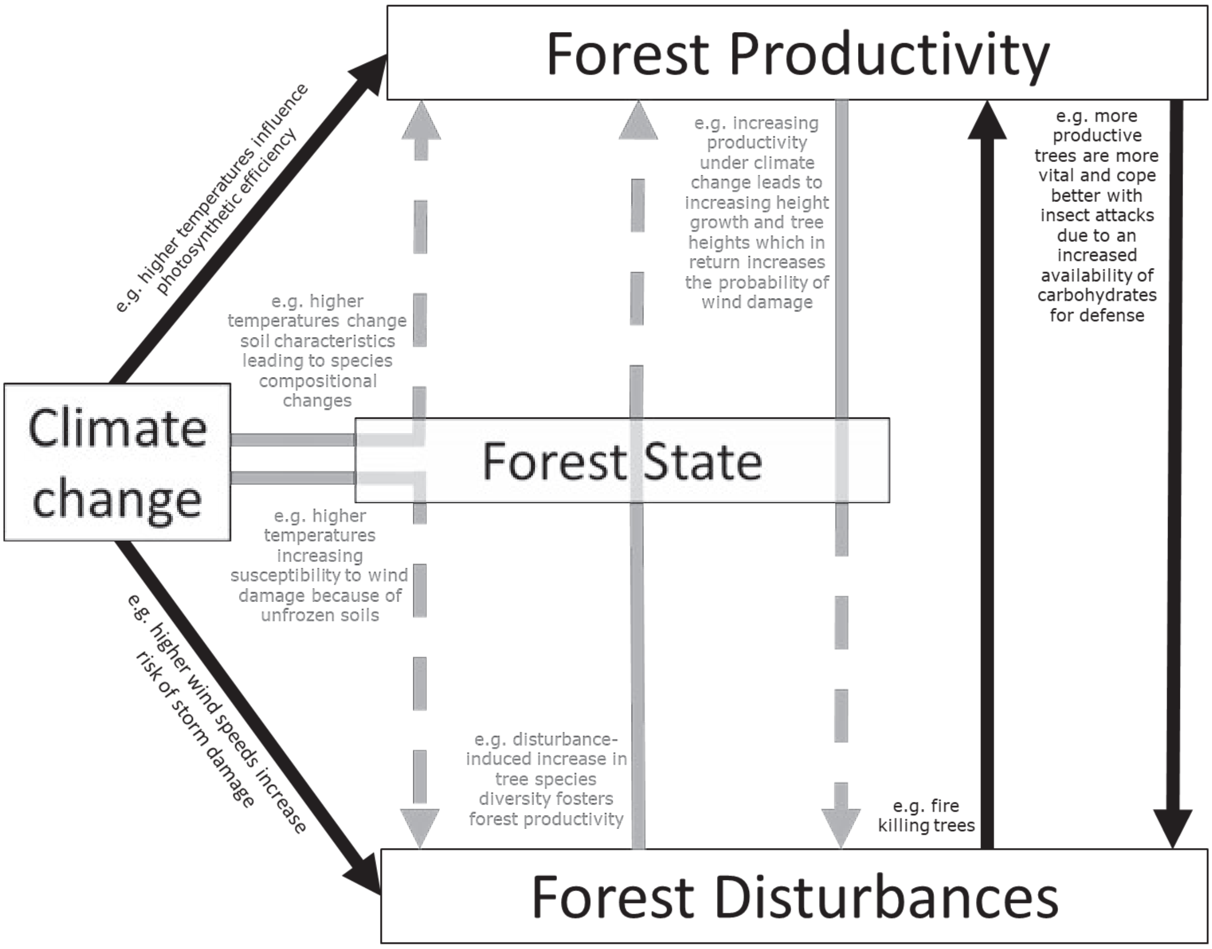
The main factors affecting forest productivity are changes in temperature, precipitation, and atmospheric CO_2 concentrations, as well as nitrogen deposition and improved land and forest management. Evidence from remote sensing, combined with process-based models, show that enhanced photosynthetic activity has helped to green many parts of the world, including northern Europe and the Russian Federation (Zhu et al., 2015). This is the result of increasing levels of atmospheric CO_2, lengthening growing seasons and warmer springs. Evidence from long-term forest monitoring plots and forest inventory data also suggests that climate change and nitrogen deposition have contributed to increasing forest productivity in central Europe (Pretzsch et al., 2013) and in the United States (McMahon et al., 2010). In Canada, positive and negative climate-induced growth changes cancel each other out (Girardin et al., 2016). In the Mediterranean area, there is contrasting evidence of growth increase and decrease depending on tree species, competition, site productivity and local climatic conditions (Sarris et al., 2011; Martin-Benito et al., 2011; Tegel et al., 2014; Charru et al., 2017).

[1] The GFPM modelling methodology is presented in more detail in the UNECE/FAO Discussion Paper "Detailed methodology for the preparation of the Forest Sector Outlook Study 2020-2040" (UNECE/FAO, 2022a); the GFPM modelling methodology, scenarios and findings are also presented in the UNECE/FAO (2022b) study paper "Structural changes in the forest sector and their long-term consequences for the forest sector: a contribution to the forest sector outlook study 2020-2040."

It is highly uncertain whether the strong positive effects of increasing atmospheric CO_2 will persist in future, or if they will be limited by physiological constraints (de Boer et al., 2011) or phosphorus and nitrogen availability (Hungate et al., 2003; Norby et al., 2010). However, there is some prospect for increasing forest productivity in many temperate and boreal forests of the UNECE region, as projected by process-based forest models (Reyer et al., 2014; Reyer et al., 2015; Friend et al., 2014; Ito et al., 2020). Some studies suggest that growth increases might not occur if water availability restricts forest carbon accumulation (Kint et al., 2012; Sperry et al., 2019); if growth increases in spring are offset by growth reductions later in the growing season (Buermann et al., 2018); or if climate change increases background mortality in forest stands (Bugmann & Bigler, 2011; Yu et al., 2019). Mediterranean forests are already limited by water availability and at greater risk of climate-induced productivity losses (FAO and Plan Bleu, 2018).

Enhanced productivity does not necessarily produce high-quality timber, as faster growth may lower wood quality (Box 2 Climate change impacts on wood quality).

FIGURE 2.1 INTERACTIONS BETWEEN CLIMATE CHANGE, FOREST PRODUCTIVITY AND FOREST DISTURBANCE



Notes: Climate change affects forest productivity and disturbance in direct (black arrows) and indirect (grey arrows) ways. Indirect effects are mediated through effects on the forest state (stand density and structural variables). Forest productivity and disturbances are linked independently of climate change through direct and indirect effects.

Source: Reyer et al., 2017.

BOX 2

Climate change impacts on wood quality

Increased productivity may produce wider growth rings and longer fibres, which will influence wood quality in terms of strength and chemical properties (Mitchell, 1961). Until now, most research focused on the physical aspects of wood quality, which is a major factor determining how timber is used. Climatic variables strongly influence characteristics like strength and stiffness, which are affected by wood density (Zhu et al., 2015). Treating wood density as constant may overestimate or underestimate the carbon storage potential of forests (Vanoppen et al., 2018). While growth rates in central Europe accelerated throughout the 20th century, wood density declined (Pretzsch et al., 2018). Warm spring conditions led to higher proportions of early wood in annual growth rings. Early wood has high numbers of large vessels for fast water transport, causing low densities and lowering overall wood density (Björklund et al., 2017). Lower wood density can reduce mechanical stability, increasing the risk of snow damage (Peltola et al., 1999) and wind damage (Meyer et al., 2008).

Water stress negatively affects radial tree growth. A higher incidence of drought may produce heterogeneous tree-ring patterns. Decreasing homogeneity and trends in wood density are likely to cause problems for use in construction and furniture (Lachenbruch et al., 2010). In a few cases, lower wood density may have a positive effect for sliced-veneer production (Zhang et al., 1993).

2.2 Climate change impacts on species distribution

Changes in growing conditions not only affect forest productivity, but also the distribution range of tree species. The concept of the *fundamental niche* describes the range of environmental conditions a species could theoretically occupy under stable conditions. The area actually occupied, the *realized niche*, is often smaller due to the presence of competition with other species and natural barriers (Griesemer, 1994). Forest management relies on this concept by cultivating economically important tree species beyond the realized, but still within the fundamental niche, which requires the continuous removal of competitors. With climate change, shifts have been observed at the leading edges of species distributions. Species expand into habitats that now increasingly provide the required environmental resources to sustain growth and competitiveness (Lindner et al., 2014). As climate change progresses, species range and their associated forest types may move towards the poles and higher altitudes (Meier et al., 2012). This would have strong implications for the profitability of commercial forestry, and the main tree species grown in Europe (Hanewinkel et al., 2013).

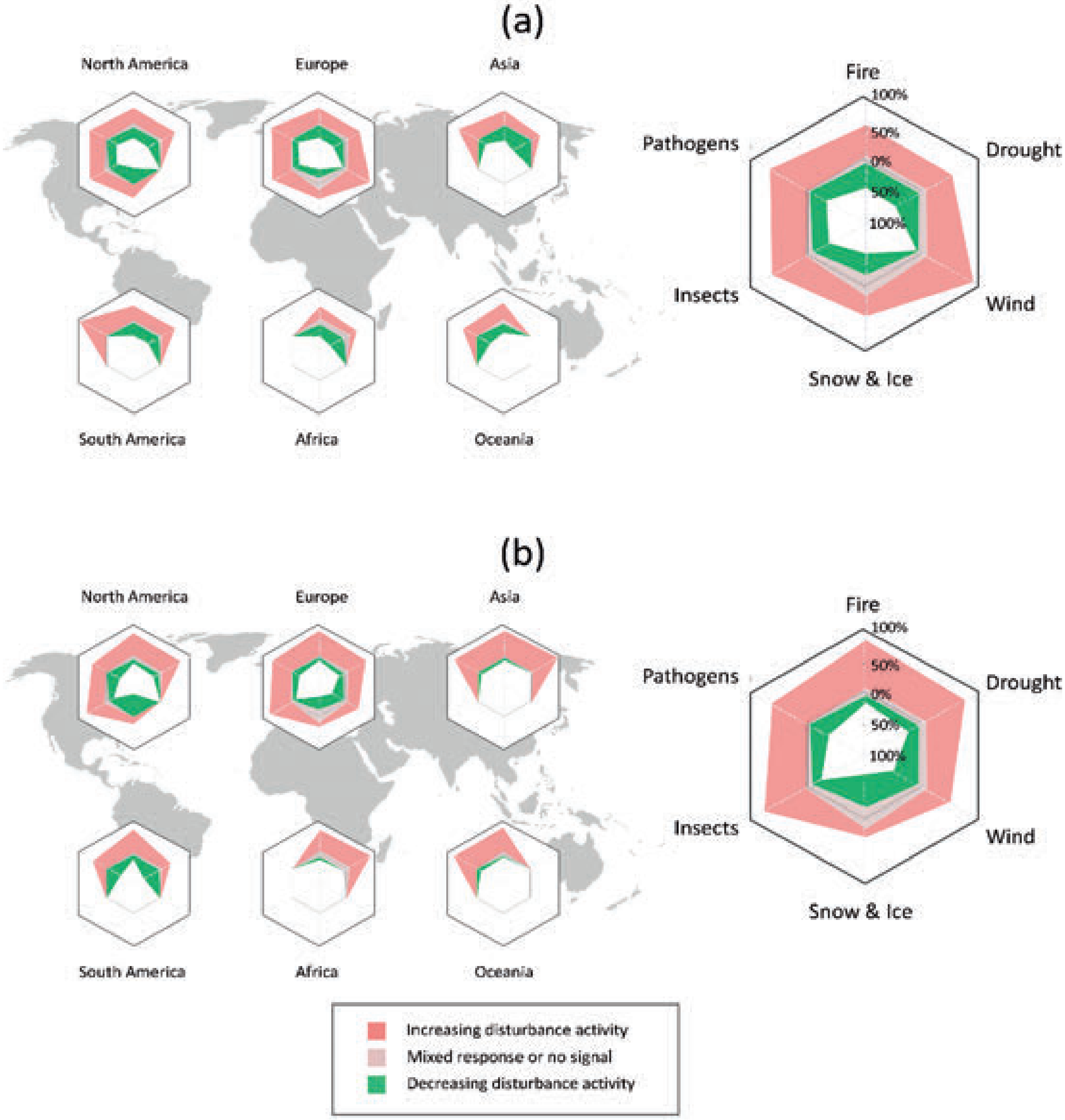
Species migration trends have been observed throughout the UNECE region. In Siberia, the slow migration of evergreen conifer species into current larch habitat has been reported (Kharuk et al., 2007). In North America, temperate deciduous tree species have migrated into the boreal zone (Boisvert-Marsch et al., 2014). At higher elevations in southern Europe, holm oak is replacing beech (Peñuelas et al., 2007). These migration trends are consistent with projected shifts in species ranges, highlighting that, for many species, the rate of migration may not keep pace with changing climatic conditions (Delzon et al., 2013; De Dios et al., 2006). Generally, distributions of species, especially at the rear edges of their range, are often susceptible to disturbances like drought, pathogens and insects. Forests that move from their fundamental niche, risk productivity loss, reduced resilience, or replacement by other vegetation types (Dyderski et al., 2018; Reyer et al., 2014).

2.3 Climate change impacts on natural disturbances

Disturbance is a natural component of forest dynamics, disrupting ecosystem structure, composition and function. In unmanaged systems, disturbances such as fire, windthrow and insect outbreaks create a heterogeneous landscape. Disturbances not only alter resource availability but also promote forest rejuvenation, which is crucial for adaptation to environmental changes, including those linked to climate change. Disturbances over large areas have a significant impact on forests (Seidl et al., 2017) and carbon storage (McNulty 2002, Seidl et al., 2014).

Forest disturbances have been increasing in frequency and severity since the early 1970s (Schelhaas, Nabuurs, & Schuck, 2003; Seidl et al., 2014). This trend is expected to continue (Chi et al., 2019; Seidl & Rammer, 2017). A combination of changes in forest structure, forest management, and climate are the main causes of increased disturbance (Seidl et al., 2011; Abatzoglou and Williams, 2016; Sommerfeld et al., 2018). Disturbance agents rarely occur alone, often acting in combination. For example, a storm may leave many dead trees, which provide a suitable environment for bark beetles or fuel wood for forest fires. How disturbances interact very much depends on the forest condition and climate zones (Dale et al.2010; Reyer et al., 2017). The main disturbance types and their interactions are illustrated in six forest regions (FIGURE 2.2 A and B.

FIGURE 2.2 **POTENTIAL CHANGES OF GLOBAL DISTURBANCE IN RESPONSE TO TEMPERATURE AND WATER AVAILABILITY UNDER WARMER AND WETTER CONDITIONS 2.2A, OR WARMER AND DRIER CONDITIONS 2.2B (SEE NOTES BELOW).**



Notes: The size and direction of the coloured radar surfaces indicate the distribution of evidence, expressed as a percentage of observations from a literature review of 674 scientific publications dealing with climate and disturbance interactions. The large radar plots to the right summarize the responses over all continents.

Source: Seidl et al., 2017.

2.3.1 Wind

The susceptibility of trees and forest stands to wind damage is strongly linked to wind speed, duration and gustiness, and varies with tree species, height, stem density and the presence or absence of broken canopy from previous disturbances. Other factors include stand location in relation to prevailing wind direction, past forest management, such as thinning and final cutting, and the soil type and topography (Hanewinkel et al., 2014). Seasonality is also important, especially for deciduous trees, which are less vulnerable in winter when there are no leaves. Wind damage may uproot or break the stems of individual trees or entire stands. Resistance to wind damage depends on tree height, stem diameter, rooting system, foliage and crown development (Hale et al., 2012). By promoting root and crown development, thinning may make stands more resistant to wind damage, although there is often a short-lived increased risk of wind damage after thinnings as canopy roughness increases. Extra-tropical storms have increased in frequency and intensity, a trend that is expected to intensify with ongoing climate change (Ulbrich et al., 2009). The typical storm tracks of hurricanes affecting eastern North America may be altered and storms are projected to reach the coasts of western Europe with increasing frequency over coming decades (Haarsma et al., 2013).

Predictions about damage to forests on both sides of the Atlantic resulting from future storm patterns remain uncertain. Current global climate models struggle to predict regional wind speeds and the associated risks of storms. Projections of increased storm impacts are based mainly on indirect effects (Lindner & Rummukainen, 2013). Enhanced forest productivity is likely to increase tree heights and stand densities, which may make stands more vulnerable to wind damage (Reyer et al., 2017). Higher winter precipitation and shorter duration of frozen soils under a warming climate may reduce stand stability, especially in boreal forests, where winter temperatures are projected to increase the most (Usbeck et al., 2010). Uprooted but unbroken trees can still yield sawlogs, but where stems have been snapped the merchantable value is reduced significantly, and salvage harvesting may only be possible in restricted time windows (Prestemon and Holmes, 2004). Uprooted trees carry a higher risk of injury to forest workers and raise the cost of removal (Kärhä et al., 2018). A recent example of a storm event in Europe was Storm Gudrun in Sweden in 2005, which caused windfall of 75 million cubic metres (m^3) within hours (Kauppi et al., 2018). Hurricanes Katrina and Rita damaged 2.23 million hectares (ha) of forests along the east coast of the United States in 2005 (Stanturf et al., 2007). In 1989, Hurricane Hugo caused damage valued at more than $1.5 billion to forests in South Carolina, with measurable economic effects on timber markets over more than two decades.

2.3.2 Drought

Droughts have increased in number, severity and duration since the beginning of the 20th century (IPCC, 2013). Climate models project a possible doubling in drought occurrence for many UNECE subregions (McDowell et al., 2018). Drought length and severity are projected to increase with lower summer precipitation and higher evapotranspiration (Dai, 2013). Trees respond to dry and hot weather by shutting down photosynthesis to conserve water and prevent xylem cavitation – the loss of conductivity within tree vessels (Li et al., 2016). Consecutive droughts impair tree health, reducing growth and weakening natural defense mechanisms, increasing susceptibility to storm, fire, pathogens and insects (Lindner, 2014). Reduced resin production, for instance, weakens a tree's defenses against insect attacks (McDowell, 2011). Reduced growth also limits root growth, potentially destabilizing the tree and lowering resistance to windthrow (Zhou et al., 2018). The risk of fire may increase during drought, as dried wood on the forest floor ignites more easily and will burn at higher temperatures than moist wood. In the Northern Hemisphere, defoliation and drought-induced mortality has increased over a wide variety of tree species (Settele et al. 2014)

2.3.3 Fire

Fire is the primary driver of forest dynamics in boreal and Mediterranean forests (Boulanger et al., 2013). Historically, fire played a part in temperate forest dynamics, although it is less significant in Europe due to a combination of fire suppression and forest fragmentation (Adámek et al., 2018). In the United States there is a debate about the role of fire suppression, human presence and climate change in affecting fire trends (Abatzoglou & Williams, 2016; Syphard et al., 2017). Fire frequency, intensity and severity determine the fire regime, which is heavily influenced by the climate (Williams et al., 2019). Rising temperatures and shifts in precipitation cause more frequent dry weather. Together with larger quantities of fuel wood and higher lightning activity, these are expected to increase the numbers, size and intensity of fires (Whitman et al., 2015; Turco et al., 2019). The changes in fire dynamics caused by climate change adversely affect the recovery of forest structure and composition, hampering the provision of forest ecosystem services (Halofsky et al., 2020).

The Mediterranean basin is a global wildfire hotspot. Between 1980 and 1990, just five Mediterranean countries – France, Greece, Italy, Portugal and Spain - experienced wildfires affecting on average more than 550,000 hectares per year. Since 1990, except for Portugal, the area affected by fire has been decreasing: from 2008 to 2018 approximately 340,000 hectares per year were burned, 95% of all burnt areas in the European Union (San-Miguel-Ayanz et al., 2018), causing an annual loss of about 1.5 billion euros (San-Miguel-Ayanz and Camia, 2010). Driven largely by changing socio-economic conditions, the forest area in the Mediterranean basin has expanded considerably (Moreira et al., 2011; Mourão and Martinho, 2014). This is partly due to active afforestation, especially in Portugal and Spain, but also caused by natural regeneration following abandonment of agricultural land (Kuemmerle et al., 2016). These young and largely unmanaged forests contain high fuel loads and connectivity over large areas, which create favourable conditions for rapid and large spread of wildfires, which produce large CO_2 emissions. The cultivation of fire-prone trees, such as eucalyptus and some pines, has increased fire risk (Gonçalves and Sousa, 2017). Wildfires show large year-to-year variation in frequency and scale: the second largest area burned was more than 900,000 hectares in 2017. Wildfires have also been increasing in other parts of Europe since 1990, particularly Germany, Poland and Sweden.

In Canada and the United States, wildfires have been trending upwards since at least the mid-1980s. From 1960 to 1979 an average of 2.8 million hectares burned in Canada and the United States each year. From 2000 to 2018, that figure rose to 5.3 million hectares (National Interagency Fire Center 2019a, Natural Resources Canada 2019). This not only results in higher carbon and other emissions but adds greatly to the cost of suppression, which reaches $2.1billion per year for federal agencies in the United States alone (National Interagency Fire Center 2019b, United States Department of Commerce 2019). Particles from fires spread to populated areas throughout North America, causing significant health effects (Kochi et al., 2010, Fann et al., 2018).

Fire is the main cause of forest disturbance in the Russian Federation. Between 1998 and 2013, fires in the Russian Federation affected between 8 million and 11 million hectares annually, of which 5 million hectares were forested (Schaphoff et al., 2016). Satellite imaging showed that between 2001 and 2019, fires affected between 2 million and 11 million hectares of forest, yearly averaging 5.6 million hectares (Leskinen et al., 2020). Despite high year-to-year variation, the results were statistically significant, revealing that fire disturbances in forests in the Russian Federation, in terms of area burned, were increasing. The distribution of fire is uneven, however. Fires occurred more often in densely populated districts but affected a smaller total area of forests than in less populated districts like central Siberia and the northern Far East. In the latter districts, there were fewer fires but significantly larger burned areas, possibly a reflection of lower levels of fire protection in less populous regions. While climate change may have a role in the increasing incidence of fires, there is also a strong socioeconomic/political element. The transition away from a centrally planned economy, taking place since 1990 in the Russian Federation, has led to an increasing area of abandoned farmland and reduced numbers of forest managers and forest firefighters leading to less efficient forest protection systems (Isaev and Korovin, 2013, Flannigan et al., 2009).

2.3.4 Insects and pathogens

Climate change directly influences the survival and metabolic rate of insects and pathogens. Warmer and wetter climate conditions are expected to increase the activity and abundance of pathogens (Müller et al., 2014). A warmer and drier future will enhance insect reproduction and survival rates (Seidl et al., 2017). Climate change will also affect the abundance, diversity and growth rates of host trees. Recurring drought, for example, may compromise host tree defenses against insects, through reduced resin production (Gaylord et al., 2013). A high population of host trees will help to disperse insects and pathogens (Temperli et al., 2013; Vacher et al., 2008). Warmer, drier conditions in recent years have favoured the spread of bark beetles. Taken together with a reduction in the natural ability of trees to resist attack, this has resulted in extensive and extended infestations, especially in central Europe and North America where even-aged, largely conifer stands have provided an ideal habitat for bark beetles. In the dry European summer of 2018, bark beetles were able to complete a third reproduction cycle, causing unprecedented outbreaks in central Europe. In the Czech Republic, the volume of infested timber equalled the scheduled annual harvest of 17 million m^3 (Ekolyst, 2019). In Germany, over one-third of the harvested volume in 2018 was of salvaged spruce timber (Destatis, 2019; Destatis, 2020). Such bark beetle outbreaks in Europe, combined with increasing drought stress, pathogens and wind, may be expected to increase the proportion of broadleaved species.

In Canada, outbreaks of mountain pine beetle have affected over 18 million hectares of forests in British Columbia and Alberta since the 1990s. Peaking in 2004, it was estimated to have destroyed 752 million m^3 of merchantable timber by 2017 (Natural Resources Canada 2018). The economic impacts of bark beetle epidemics in this area are also potentially huge (Holmes 1991, Prestemon et al., 2013), particularly in jurisdictions where the forest sector contributes substantially to the economy (Corbett et al., 2016).

The Siberian silk moth is one of the most damaging insect pests affecting boreal forests. Rising temperatures have allowed it to extend its range in the Russian Federation, and there is concern that it is spreading into northern and north eastern Siberia. It is even possible that it may spread west to Belarus and Finland (CABI, 2021). An outbreak that began in 2014 on the Yenisei plain has continued its northward spread, extending well beyond its historical northern limit (Kharuk and Yagunov, 2018).

2.3.5 Snow & ice

The weight of snow and ice that accumulates on tree crowns can break branches and tree stems. In combination with a lack of frozen soil and strong winds, heavy ice and snow may even uproot trees (Gregow et al., 2011). Young, unthinned stands are most likely to suffer (Päätalo, 2000). In mountainous regions, avalanches, though declining in frequency, are a continuing hazard for forests (Teich et al., 2012). Snow cover in the northern hemisphere has been decreasing since the 1930s (Brown & Robinson, 2011), and it is likely this trend will continue (IPCC, 2013). Disturbances from snow and ice are likely to decrease during climate change (Seidl et al., 2017). Between 1950 and 2000, snow-damaged timber from European forests was recorded at a mean annual volume of one million m^3 (Schelhaas, Nabuurs & Schuck, 2003). Ice storms, though uncommon, have a strong impact on forests. It is difficult to assess from climate models, how future changes in climate might influence the scale and frequency of such events. In 2014, ice damaged an estimated 9.3 million m^3 of timber in Croatia and Slovenia (Nagel et al., 2016). Ice storms have been a particular concern in the east of North America, where they occur more often. The 1994 Mississippi ice storm damaged 41 million m^3 of timber, including 18 million $m^3$of sawtimber, a volume greater than the annual intake of the state's sawmilling sector (Irland, 2000).

2.4 Climate change impacts on harvest conditions

In boreal and cold-winter temperate forests, harvesting has traditionally been undertaken in winter when frozen soils improve the efficient operation of forest machinery and reduce soil damage.

et and waterlogged soils, such as sites with deep clay or loamy soils, are much more prone to damage, which may result in reduced productivity (Toivio et al., 2017). Damaged soils may also affect species compositions and forest functioning (Closset-Kopp et al., 2019). Rising winter temperatures may restrict harvesting operations due to the reduced number of days when soils remain frozen (Henry, 2008, Rittenhouse and Rissmann, 2015). Excessive off-season rainfall may have a similar impact, making it difficult to continue harvesting without damaging vulnerable soils, with potentially serious consequences for timber production. For example, there are concerns about the ability of Finland to meet its climate mitigation targets (Lehtonen et al. 2019). These rely heavily on bioenergy from forested peatlands, where harvesting may become impossible because of shortening periods when soils remain frozen.

In Wisconsin, US, a study reported that frozen ground conditions had shortened by three weeks on average since 1948, leading to a shift in harvesting pine, rather than hardwoods and other coniferous species (Rittenhouse and Rissmann 2015). Pine forests tend to grow on sandy soils, which withstand heavy equipment better during harvesting, because they have a higher load-bearing capacity than unfrozen ground. The proportions of tree species, such as spruce, aspen and maple, that tend to be found on soils with low bearing capacity have decreased as the frozen-ground period has shortened.

In southwest Germany, forest conversion partly motivated by adapting forests to climatic changes has increased the area of broadleaf-mixed forests. While even-aged coniferous forests are generally harvested with fully mechanized harvesting systems throughout the whole year, broadleaf-mixed forests rely on motor manual felling and cable yarding during winter (Berendt et al, 2017). Extraction could be shifted towards summer months when soils tend to be dry; however, motor manual felling during the growing season could damage and devalue timber. This is because large-crowned trees tend to splinter when in sap, reducing the volume of merchantable timber.

Damage from natural disturbance will increase harvesting costs as a consequence of greater planning effort. It will also lower efficiency due to the chaotic effects of windthrow, for example, and the higher safety standards essential under such conditions (Kärhä et al., 2018).

Changing winter conditions and increased natural disturbance, both as a result of climate change, might lead to a cascade of problems for: commercial and pre-commercial harvesting; year-round working, and; maintaining a steady labour supply. Forest managers might be able to time harvesting operations where soils and species allow, but harvesting operations are increasingly constrained by a shrinking winter window, salvage logging and essential sanitary felling. Forest operations are becoming more seasonal, and harvesting will become variable across the year. This will restrict employment of forest workers, create logistical challenges for wood-processing plants that rely on stable roundwood supplies, and limit opportunities to carry out pre-commercial thinning.

2.5 Impacts of changes in net primary productivity induced by climate change on forest products' markets

This section summarizes the simulated impacts of projected changes in forest productivity due to greenhouse gas accumulations and associated climate change on global forest products' markets. To model this, changes in net primary productivity (NPP) of forest were modelled using the Dynamic Vegetation Model MC2 (Kim et al., 2017). The changes in NPP were inputted to the GFPM, and the projected forest products' market outcomes were compared to a reference under Shared Socioeconomic Pathway 5 (SSP5). Box 3 explains the methodology and selection of SSP5 in more detail[2]. It is important to note that this modelling approach (as in similar approaches used by other models at the global level) includes only the effects of changing temperatures, precipitation, and CO_2 on NPP of forest; it does not directly include the effects of all possible sources of disturbances. Although wildfire is directly modelled, modelling does not directly account for the individual effects of other forms of disturbances (storms, insects, diseases, ice, etc.).

[2] The full methodology is presented in UNECE/FAO (2022a)

TABLE 2.1 summarizes the projected average NPP values obtained for 2015 and 2040, and the corresponding percentage changes from 2015 to 2040. The projections show gains in NPP for most regions.

Projected increases in forest growing stock, arising from increased tree growth rates as a result of climate change, were shown to raise the productive capacity of forests. The increased productivity enabled lower prices for roundwood and manufactured wood products in all countries (TABLE 2.2). For products in countries with higher projected NPPs, domestic price declines were similar to or larger than the projected declines in world prices. The largest projected productivity gain was in the United States, which led to the largest projected falls in prices for roundwood (-6%) and sawnwood (-4%) by 2040, compared with projected prices excluding climate change effects on productivity. Industrial roundwood and sawnwood prices in Argentina, Brazil, Canada, Chile, Indonesia, and Japan were also projected to fall when climate change increased productivity. Overall, climate change-induced productivity changes might change the comparative advantage of each country in producing and trading forest products.

TABLE 2.1 Projected trends in forest net primary productivity values (g/m²), under Representative Concentration Pathway 8.5, for 2015 and 2040.

	MC2 projected NPP values (g/m²)		
Regions	***2015***	***2040***	***% change***
Asian Islands (SAS)	2,139	2,257	6
Australia/ New Zealand (ANZ)	509	525	3
Canada (CAN)	233	250	7
Central America (CAM)	944	947	0
China (CHN)	409	423	3
Eastern Europe & Central Asia (EEU)	187	186	-1
India (IND)	664	682	3
Japan (JPN)	1,143	1,264	11
Northern Africa (NAF)	218	233	7
Russian Federation (RUS)	172	178	3
Southern Africa (SAF)	1,041	1,097	5
South America (SAM)	1,634	1,762	8
United States of America (USA)	358	413	15
Western Europe (WEU)	534	541	1
Western South America (WSA)	1,192	1,258	6

Note: Dynamic Vegetation Model MC2 The values are average trends for seven different climate model realizations, encompassing different combinations of climate sensitivities, net aerosol forcing, and initial conditions. For further explanations see box 3. A map of the regions presented in this table is available in *Kim et al., 2017*

Source: Kim et al., 2017

TABLE 2.2 GFPM projected differences in domestic and world prices of wood products in major wood-producing countries by 2040[1]

	Ind. Roundwood		Sawnwood		Panels		Paper[3]	
Regions	*$/m³*	%	*$/m³*	%	*$/m³*	%	*$/tonne*	%
Asia								
China	-3.4	-2.50	-5.0	-1.60	-3.53	-0.70	-3.53	-0.40
India	-3.3	-2.20	-7.8	-2.30	-5.93	-1.10	-8.57	-1.00
Indonesia	-4.7	-4.00	-11.8	-3.90	-7.9	-1.50	-8.95	-1.30
Japan	-5.1	-3.80	-5.0	-1.60	-5.73	-1.10	-4.43	-0.50
Europe								
Finland	-2.4	-1.80	-5.1	-1.80	-4.63	-0.90	-12.47	-1.50
France	-3.4	-2.90	-5.1	-1.60	-4.80	-0.90	4.50	0.50
Germany	-3.3	-2.40	-3.8	-1.30	-5.13	-0.90	-9.20	-1.10
Italy	-3.4	-2.50	-5.1	-1.60	-2.97	-0.50	-8.03	-0.90
Norway	-3.4	-2.90	-4.1	-1.30	-5.60	-1.10	-9.57	-1.10
Poland	-1.9	-1.70	-5.4	-1.70	-3.67	-0.70	-5.50	-0.70
Portugal	-2.3	-1.60	-4.7	-1.50	-4.40	-0.80	-7.90	-0.90
Spain	-4.1	-3.60	-7.8	-2.40	-5.33	-1.00	-4.27	-0.50
Sweden	-2.4	-1.80	-5.1	-1.80	-4.43	-0.80	-8.70	-1.00
United Kingdom	-4.1	-2.80	-5.1	-1.60	-5.77	-1.00	-9.00	-1.00
Russian Federation								
Russian Federation	-3.1	-2.70	-7.6	-2.60	-5.80	-1.20	-7.10	-0.90
North America								
Canada	-5.9	-4.40	-10.9	-3.70	-6.70	-1.30	-13.3	-1.50
United States	-7.0	-6.10	-12.4	-3.90	-7.40	-1.40	-9.00	-1.00
Oceania								
Australia	-3.4	-2.90	-5.4	-1.70	-5.67	-1.10	-8.07	-0.90
New Zealand	-3.4	-2.90	-5.1	-1.80	-3.9	-0.80	-6.47	-0.80
South America								
Argentina	-4.0	-3.40	-9.8	-3.40	-6.53	-1.30	-6.43	-0.80
Brazil	-4.8	-4.20	-12.0	-4.20	-9.10	-1.80	-9.50	-1.10
Chile	-4.1	-3.60	-9.8	-3.00	-5.30	-1.00	-7.47	-0.80
World	**-3.4**	**-2.90**	**-5.1**	**-1.80**	**-5.70**	**-1.10**	**-9.00**	**-1.10**

Notes: A map of the regions presented in this table is available in *Kim et al., 2017*

[1] Projected prices in 2040 in SSP5 with forest productivity change according to RCP8.5 minus projected prices in 2040 in SSP5 without climate change effects on productivity. Numbers in "%" columns are the percentage changes from SSP5-no productivity change in 2040.

[2] Prices for panels are the average of prices for plywood, particle board, and fibreboard.

[3] Prices for paper and paperboard are the average of prices for newsprint, printing and writing paper, and other paper and paperboard.

Source: GFPM projections.

TABLE 2.3 GFPM projected differences in production of wood products by 2040[1]

Regions	*Ind. Roundwood*		*Sawnwood*		*Panels[2]*		*Paper[3]*	
	million m^3	*%*	*million m^3*	*%*	*million m^3*	*%*	*million tonnes*	*%*
Asian Islands	3.39	2.10	-4.99	-11.50	-0.51	-2.10	-0.62	-1.70
Australia/ New Zealand	-0.31	-0.40	-2.45	-16.80	-0.14	-4.50	-0.52	-8.20
Canada	5.97	3.20	3.1	7.10	0.13	1.10	-0.21	-1.40
Central America	-0.52	-3.80	-0.34	-7.00	0.01	0.30	-0.05	-0.40
China	1.57	0.50	-13.87	-11.20	1.09	0.30	-0.34	-0.20
Eastern Europe & Central Asia	-0.74	-5.40	-2.21	-25.20	-0.02	-0.70	-0.10	-4.30
India	0.61	0.70	0.19	1.20	0.23	2.90	-0.19	-0.60
Japan	2.25	9.10	0.31	43.90	0.43	7.60	-1.14	-3.80
Asia other	0.6	7.10	0.01	0.10	-0.23	-5.20	-0.22	-1.60
Northern Africa	0.17	3.80	0.01	4.70	0.14	3.80	-0.44	-6.20
Russian Federation	0.25	0.10	17.01	51.10	0.24	0.80	-0.13	-1.20
Southern Africa	0.95	1.90	0	0	0.17	2.60	-0.01	-0.20
South America	6.98	4.10	0.29	1.30	0.34	1.40	-0.1	-0.60
United States	56.6	11.50	16.7	16.00	6.84	16.30	11.25	13.70
Western Europe	-10.04	-1.70	-7.67	-3.60	-2.98	-2.20	-3.86	-3.00
Western South America	2.15	2.40	0.41	2.30	0.37	4.60	-0.08	-1.00
World	**69.86**	**2.70**	**6.51**	**1.00**	**6.1**	**0.90**	**3.23**	**0.50**

Notes: A map of the regions presented in this table is available in *Kim et al., 2017*

[1] Projected quantities in 2040 in SSP5 with forest productivity change according to RCP8.5, minus projected quantities in 2040 in SSP5 without climate change effects on productivity. Numbers in "%" columns are the percentage changes from 'SSP5-no change to productivity' in 2040.

[2] Values for panels are the sum of values for plywood, particle board, and fibreboard.

[3] Values for paper and paperboard are the sum of values for newsprint, printing and writing paper, and other paper and paperboard.

Source: GFPM projections.

Falling prices for manufactured products under climate change were projected to increase production and consumption globally. Whether production declined or increased in individual countries depended on the comparative advantages in making those products (TABLE 2.3).

Projected consumption of sawnwood, panels and paper was higher in all countries, reflecting projected lower prices. Consumption of industrial roundwood was also higher globally, but changes varied by country (TABLE 2.4).

Enhanced forest productivity under climate change lifted global roundwood production and consumption by 2.7% by 2040, compared to SSP5 without climate effects. This supported increased sawnwood production of 1.8% and increases of 1.1% for each of panels and paper products (TABLE 2.3). Though roundwood production increased in most regions, it declined in Australia/New Zealand, Asian Islands, Central America, Western Europe and Eastern Europe and Central Asia, reflecting lower comparative advantages. Sawnwood production increased most in the Russian Federation (51%), followed by Japan (44%) and the United States (16%). Projected increases in consumption of manufactured products in each country/region were generally smaller than projected production increases, providing gains in exports for countries with increased production and reduced exports for countries showing reduced production (TABLE 2.5). China and the Asian Islands benefited from the largest percentage increase in trade competitiveness for roundwood.

The coupling of the MC2 model and GFPM under climate change (Box 3) illustrates how projected climate change impacts on NPP can be integrated into a global forest products model to project the associated impacts on global forest products' markets. The modelling results suggest that climate change will generally increase forest productivity, shifting supply outward, in turn reducing prices and increasing global forest product consumption which ties in with findings from earlier studies (Tian et al., 2016). However, results also suggest that price declines brought about by higher global forest productivity will alter production and trade competitiveness of individual countries. Consequently, countries with greater comparative advantages will increase production and exports of wood products, while countries with lower comparative advantages will do the opposite

TABLE 2.4 GFPM projected differences in consumption of wood products by 2040[1]

Regions	*Ind. Roundwood*		*Sawnwood*		*Panels[2]*		*Paper[3]*	
	million m^3	*%*	*million m^3*	*%*	*million m^3*	*%*	*million tonnes*	*%*
Asian Islands	-5.81	-4.20	0.38	1.00	0.25	1.00	0.31	0.80
Australia/ New Zealand	-3.93	-13.00	0.09	0.70	0.06	1.00	0.04	0.70
Canada	5.97	3.20	0.36	1.60	0.15	1.40	0.07	1.00
Central America	-0.47	-3.50	0.07	0.60	0.04	0.90	0.04	0.20
China	-15.39	-3.00	1.67	0.70	2.49	0.70	0.48	0.30
Eastern Europe & Central Asia	-2.35	-18.90	0.11	0.60	0.12	1.20	0.01	0.40
India	0.6	0.60	0.2	1.10	0.16	1.20	0.3	0.70
Japan	-0.32	-0.90	0.15	0.70	0.1	1.10	0.18	0.70
Asia other	-0.51	-3.50	0.03	0.80	0.06	1.00	0.07	0.70
Northern Africa	0.16	2.90	0.23	0.70	0.18	1.10	0.1	0.70
Russian Federation	42.8	23.00	0.13	1.10	0.19	1.40	0.05	0.70
Southern Africa	0.42	1.20	0.16	1.20	0.03	0.30	0.06	0.70
South America	6.98	4.40	0.31	1.80	0.25	1.90	0.1	0.80
United States	56.6	13.40	2.42	1.70	0.84	1.40	0.67	0.70
Western Europe	-16.45	-2.60	1.32	0.70	1.06	1.10	0.67	0.60
Western South America	1.56	2.50	0.23	1.30	0.11	1.20	0.06	0.60
World	**69.86**	**2.70**	**6.51**	**1.00**	**6.1**	**0.90**	**3.23**	**0.50**

Notes: A map of the regions presented in this table is available in *Kim et al., 2017*

[1] Projected quantities in 2040 in SSP5 with forest productivity change under RCP8.5, minus projected quantities in 2040 in SSP5 without climate change effects on productivity. Numbers in "%" columns are the percentage changes in 2040, from 'SSP5-no change to productivity'.

[2] Values for panels are the sum of values for plywood, particle board, and fibreboard.

[3] Values for paper and paperboard are the sum of values for newsprint, printing and writing paper, and other paper and paper board.

Source: GFPM projections.

TABLE 2.5 GFPM projected differences in net exports of wood products by 2040

Regions	*Ind. Roundwood* *million m*	*Sawnwood* *million m^3*	*Panels*[2] *million m^3*	*Paper*[3] *million tonnes*
Asian Islands	9.20	-5.30	-0.76	-0.93
Australia/ New Zealand	3.62	-2.53	-0.20	-0.57
Canada	0	2.71	-0.02	-0.28
Central America	-0.05	-0.40	-0.03	-0.09
China	16.96	-15.18	-1.40	-0.82
Eastern Europe & Central Asia	1.61	-2.28	-0.14	-0.12
India	0	-0.04	0.07	-0.49
Japan	2.57	0.20	0.33	-1.32
Asia other	1.11	-0.03	-0.29	-0.29
Northern Africa	0.01	-0.12	-0.04	-0.54
Russian Federation	-42.55	16.88	0.06	-0.19
Southern Africa	0.53	-0.12	0.14	-0.07
South America	0	0.01	0.09	-0.20
United States	0	14.63	5.99	10.58
Western Europe	6.41	-8.64	-4.05	-4.53
Western South America	0.59	0.21	0.26	-0.15
World	**0.00**[4]	**0.00**[4]	**0.00**[4]	**0.00**[4]

Notes: Net exports: Export quantities minus imports; A map of the regions presented in this table is available in *Kim et al., 2017*

[1] Projected net exports in 2040 in SSP5 with fRCP8.5 productivity change minus projected net exports in 2040 for SSP5 without climate change effects on productivity. Values for panels are the sum of values for plywood, particle board, and fibreboard.

[2] Values for panels are the sum of values for plywood, particle board, and fibreboard.

[3] Values for paper and paperboard are the sum of values for newsprint, printing and writing paper, and other paper and paperboard.

[4] World net exports must be zero and are shown here to demonstrate that adding-up constraints are met in GFPM

Source: GFPM projections.

BOX 3

Modelling the effects of changes in forest net primary productivity (NPP) on global forest products and markets

The projections of NPP, which were modelled mainly as a function of ambient CO_2 concentration, temperature, and available soil water, were provided by the Dynamic Vegetation Model MC2 (Kim et al., 2017), in conjunction with the CENTURY Soil Organic Matter Model (Parton, 1996). The chosen climate scenario closely mimics the IPCC's Representative Concentration Pathway (RCP) 8.5, the unconstrained emissions scenario leading to the highest projected greenhouse gas concentration trajectory over the next century. Projections were provided for 16 world regions defined in MC2 (see map in *Kim et al., 2017*) for the period 1980-2100. The projected change for each region was for seven different climate model ensemble members, called realizations, representing different combinations of climate sensitivities, net aerosol forcing, and initial conditions. These projections were derived from the Massachusetts Institute of Technology (MIT) Integrated Global System Model-Community Atmosphere Model (IGSM-CAM) general circulation model (Kim et al., 2017, Tian et al., 2016). In this analysis, the average values from the seven realizations were inputted to the Global Forest Products Model (GFPM), which was obtained by estimating the trend in projected NPP values from 1980 to 2100.

The changes in NPP were inputted to the GFPM, reflecting a case with productivity change, where the endogenous forest stock growth in each of the 180 GFPM countries was adjusted by the corresponding projected change in NPP (TABLE 1.1). The projected forest products' market outcomes were compared to a reference under Shared Socioeconomic Pathway (SSP5), where no adjustment was made to the endogenous forest growth stock in GFPM. The differences in market outcomes between the two runs were attributed to climate-change-induced changes in forest productivity. In both runs, demand for forest products was driven by Gross Domestic Product (GDP) (IIASA, 2019). The supply of industrial roundwood was driven by changes in forest and planted forest - areas projected under SSP5. In turn, this was affected by projected per capita GDP, labour force, and projected rural population density (Nepal et al., 2019b). The climate change effect on forest products' markets was evaluated using SSP5 because the assumed socio-economic vision best aligns with the RCP 8.5 climate forcing scenario.

The GFPM results depend on the global NPP projections, which are dependent on the general circulation model (GCM) from which NPP projections were made with the MC2 model. Inputting different GCMs to the MC2 would generate different global forest productivity projections, leading to different market outcomes from those shown. Projected changes in forest productivity under RCP 8.5 may be expected to differ from those generated under another climate forcing scenario, such as RCP 4.5. Future analyses would be needed to fully understand the implications of differing GCMs and RCPs when drawing inferences about the global forest sector effects of climate change.

3

Climate change mitigation

KEY QUESTION:

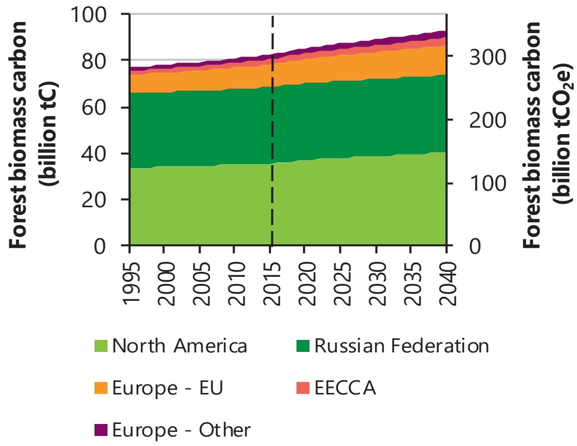
How can UNECE forests and the forest sector contribute to climate change mitigation?

Forests mitigate climate change by taking up carbon while growing and storing carbon in the living biomass above and below ground, in dead wood and soils. Forest disturbances strongly affect forest carbon (Seidl et al., 2014, McNulty 2002). Harvesting trees releases part of the carbon into the atmosphere, but another part remains stored in wood products, where the lifespan may vary from days to centuries. Using wood to replace energy-intensive materials, such as concrete, steel and plastic could play a significant part in limiting emissions from fossil fuel sources. Generating energy from woody biomass instead of fossil fuels avoids the use of fossil fuels and their associated emissions. Forest management strategies should consider the carbon balances of growing forests and wood products. Forest management may also have biophysical climate impacts, related to surface reflectance and roughness and emissions of biogenic volatile organic compounds (Astrup et al., 2018; Luyssaert et al., 2018). These biophysical climate impacts are not well understood.

3.1 Projected mitigation in the SSP scenarios

Based on the Global Forest Resources Assessment (FRA) 2015 data on forest growing stock, carbon stock and estimated conversion factors[3], carbon stock in above and below ground forest biomass in the UNECE region in 2015 totaled 83 billion metric tonnes of carbon (tC), or 303 billion metric tonnes of carbon dioxide equivalent (tCO_2e), (Johnston et al., 2019). The FRA 2015 reported 1,668 million hectares of forest in the UNECE region (FAO), so this would translate to an estimated carbon stock of 50 tC/ha (182 tCO_2e /ha). The largest stocks are located in the Russian Federation (33 billion tC or 121 billion tCO_2e – 40%) and North America (35 billion tC or 130 billion tCO_2e – 43%) (FIGURE 3.1). The projected average annual carbon sequestration rate for the whole of the UNECE region between 2015 and 2040, was 1.5 billion tCO_2e per year in the reference scenario and SSP5, and 1.6 billion tCO_2e per year in SSP3. For comparison, fossil fuel emissions in 2019 were 5.9 billion tCO_2e in North America, 1.6 billion tCO_2e in the Russian Federation and 3.9 billion tCO_2e in Europe. All UNECE subregions represented a net forest carbon sink in until 2040, with little variation across the three modelling scenarios. The trend was stable in the reference scenario, falling slightly in SSP5 and rising slightly in SSP3. The highest rate of sequestration was projected in North America at 0.7 billion tCO_2e per year. The Europe-EU subregion registered 0.5 billion tCO_2e per year. Other subregions collectively sequestered about 0.3 billion tCO_2e per year. Globally, the net annual sink was 1.2 billion tCO_2e per year: forests in Africa, Oceania and South America were all net sources of carbon.

FIGURE 3.1 CARBON STOCK IN ABOVE- AND BELOW-GROUND FOREST BIOMASS IN THE UNECE REGION UNDER THE REFERENCE SCENARIO



Note: Historical data until 2015, followed by GFPM projections until 2040. Though not shown, results for SSP3 and SSP5 are similar.

Source: GFPM projections.

After trees have been harvested, part of their stored carbon remains in harvested wood products (HWP), such as construction materials, furniture, packaging, and paper products. Their contribution to climate change mitigation has long been recognized. Since the United Nations Framework Convention on Climate Change (UNFCCC) Conference of Parties in Durban in 2011, countries have

[3] The ratio of the FAO FRA (2015) reported carbon stock (tonnes) in above-and below-ground biomass pool and the forest growing stock (m^3) data in a country. It should also be noted that FRA 2015 uses FAO's regional definition, e.g., North America (Canada, Greenland, Mexico and the US), vs. the UNECE definition of North America (Canada and the US).

had to account for carbon stored in HWPs when reporting annual greenhouse gas emissions. Reporting HWP carbon storage follows the convention that carbon in the HWP pool is assigned to the country that produced the wood, rather than the country that consumed the wood product. The HWP pool may be a carbon sink or source, depending on the balance between carbon entering and leaving the pool. The manufacture of new wood products adds carbon to the HWP pool. As older products reach the end of their life, they may be incinerated or landfilled, releasing carbon from the pool.

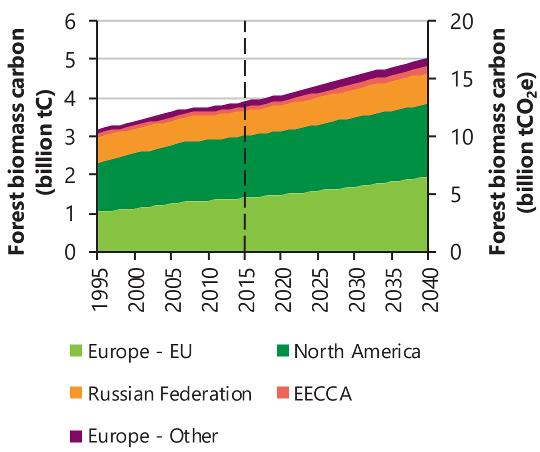
Based on this approach, an estimated 3.9 billion tC (14.3 billion tCO_2e) were stored in HWP in 2015 in the UNECE region. North America had the largest stocks (1.6 billion tC or 5.9 billion tCO_2e, 34%), followed by Europe-EU (1.4 billion tC or 5.1 billion tCO_2e, 32%) (FIGURE 3.2). Globally, in 2015, the HWP carbon pool acted as a net annual sink of 0.47 billion tCO_2e per year. How the HWP sink behaves in future will depend strongly on the development of wood product markets (Johnston and Radeloff 2019; Pilli et al., 2015). The reference scenario outlines that HWP will increase their storage of carbon by 0.5 billion tCO_2e (TABLE 5.1 and FIGURE 3.2). Under SSP3, the annual sink is projected to fall slightly to 0.44 billion tCO_2e per year. Under SSP5, it might increase to 0.63 billion tCO_2e per year by 2040. In 2015, the UNECE region accounted for 24% of the global HWP sink (0.11 billion tCO_2e per year). This share would increase under all SSP scenarios (including the reference scenario), to 30% in 2040 (0.15 billion tCO_2e per year in SSP3 and 0.21 billion tCO_2e per year in SSP5). Asia, with its rapidly growing population and economic growth, accounts for 60% of the global HWP carbon sink.

The HWP sink is developing differently between the five UNECE subregions. In the Europe-Other, EECCA and the Russian Federation, the sink is projected to remain constant or to increase slightly in all scenarios. In North America, the sink would increase until 2030, declining thereafter. SSP3 shows the lowest rise and strongest decline, while in in SSP5, there would be a stronger initial rise, followed by a smaller decline. Europe-EU shows an increase of 60% in SSP3, or 103% in SSP5. Projections of carbon storage in HWPs are small compared to the projections for above- and below-ground biomass carbon. The projected HWP carbon storage rate in the reference scenario for the UNECE region would be only around 13% of the projected sequestration rate for above and below ground biomass (see TABLE 5.1 on page 44 in Chapter 5).

3.2 Options for increased mitigation

The principal strategies for enhancing forestry's contribution to climate change mitigation are through boosting carbon storage by existing forests (mainly biomass and soil) through forest management, reforestation and afforestation; increasing use of wood products, for example by promoting wood as an alternative to higher carbon content products thereby increasing carbon stored in HWP and; encouraging use of logging and wood processing residues and post-consumer wood for energy. Applying these strategies is not straightforward and may involve trade-offs. For instance, using more wood in manufacturing or energy may result in more intensive harvesting. This would lower forest carbon stock but would also cut carbon emissions from the energy sector. Conversely, harvest reductions may lead to greater forest carbon stock but result in lower mitigation in manufacturing and energy. Efficient use of forest resources may be the only way to increase manufacturing and energy mitigation without diminishing forest carbon. Other approaches to maintain forest carbon stock while increasing harvesting would include stimulating volume increment, planting faster-growing or better-adapted tree species or provenances, or adopting carbon-preserving management such as continuous cover forestry. Expanding the forest area, preventing forest loss, and preserving and increasing soil carbon stocks in forests, also increase the forest carbon stock.

FIGURE 3.2 CARBON STOCK IN HWP IN THE UNECE REGION UNDER THE REFERENCE SCENARIO



Note: Historical data until 2015, followed by GFPM projections until 2040. Though not shown, SSP3 and SSP5 results are similar.

Source: GFPM projections.

3.2.1 Potential for carbon sequestration by forest ecosystems through forest management

The global potential for improved forest management, such as reduced-impact logging or extended rotations in natural and planted forests is estimated at 0.4-2.1 billion tCO_2e per year (Roe et al., 2019). These measures may be broadly categorized as improving management of natural and planted forests and more active wildfire management (Griscom et al., 2017). The potential for such measures, and thereby boosting carbon sequestration, will depend on current and future forest conditions, and management limitations due to economics and policies.

Natural disturbances can disrupt the forest carbon cycle. In the short term, they may release large volumes of CO_2, but in the longer term they may help maintain the carbon sink by altering age-class distribution and introducing younger trees (Pugh et al., 2019). Forest structure and climatic conditions may also affect the impact of natural disturbances. More frequent and severe natural disturbances may offset carbon sequestration gains from improved management (Seidl et al., 2014). This should be borne in mind when designing mitigation strategies based on forest management.

Several studies have estimated mitigation potentials for parts of the UNECE region. These are summarised in TABLE 3.1, TABLE 3.2 and TABLE 3.3, indicating for each study the reference scenario, the biomass carbon sink in the reference scenario, and the change in sink for the alternative scenarios, compared to the reference. The biomass sink in Europe-EU as estimated in this Outlook is relatively high, but it includes a larger forest area (178 million ha) than the other studies (132-138 million hectares) shown in TABLE 3.1. Most studies have quantified only the impacts of reduced or increased harvests which increase or reduce the sink. On average, for a 10% change in harvest, the sink changes by 59 million tCO_2e. There is a stronger effect in the Priority on Biodiversity scenario of the European Forest Sector Outlook Study II (EFSOS-II), as this includes longer rotations and the intensity of thinning. EFSOS-II is the only study that features a scenario combining changes in rotation length and thinning intensity with an unchanged harvest level, yielding a potential carbon sink of 0.13 billion tCO_2e per year if the modelled management practices were implemented. The climate change scenario implemented for this Outlook can be used as a proxy for a scenario where volume increment is stimulated, but the effect is small, at 0.01 billion tCO_2e per year, due to the small increase in net primary productivity (NPP) (1%). A conversion to more productive species is unlikely to have much effect until after 2040 (Nabuurs et al., 2014).

TABLE 3.1 Europe-EU: Forest carbon sink baseline and changes by scenario summarized from several studies (billion tCO_2e).

		Scenarios							
		Reference scenario		Change in sink in decreased harvest scenario		Change in sink in increased harvest scenario		Change in sink in increased biomass sink scenario	
Study	This Outlook	SSP2	0.47	SSP3 (-4%)	0.04	SSP5 (+3%)	-0.02	Climate change	0.01
Study	EFSOS-II	Baseline	0.27	Priority to biodiversity (-17%)	0.21	Promoting wood energy (+2%)	-0.02	Maximizing biomass carbon	0.13
Study	Pilli et al., 2017	Constant harvest	0.46	Harvest (-20%)	0.1	Harvest (+20%)	-0.1		
Study	Rüter et al., 2016	Reference	0.15	Increase in C stock in existing forests (-19%)	0.16	Strongly increases material wood use (+3%)	-0.02		

Notes: Values in parentheses are estimated percentage changes of the harvest for the corresponding periods, compared to the studies'-specific reference scenarios.

Each study uses different scenarios which have been grouped here as reference scenarios, decreased harvest, increased harvest and increased biomass sink scenario. The total biomass sink under the reference scenario (billion tCO_2-eq per year) is shown and the additional effect of the other scenarios (billion tCO_2-e per year) compared to the study-specific reference scenario, averaged over 2015-2040 (this Outlook), 2015-2030 (EFSOS-II), 2000-2030 (Pilli et al. and Rüter et al.) and are also indicated.

For the Europe-other subregion, only estimates generated for the current Outlook and EFSOS-II are available (TABLE 3.2). The current Outlook has higher values for the forest biomass carbon sink (0.13 tCO_2e per year) than in EFSOS-II (0.04 billion tCO_2e per year), despite little difference in forest area, at 33 million ha and 34.9 million ha respectively. The impacts of management changes are minimal for both studies. A study of vulnerability to disturbances under the EFSOS-II scenarios, for Europe as a whole, found a potential loss of 0.185 billion tCO_2e per year for 2021-2030, which would negate the mitigation effect of these scenarios (Seidl et al., 2014).

TABLE 3.2 Europe-other: Forest carbon sink baseline and changes by scenario summarized from this Outlook study and EFSOS-II (billion tCO_2e)

		Scenarios							
		Reference scenario		Change in sink in decreased harvest scenario		Change in sink in increased harvest scenario		Change in sink in increased biomass sink scenario	
Study	This Outlook	SSP2	0.13	SSP3 (-4%)	0.01	SSP5 (+4%)	0	Climate change (-1%)	0
Study	EFSOS-II	Baseline	0.04	Priority to biodiversity (-0.4%)	0.01	Promoting wood energy (+4%)	0	Maximising biomass carbon	0.04

Note: Values in parentheses are estimated percentage changes of the harvest for the corresponding periods, compared to the studies'-specific reference scenarios.

Each study uses different scenarios which have been grouped here as reference scenarios, decreased harvest, increased harvest and increased biomass sink scenario. The total biomass sink under the reference scenario (billion tCO_2-eq per year) is shown and the additional effect of the other scenarios (billion tCO_2-e per year) compared to the study-specific reference scenario, averaged over 2015-2040 (this Outlook) or 2015-2030 (EFSOS-II) are also indicated.

TABLE 3.3 Canadian und United States: Forest carbon sink baseline and changes by scenario summarized from different studies (billion tCO_2e)

		Scenarios							
		Reference scenario		Change in sink in decreased harvest scenario		Change in sink in increased harvest scenario		Change in sink in increased biomass sink scenario	
Study	This Outlook-Canada	SSP2	-0.02	SSP3 (-3%)	0.01	SSP5 (+3%)	-0.01	climate change (+3%)	0.15
Study	This Outlook-US	SSP2	0.71	SSP3 (-3%)	0.03	SSP5 (+3%)	-0.02	climate change (+12%)	0.52
Study	Nepal et al. (2012) and Ince et al. (2011) – US	B2[1]	0.75	HFW[1] (-5%)	0.04	A1B[1] (+55%)	-0.3		
Study	Nepal et al. (2013) -US	Baseline	0.74					Timber set asides (-7% to -14%)	0.03 to 0.14
Study	US Environmental Protection Agency (2005)-US							Longer rotation + increased growth + timber preserve	0.11 to 0.39

Notes: This Outlook covered the period 2015-2040. The period for the other studies was 2010-2060. Values in parentheses are estimated percentage changes of the harvest for the corresponding periods, compared to the studies'-specific reference scenarios.

Each study uses different scenarios which have been grouped here as reference scenarios, decreased harvest, increased harvest and increased biomass sink scenario. The total biomass sink under the reference scenario (billion tCO_2-eq per year) is shown and the additional effect of the other scenarios (billion tCO_2-e per year) compared to the study-specific reference scenario, averaged over 2015-2040 (this Outlook) or 2010-2060 (other studies) are also indicated

[1] IPCC-based scenarios assuming high (A1B), low (HFW), and medium (B2) global expansion of primary biomass energy production and, in the United States, expansion of wood fuel feedstock consumption

Examining the effects of forest management and harvesting in North America has focused mainly on quantifying aggregate forest carbon and the overall effect of economic, technology, as well as demographic changes, on net carbon status. In 2018, net carbon sequestration by forests in the United States was estimated at 0.57 billion tCO_2e per year (US Environmental Protection Agency 2020a). The 2018 estimate for Canada was 0.14 billion tCO_2e per year (Environment and Climate Change Canada, 2020). Studies have examined how forest management aimed at increasing carbon stock per hectare, or providing incentives to use wood for energy, might affect carbon sequestration in the United States (McKinley et al., 2011). Strategies considered include extended rotations, management inputs to boost growth rates, developing a robust carbon market, and preserving some forests. Combining some of these strategies could increase carbon sequestration by as much as 0.11-0.39 billion tCO_2e per year, compared to existing sequestration (TABLE 3.3), though actual figures would be dependent on carbon pricing (United States Environmental Protection Agency 2020b).

Discussion of the complexity of managing or expanding forest carbon while facing rising rates of natural disturbances, particularly wildfire, has focused on forests of the western United States (Sample et al., 2015). It has been estimated that emissions from forests in the United States due to natural disturbance have generated more than 0.73 billion tCO_2e per year, though regrowth of forests roughly balanced these out (Williams et al., 2016). Summarizing a range of studies, Williams et al., (2016) find that emissions from wildfires average at 136 million tCO_2e per year, ranging from 33-294 million tCO_2e per year. For comparison, emissions resulting from insect outbreaks range from 7-84 million tCO_2e per year, and for tropical cyclones, the range was 51-385 million tCO_2e per year (Williams et al., 2016). These figures are already taken into account in estimating the current net positive carbon sequestration rate for the United States. In terms of scale, these rates of emission are roughly the same order of magnitude as the benefits from improved forest management. A hypothetical doubling of the effects of greater disturbance would completely offset any mitigating effect of improved forest management. In sum, improved management, and measures to reduce disturbances have apparently comparable effects on net carbon sequestration; direct trade-offs between these two approaches are not yet well studied. Comparative costs and effectiveness must be considered before deciding the best approach.

Analyses of external factors affecting the North American and global forest sectors show how differing growth rates or harvesting intensity might affect carbon (Ince et al., 2011; Nepal et al., 2013; this Outlook). Modelling the carbon mitigation potential of the forest sector in the United States, 2010-2060, under IPCC's 4th assessment and the United States Department of Agriculture (USDA) Forest Service 2010 Resources Planning Act (RPA) Assessment scenarios, showed that a large increase in wood removals, driven by economic and population growth, together with higher wood energy consumption, would result in forests in the United States becoming a carbon source after 2045. Between 2010 and 2060, average net carbon sequestration would be reduced by 0.3 billion tCO_2e per year by the modelled increase in wood removals, compared to the reference scenario used in the study Nepal et al., 2012. By contrast, modelling of reduced wood removals (-5%), linked to historically low wood energy consumption, projected increased average net carbon sequestration by 0.04 billion tCO_2e per year (TABLE 3.3).

The average forest biomass net carbon sequestration rates in the United States projected under different SSP scenarios modelled by GFPM in this Outlook concur with the projections of past studies (TABLE 3.3).

Studies that looked at extreme shifts in forest management, such as the absolute preservation of forests, found that these give only modest mitigation potential, because increased carbon sequestration in preserved forests would be negated by increased harvests elsewhere. This economic "leakage" effect is caused by lower overall timber supplies driving up prices and leading to more harvesting from other forests. For instance, increased carbon sequestration between 2010 and 2060 ranged from 0.03 billion tCO_2e per year, if 49 million hectares (21%) of projected timberland in the United States were set aside, to 0.14 billion tCO_2e per year if the projected set-aside area were increased to 68 million hectares (35%) of timberlands (Nepal et al., 2013).

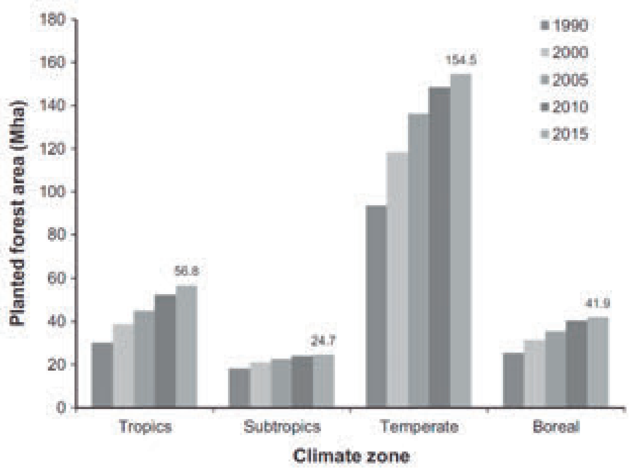
Varying assessments of the forest carbon sink in the Russian Federation make it challenging to assess the current carbon budget. Reporting to UNFCCC relies on data from the State Forest Register, which quoted a carbon sink of 0.55-0.73 billion tCO_2e per year for managed forests, lower than most other estimates (National Inventory Report, 2019). Extending the same approach to all Russian Federation forests produced an estimated carbon sink of 0.76–0.84 billion tCO_2e per year (Zamolodchikov et al., 2017). This is much higher than the 0.1 billion tCO_2e per year estimated by this Outlook. Other inventory-based assessments using official data estimated a carbon sink of 1.5-2.4 billion tCO_2e per year (Filipchuk et al., 2018). Inverse modelling studies estimated a land carbon sink of 2.2–2.6 billion tCO_2e per year (Sitch et al., 2015; Shvidenko and Schepaschenko, 2014). Estimates of dynamic vegetation models (DGVMs) calculate a sink of 0.7 billion tCO_2e per year (Dolman et al., 2012). It is not known to which extent these figures include for recent forest fire increases. The multi-year average of forest fires has been estimated at 5.6 million ha per year (Vega-Science, 2020). From 1998-2010, annual forest fire emissions have been estimated at 300±55 million tCO_2e per year (Shvidenko et al., 2011; Shvidenko and Schepaschenko, 2013). Uncertainty about fire emissions is large because of post-fire dieback and differing definitions of burn severity, plus unknown effects on permafrost.

Options to boost carbon sequestration by forests in the Russian Federation include the potential to mitigate greenhouse gas emissions from wildfires by 0.8–1.5 billion tCO_2e per year (Romanovskaya et al., 2019; Karjalainen et al., 2009). Furthermore, minimizing soil disturbance during logging could reduce them by 0.06–0.22 billion tCO_2e per year. Current data show wood residues from forest harvesting in the Russian Federation ranging from 40% to 50% of tree biomass. Reducing this could mitigate 0.22–0.28 billion tCO_2e per year (Romanovskaya et al., 2019; Shvidenko et al., 1997). However, it is unlikely that any of these options will be implemented soon and on a large scale.

3.2.2 Potential for carbon sequestration by forests through reforestation and afforestation

Research since the IPCC special report on Land Use, Land-Use Change and Forestry (IPCC, 2018) suggests afforestation could significantly reduce global net carbon emissions. Afforestation's ability to sequester large volumes of CO_2 per unit of forest area combined with the opportunity to expand forest area make afforestation an attractive option compared to other mitigation strategies. Moreover, when global integrated assessment models are run with the objective of limiting temperature rises to a maximum1.5°C or 2°C maximum (compared to the 20th century global average), substantial emission reductions result, when accompanied by a commitment to substantial growth in land areas dedicated to Bioenergy and Carbon Capture and Storage (BECCS) (Popp et al., 2017). In the absence of this commitment, continued emissions from fossil fuels inhibit lower net emissions. An IPCC Special Report recommended that an expansion of global forest area by 1 billion hectares would be a cost-effective way of limiting a temperature increase to 1.5°C above pre-industrial levels by 2100 (IPCC, 2018). Estimates exist that confirm this restoration potential, with mitigation benefits of 750 billion tCO_2e, if forests were allowed to grow to maturity (Bastin et al., 2019). However, the study was heavily criticized for assumptions about where forests could grow and other technical aspects. Forest loss is greatest in the tropics, while forest area is generally expanding in China, Europe, and North America (FIGURE 3.3) (Payn et al., 2015).

FIGURE 3.3 TRENDS IN PLANTED FOREST AREA BY MAJOR BIOME FROM 1990 - 2015



Source: Payn et al., 2015.

There is a common view that global forest area is still in decline, though a recent report claims that, since 1982 there has been a 7.1% increase in global forest cover of 224 million hectares (+relative to the 1982 level) (Song et al., 2018).

The High Forest Area (HFA) scenario in this Outlook assumes a global forest area increase of 10% by 2040. This translates to a sixfold increase in the rate of global carbon sequestration in above- and below-ground forest biomass. The additional sequestration compared to the reference scenario is 5.87 billion tCO_2e per year over the period 2015-2040. Of this figure, Europe would account for 0.83 billion tCO_2e per year (14%), North America for 0.61 billion tCO_2e per year (10%), and the Russian Federation for 0.51 billion tCO_2e per year (9%), with 1.95 billion tCO_2e per year for the UNECE region. This aligns with a study that found an afforestation potential of 1.9 billion tCO_2e per year for the UNECE region (Griscom et al., 2017) (TABLE 5.1). This figure would make a significant contribution to global emissions compensation of close to 4% but would require an unprecedented extra 180-320 million hectares of new plantations. For example, in the study by Griscom et al. (2017), France would need to almost double its forest area, requiring huge efforts to identify areas, involve landowners and local communities, introduce socio-economic incentives, and expand wood manufacturing. Only then could long-term maintenance and sustainable management be assured. Historically these contingencies have not been available to other large-scale planting drives, highlighting the complex set of conditions needed to meet such goals. It is estimated that establishing forest on non-forested land in the United States sequestered 0.11 billion tCO_2e in 2018 (US Environmental Protection Agency, 2020a). An earlier study in the United States produced an estimate of 0.83 billion tCO_2e per year as the maximum potential mitigation from afforestation, dependent on the price of carbon (McKinley et al., 2011).

The level of forest expansion assumed in the Outlook scenarios for the UNECE region alone are of the same magnitude as the Bonn challenge. This global effort aims to restore 150 million hectares of the world's deforested and degraded land by 2020, and 350 million hectares by 2030. Launched in 2011 by the German Government and the International Union for Conservation of Nature (IUCN), it was later endorsed and extended by the New York Declaration on Forests (NYDF) at the 2014 UN Climate Summit. Meeting these goals would secure carbon sequestration similar to the Outlook scenarios. However, five years after adoption, there is little evidence that these goals will be achieved (NYDF, 2019). Tropical deforestation has continued since 2014, and while political will for restoration has increased, restoration promises have been slow to gain traction. Until now, most restoration has been outside natural forests.

3.2.3 Potential for carbon storage and substituting carbon intensive materials with wood products and bioenergy

Strategies for increased carbon storage and substituting carbon intensive materials with wood aim at increasing storage of carbon in long lived wood products, replacing energy intensive materials like concrete, steel or glass, replacing fossil fuels use in plastics or synthetic fibres for fashion production and for energy generation (Petersen & Solberg 2005; Werner & Richter 2007; Sathre & O'Connor 2010). These strategies would require increased harvesting (with trade-offs in biomass carbon pools) as well as improved recycling rates and extended life for wood products (Brunet-Navarro et al., 2017). There has been progress in estimating the size and changes in the HWP carbon pool but estimating the potential for avoiding carbon emissions by replacing carbon intensive materials with wood is challenging.

The climate benefits of substituting wood are best estimated by calculating greenhouse gas emissions from the manufacture of a wood product and then comparing with emissions for manufacturing the product that would be replaced, taking into account its full life from production to end of life (Churkina et al., 2020). This will not be feasible for every product and its substitute. Typically, a general substitution or displacement factor is used to quantify greenhouse gas reductions if a wood-based product were used instead of a chemical compound, construction element, energy service, or textile fibres. Estimates of the substitution impact are made by multiplying wood product quantities by the product-specific substitution factor. A literature review of substitution factors found that, by far, the majority of factors for wood and wood-based products had lower fossil and process-based emissions than equivalent non-wood products (Box 4 Substitution factors). Most substitution factors in the literature review were connected to construction, with the emphasis on manufacturing. There were significantly fewer substitution factors for products like furniture, packaging, and textile fibres, and no substitution factors for the biochemicals and biofuels which will be important products in a future bioeconomy (Lettner et al., 2018).

There is substantial variability and uncertainty in published substitution factors, even for the same type of product, which can be explained by different assumptions, data and methods (Leskinen et al., 2018). For example, substitution effects assume the type of non-wood product substituted, its operating life, and end-of-life management of wood and non-wood products. Analyses are also complicated by integrated wood production systems that produce multiple products, and the interdependencies between these. For instance, the sawmilling industry produces wood for construction, while the residue is raw material for energy and paper products. Furthermore, substitution factors are usually static, as they do not account for production efficiency changes of substitute products, or new production technologies, product developments, and the development of bioeconomy markets, all of which are likely to change greenhouse gas (GHG) emissions. The future scale of production and consumption of products also has an influence on the substitution effect. Proper upscaling of the substitution benefits on a regional or market level requires an understanding of market dynamics and detailed substitution processes (e.g., Knauf, 2016; Soimakallio et al., 2016; Braun et al., 2016; Suter et al., 2017; Smyth et al., 2017). However, few studies report such weighted substitution factors (Suter et al., 2017; Smyth et al., 2017; Geng et al., 2019a, b).

Given that wood is already used extensively, there are clear historical climate benefits from material substitution. However, to work towards ambitious climate targets, it is important to focus on future changes in wood product market share, new wood-based products, technological changes, and potential additional climate benefits (Leskinen et al., 2018).

BOX 4
Substitution factors

A review of 51 studies with information on 433 substitution factors, found that most focused on North America and the Nordic countries, whereas few focused on Asia or South America, and none on Africa (Leskinen et al., 2018).

The 51 studies suggested an average substitution effect of 2.2 kg CO_2/kg wood, which means that for each kilogram of wood product that substitutes non-wood products, an average emission reduction occurs of approximately 2.2 kg CO_2. Substitution factors are highly variable, with 95% of values in the range 1.3-9.3 CO_2/kg wood. This reflects values based on many different products, non-wood materials that are substituted, production technologies, numbers of life cycle stages considered, and end-of-life management practice.

The construction sector accounted for 79% of published substitution factors. These covered structural uses such as building internal and external walls, wood frames and beams, and non-structural uses like windows, doors, ceilings or floor coverings, cladding, and civil engineering. For structural components, the average substitution factor was 2.4 kg CO_2/kg wood product. For non-structural products it was 2.9 kg CO_2/kg wood product. Variability was high for both.

Using wood fibre to manufacture textiles may have a substitution effect of up to 5.1 kg CO_2/ kg, the largest benefit across all products considered. Two studies (Rüter et al., 2016; Shen et al., 2010) reported that viscose, lyocell and modal production from wood fibres resulted in lower CO_2 emissions than for producing cotton or synthetic fibres. The production technology and resource base could have a significant impact on estimated substitution effects. For example, an integrated plant using modern technology to produce textile fibres, pulp, and factory biomass for process energy, had lower GHG emissions than conventional textile production technology using market pulp supplies (Shen et al., 2010).

Other products, such as wood-based chemicals, paper, packaging and furniture, generally have moderate substitution benefits, with factors averaging 1.8-2.7 kg CO_2/kg wood product. These results were based on few studies and were limited to few product comparisons. Only one study compared the life cycle emissions of a printed magazine with an electronic tablet version; it highlighted that the substitution factor may be positive or negative, depending heavily on readership for the tablet edition, readers per copy for the print edition, file size, and the use of the tablet for other purposes (Achachlouei & Moberg, 2015).

3.2.3.1 *Construction*

Engineered wood products are a relatively new product category with high potential for mitigation (Churkina et al., 2020). Products include cross laminated timber (CLT), laminated veneer lumber (LVL) and glue laminated timber (glulam).

Most CLT is manufactured in Europe, and production is rising steadily but slowly in North America. At least two plants are soon expected to begin making engineered wood products in the Russian Federation (Jauck, 2019). CLT is also manufactured in Japan and New Zealand, and more recently in South Africa. Pilot plants or feasibility studies are underway in Brazil, Chile, China, and Indonesia (Muszynski et al., 2020).

Engineered wood products have been used to construct high-rise wooden buildings, and in the last decade buildings over six storeys have been constructed in Canada, Norway, Sweden, the United States and the United Kingdom, using CLT and LVL panels, as well as glulam and parallel strand lumber (Green and Taggart, 2017).

Between 2020 and 2050, 2.3 billion new urban dwellers will need housing and commercial buildings. Using conventional materials would generate annual emissions of 0.53 billion tCO_2e per year, assuming an average floor area of 30 square metres (m^2) per capita. Using wood for half of these buildings could see this reduced by 0.15 billion tCO_2e per year, with an additional 0.52 billion tCO_2e per year stored in the buildings (Churkina et al., 2020). There would be a corresponding, though temporary, reduction in forest biomass carbon storage. A transition to bio-based building materials will only succeed as a climate mitigation strategy if forests are managed and harvested sustainably to avoid forest degradation and soil depletion. It is also important that wood from existing and future buildings should be recovered and reused, preferably as other long-lived consumer products, to the extent practicable.

The China-High Wood Consumption (China-HWC) scenario and the Europe-High Wood Consumption (Europe-HWC) scenario assume sawnwood and panels will increasingly be used in construction. Using the average substitution factor for structural wood construction materials for sawnwood of 2.4 kg of CO_2 per kg wood, and 2.9 kg CO_2 per kg product for products such as plywood, panels and fibreboard, it was assumed that all increased consumption of these products would be used in construction, replacing non-wood products. The IPCC's production approach to HWP carbon accounting was used, hence the carbon is assigned to the country where the wood was grown.

The projected carbon stored in the China-HWC scenario was 86.7 million tCO_2e per year, 16% more than the reference scenario, from 2015-2040. Most of this additional wood was grown within Asia, which accounted for 73.1 million tCO_2e per year of the carbon stored in HWPs, while the UNECE region contributed 12.3 million tCO_2e per year (TABLE 3.5). An additional 139.7 million tCO_2e per year of GHG emissions were avoided globally. The combination of increased HWP carbon storage and avoided emissions did not compensate fully for the contraction in above- and below-ground carbon pools due to increased harvesting. This produced a small negative change in global carbon stock of -32.2 million tCO_2e per year. This value is subject to considerable uncertainty in the choice of substitution factor, and assumptions about harvesting losses, processing efficiency, and the fate of co-products during manufacture. The net carbon sequestration effect in Asia was positive (12.4 million tCO_2e per year), while it was negative in the UNECE region (-21.9 million tCO_2e per year) and other parts of the world.

The Europe-HWC scenario projected greater carbon storage in HWP in all UNECE subregions except for the Russian Federation. The differences between this and the reference scenario are shown below (TABLE 3.5).

The values shown are subject to the same uncertainties as the China-HWC scenario. The projected reductions in forest biomass carbon due to increased harvests in Europe-EU, Europe-Other and EECCA were more than offset by increased HWP carbon storage and avoided emissions. The balances in North America and the Russian Federation were negative, but the UNECE region had a positive carbon balance of 43.1 million tCO_2e per year. Both the China-HWC and the Europe-HWC scenario show a positive net carbon effect in their respective regions, but a negative global carbon balance highlighting the risk of leakage effects in other world regions.

TABLE 3.4 **Annual average differences in carbon storage and avoided emissions between the China-HWC and reference scenarios** (million tCO_2e per year)**, 2015-2040, and the overall balance.**

	Biomass	HWP	Avoided emissions		Balance
			Construction	*Other*	
Europe-EU	-10.2	2.8	-1.6	0	-9.0
Europe-Other	-1.7	0.1	-0.3	0	-1.9
North America	-10.6	5.5	-1.0	0	-6.1
EECCA	-0.9	1.0	-0.3	0	-0.2
Russian Federation	-7.3	2.9	-0.4	0	-4.7
Africa	-1.4	0.3	-0.2	0	-1.4
South America	-7.7	-0.1	-0.3	0	-8.2
Central America	-9.5	0.3	0.3	0	-8.9
Asia	-204.3	73.1	143.7	-0.1	12.4
Oceania	-4.9	0.8	-0.1	0	-4.2
World	**-258.6**	**86.7**	**139.7**	**-0.1**	**-32.2**
of which UNECE-Total	**-30.6**	**12.3**	**-3.6**	**0**	**-21.9**

Note: HWP C stocks are assigned to wood producing countries, while avoided emissions are assigned to wood consuming countries. The column "other" refers to emissions occurring in other sectors where wood will be replaced by non-forest materials as a consequence of increased competition for the use of wood.

Source: GFPM projections

TABLE 3.5 **Annual average differences in carbon storage and avoided emissions between the Europe-HWC and reference scenarios** (million tCO_2e per year)**, 2015-2040, and the overall balance.**

	Biomass	HWP	Avoided emissions		Balance
			Construction	*Other*	
Europe-EU	-14.4	15.6	46.5	0	47.7
Europe-Other	-1.7	1.2	2.7	0	2.2
North America	-11.2	4.6	-0.2	0	-6.8
EECCA	-0.8	1.5	1.8	0	2.5
Russian Federation	-6.1	-4.0	5.9	0	-4.2
Africa	-1.2	0.2	-0.1	0	-1.1
South America	-7.0	0.4	-0.3	0	-6.8
Central America	-10.6	-0.1	0.0	0	-10.7
Asia	-26.7	10.5	-3.4	0	-19.6
Oceania	-4.2	0.7	-0.1	0	-3.5
World	**-83.8**	**30.7**	**52.9**	**0**	**-0.3**
of which UNECE-Total	**-34.2**	**18.9**	**56.8**	**0**	**41.4**

Note: HWP C stocks are assigned to wood producing countries, while avoided emissions are assigned to wood consuming countries. The column "other" refers to emissions occurring in other sectors where wood will be replaced by non-forest materials as a consequence of increased competition for the use of wood.

Source: GFPM projections.

3.2.3.2 *Textiles*

New technologies use pulpwood, industrial co-products and agricultural waste for textile production. Not all are operationally feasible on a commercial scale at present, but they do have potential as sustainable alternatives to current textile production. They would also resolve issues arising from fossil-based, GHG-intensive fibres like polyester, or cotton using scarce water and damaging pesticides (Ellen MacArthur Foundation, 2017). These new technologies reduce use of harmful chemicals and improve textile value chain circularity (Antikainen et al., 2017).

Estimating the substitution effect of increased production of wood-based textiles in the Textile-High Wood Fibre Consumption (Textile-HWFC) scenario was based on life-cycle emissions from producing lyocell fibres. Substitution values of 1.95 kg CO_2/kg fibre have been reported when lyocell replaces cotton, and 2.75 kg CO_2/kg fibre when lyocell replaces the synthetic petroleum-based polypropylene, or 4.05 kg CO_2/kg fibre when replacing polyethylene (Shen et al., 2010). Assuming lyocell replaced 25% of cotton and 75% of synthetic, petroleum-based fibres, gives a weighted average substitution factor of 3.04 kg CO_2/kg fibre.

Under the Textile-HWFC scenario, average annual global forest carbon sequestration over the period 2015-2040, would shrink by 7%, or 76 million tCO_2e per year, from 1.15 billion tCO_2e per year in the reference scenario, to 1.08 billion tCO_2e per year (TABLE 3.6). Only 7%, or 5.4 million tCO_2e per year, of this projected reduction in global biomass carbon was projected to be offset by global increase in carbon storage in harvested wood products. This was mainly because textiles products are proxied with paper products in the GFPM, and higher volumes of such short-lived wood products are needed. Increased use of wood fibres for textiles avoided emissions of 77 million tCO_2e per year. Increased competition for wood resulted also in increased use of non-wood alternatives causing emissions to rise by 8.9 million tCO_2e per year, challenging the carbon neutrality of this scenario at global level. In the UNECE region, the loss of carbon from forest biomass in this scenario was offset, giving an overall net positive carbon balance of 0.3 million tCO_2e per year (TABLE 3.6).

In addition, it is important to note that the results of the model assume that there is no long-term carbon storage in textiles, as they are not considered a long-lived wood product. In fact, research has shown that lyocell stores more carbon than is emitted during its production (Kalnbalkite et al., (2017). This would be highly relevant if textile recycling improved in the future, which could significantly extend the life of fibres.

3.2.3.3 *Chemicals*

Fossil-based production processes for chemicals, plastics and composites, are evolving to use industrial wood-based side streams and coproducts as raw material. This reduces GHG emissions and improves circularity. For example, tall oil or black liquor from pulping can be used for generating process energy. Fractionating the crude tall oil into chemical compounds can add significant value. Naphtha is just one derivative used to produce biodiesel or bioplastics (De Bruycker et al., 2014). Some wood-based plastics are already used as linings for beverage cartons. These renewable raw materials from industrial side streams also improve circularity by being recyclable with cardboard. Lignin is another chemical from industrial side streams and could replace fossil-based phenols in several products (Collins et al., 2019). These include adhesives for wood panels (Kouisni et al., 2011), biocomposites (Tanase-Opedal et al., 2019), bioplastics, and polyurethanes (Wang et al., 2019). Currently, 50 million tonnes of kraft lignin are produced worldwide annually during pulp production (Lettner et al., 2018). Only 1-2% is recovered and used as raw material for higher-value products, which is a missed opportunity to reduce GHG emissions (Lora and Glasser, 2002).

TABLE 3.6 Annual average differences in carbon storage and avoided emissions, between the Textile-HWFC and reference scenarios (million tCO_2e per year) over 2015-2040, and the overall balance

	Biomass	HWP	Avoided emissions		Balance
			Textiles	*Other*	
Europe-EU	-7.9	-1.7	11.5	-1.3	0.5
Europe-Other	-1.0	0.3	-0.9	-0.3	-1.8
North America	-16.4	0.7	26.4	-1.8	8.8
EECCA	-0.5	0.7	-0.3	-0.2	-0.4
Russian Federation	-3.3	-2.9	-0.5	-0.2	-6.9
Africa	-3.7	0.8	8.6	-0.2	5.6
South America	-7.8	-0.1	6.0	-0.5	-2.4
Central America	-14.3	-0.4	-0.6	0.3	-15.0
Asia	-18.4	7.2	27.2	-4.5	11.5
Oceania	-2.6	0.7	-0.4	-0.1	-2.5
World	**-76.1**	**5.4**	**77.0**	**-8.9**	**-2.6**
of which UNECE-Total	**-29.1**	**-2.9**	**36.2**	**-3.8**	**0.3**

Note: HWP C stocks are assigned to wood producing countries, while avoided emissions are assigned to wood consuming countries. The column "other" refers to emissions occurring in other sectors where wood will be replaced by non-forest materials as a consequence of increased competition for the use of wood.

Source: GFPM projections.

3.2.3.4 *Energy*

In 2010, 35% of global GHG emissions were from the energy sector (IPCC, 2014). By substituting for fossil fuels, wood could potentially decrease the energy sector carbon footprint. Demand for wood for energy in the UNECE region is expected to mainly be driven by policy developments.

The most recent UNECE/FAO Joint Wood Energy Questionnaire revealed that wood accounts for 35% of all renewable energy in the UNECE region (UNECE/FAO, 2021a). Wood generates between two and three times as much energy as solar, wind, geothermal and hydropower combined in countries providing data. Energy derived from biomass in all its forms accounted for almost 60% of renewable energy in Organization for Economic Cooperation and Development (OECD) countries in 2018, and non-OECD countries had an even larger share at 70% (IEA, 2020).

The primary sources of wood for energy in the UNECE region, are industrial co-products, such as chips, bark, sawdust and shavings from sawmills, as well as material such as black liquor produced from pulping. Together, these account for 51% of wood used for energy. Wood directly harvested from forests, other wooded land, and individual trees account for 34%. Post-consumer wood[4] makes up only 5%, and the remaining share cannot be defined (UNECE/FAO, 2021b). These shares have remained fairly constant between 2007 and 2019.

The production of pellets relies heavily on the use of sawmill residues, except in the southeastern coastal United States, where a study found 69% of biomass was derived from low-value forest biomass in 2017 (Aguilar et al., 2020).

The timescales and leakage effects of using wood energy need to be carefully considered to assess whether wood energy can mitigate climate change. Fossil fuels emit less CO_2 per unit of energy than biomass. In the short-term, atmospheric CO_2 released by burning wood exacerbates climate change (Zanchi et al., 2012). However, the CO_2 in fuelwood was captured from the atmosphere, and will be re-captured by forest regrowth under sustainable management. Depending on the biomass feedstock used to generate energy, notably whether it is residues or roundwood and its origins (e.g., from thinning or clear-felling) it could take many years, perhaps centuries,

[4] This includes wood waste from construction, but also packaging and old furniture, and is mainly consumed in power applications and waste to energy plants

to reach parity (Zanchi et al., 2012, Nabuurs et al., 2017). Furthermore, wood residues and post-consumer wood would release carbon if not used in products, recycled or used for energy, so there could be an opportunity cost for not using them for energy (unlike wood in the forest which would continue to sequester carbon if not burnt).

The carbon footprint of harvesting, processing and transporting wood fuels is lower than for fossil fuels. The revised European Renewable Energy Directive sets out detailed values for greenhouse gas emissions of biomass fuels and fossil fuel, if produced with no net-carbon emissions from land-use change. For wood energy most pathways indicate a reduction in carbon emissions of 70% to 80%, compared to fossil fuels (European Parliament, 2018).

A review of research about wood energy and its impacts on GHG emissions revealed four main insights into its emission-mitigating role (Miner et al., 2014). Though focused primarily on the United States, the conclusions are generally valid.

1) Wood energy reduces fossil fuel use and long-term carbon emissions, provided forest area or growing stock does not decrease.
2) Demand for wood energy provides economic incentives, such as higher timber prices, encouraging investment in forestry, increasing forest area and productivity, helping offset emissions from additional harvesting and wood burning.
3) Though burning wood can increase short-term emissions, long-term cumulative biogenic CO_2 emissions are reduced by replacing fossil fuel.
4) Over 100 years, increased use of wood energy in the United States would result in lower net GHG emissions, compared with fossil fuel emissions.

Energy and climate policies are designed to cut energy and transport sector emissions, increase energy efficiency and raise the share of energy from renewable sources. The Renewable Energy Directives (RED) I and II of the European Union set the most ambitious goals for renewable energy in the UNECE region. RED II set a minimum target to meet 27% of the EU's energy needs from renewable energy sources by 2030 (EU, 2018). In 2020, the European Commission released the 2030 Climate and Energy Framework, which aims to raise the renewable energy share to at least 32% by 2030 (European Parliament, 2020). Given that wood energy already accounts for a significant share of renewable energy, these regulations are likely to strongly impact wood use by the energy sector.

The second European Forest Sector Outlook Study modelled the impact of promoting wood energy in Europe, based on the RED I goals (UNECE/FAO, 2011). It concluded that it would only be possible for wood to continue its leading role in renewable energy production if energy efficiency improved and all potential biomass sources were mobilized. This would include harvesting as much as possible of the annual volume increment, sevenfold increase in extraction of harvesting residues, doubling the volume of landscape care wood and post-consumer wood, and tripling imports. Achieving such a large increase in wood supplies would entail significant trade-offs, especially for land use and biodiversity. Many other factors would present a challenge, including increasing the workforce and harvest equipment pool to achieve such levels (Orazio et al., 2017).

A study covering 2015-2050, looked at how a doubling of wood consumption by the wood energy sector in the United States might affect the net carbon status of the forest products sector in the United States, compared to a base scenario (Nepal et al., 2019a). It found that higher consumption would lead to higher timber prices. Since timberland area in the United States tends to respond positively to timber prices, the study projected that the timberland area in this high wood energy scenario would be 2.5% higher, or 5.2 million hectares, than projected for the base assumption, and that timber stocks would also be higher. The projected increase in forest stocks suggests there would be a net increase in carbon sequestration from expanded wood energy use, but the study did not quantify how increased wood energy consumption might offset fossil fuel emissions. An earlier study that evaluated how emissions might change by modelling a high wood energy consumption scenario and compared it with a business-as-usual case, found that up to 78% of cumulative carbon emissions associated with increased harvesting (declining forest biomass carbon) and burning of wood to generate energy in the United States, would be offset over the fifty years between 2010 and 2060 (Nepal et al., 2015). The projected reduction in emissions under this high wood energy scenario, was brought about by higher timber prices that supported forest expansion, increased carbon storage in wood products, and carbon stored in logging residues left to decay in forests.

4

Climate change adaptation

KEY QUESTION:

How can UNECE forests adapt to climate change?

Forest management has evolved over centuries to meet the demand for forest ecosystem services. Silviculture has focused primarily on satisfying the need for a stable, sustainable supply of materials, especially timber. In recent decades, attention has focused on the provisioning of other ecosystem services as well, including habitat that conserves biodiversity, the need to maintain soil fertility and to protect water and air quality, and the sequestration of atmospheric carbon by forests.

Faced with the uncertainty of climate change impacts, forest ecosystem services assume even greater significance. There will be a need for adaptation strategies to avoid the worst negative impacts and to take advantage of opportunities that result from current and future climatic change. The following section describes potential forest management strategies and adaptation measures to respond to this uncertain future. It includes an overview of national forest management strategies in the UNECE region and concludes with specific adaptation cases.

4.1 Adaptation in natural and managed forests

Adaptation may occur through natural processes, such as genetic selection, or through management. The inherent adaptive capacity of forests allows them to be resilient in the face of changing environmental conditions over longer time frames. However, genetic adaptive processes are still poorly understood, and their potential role in adapting forests to rapid anthropogenic climate change is even less well understood (Lindner et al., 2010). Natural adaptation relies strongly on successional and selective processes. It is unclear whether forest ecosystems, already constrained by stressors such as nitrogen deposition and harvesting, would be able to adapt quickly enough to rapidly changing conditions under climate change without substantial changes to their function and structure.

Management strategies designed to facilitate forest adaptation are founded on the principles of adaptive forest management. They utilize ecological understanding of future climate change impacts to create a resilient forest that is able to cope with a range of future conditions while still providing the main services requested by society. Timely intervention, such as planting better-adapted species, tending and thinning, is intended to enhance forest adaptive capacity by adjusting structure and composition. Such adaptation measures depend on data availability and projections that assess how forests might react to future climate change. Developing adaptation strategies will also depend on funding and other socioeconomic factors, including availability of a skilled workforce.

BOX 6

How quickly could forest management adapt?

Forests management cycles range from decades for fast-growing, intensively managed plantations, to centuries for slow-growing managed forests. The timeframe for adapting forests will depend on the initial condition, predicted changes in climate, the management system employed, as well as the willingness of owners to actively manage change. Financial and scientific support will also play a strong role. Disturbed, harvested and young stands generally offer the greatest opportunities to swiftly enhance the adaptive capacity by altering forest structure and species composition through planting, natural regeneration, tending and thinning. Later growth stages are more difficult because stem numbers have already been reduced; however, these stands are also closer to being harvested and replaced anyway. Forest management will need to adapt continuously as environmental conditions and society's expectations change. For example, vulnerable spruce stands in central Europe are underplanted with beech and fir 30 years before final harvest, so that they integrate into the stand through continuous cover management. Recent years have seen dieback of beech and fir following successive summer droughts. It remains unclear how beech and fir species will recover and whether young stands will adapt better than mature ones. Monitoring how forests respond to site factors, climate and its associated extremes and disturbances, and earlier management regimes, will become essential to allow the early introduction of measures which provide fast and suitable adjustments to forest management strategies. The speed of adaptation will require integration of natural and human-driven adaptive strategies. Examples include encouraging genetic diversity and using silviculture to introduce new provenances of existing species (e.g., planting seedlings from the same species growing in a hotter and drier climate), or mixtures of species.

4.2 Adaptive forest management

Adaptation measures may be reactive or proactive. Reactive measures respond to climate change following an impact, for example by planting alternative tree species after a disturbance or die-back. Waiting until the impact of climate change becomes evident, and only then taking targeted management action, involves a high degree of risk. This approach could result in the loss of ecosystem services, such as a diminishing of scenic landscape value with consequences for tourism, or losses in protective services. Delaying action could result in higher volumes of dead or damaged timber, due to disturbances, magnifying economic effects on landowners and timber processors.

Proactive management takes place before climate change-induced impacts have occurred, with the aim of preventing or alleviating negative impacts. For example, it could mean adopting mixtures of species or reducing stand density to diminish disturbance likelihood and damage. Proactive management also carries risk, such as introducing less well-adapted species or genotypes, disturbing stand stability during thinning, and creating openings that might allow the introduction of invasive exotic plants.

Whether reactive or proactive measures are adopted, the scale and timing of specific adaptation measures will depend on local circumstances and may range from short-term resistance strengthening to climate change impacts, to longer term improvements in forest resilience. A list of possible reactive and proactive adaptations to deal with current and future bark beetle impacts appears below (TABLE 4.1).

A general recommendation for proactive adaptation is to spread risks among stand members. A conversion of monocultures into mixed forests can. for example. alleviate disturbance impacts and simultaneously boost forest productivity (Pretzsch et al., 2013). Likewise, increasing genetic and structural diversity leads to higher resource use efficiency (Pretzsch et al., 2016, Zeller et al., 2018, Liang et al., 2016) and resilience against disturbance impacts (Jactel et al., 2017, Sousa-Silva 2018). Other measures concern management techniques. A reduction of rotation length can very effectively decrease a forest's disturbance vulnerability (Seidl, 2011). Tending and thinning, on the other hand, promote individual tree performance. With the initial aim to direct growth towards individual trees with the highest expected timber value, disturbance resistance also increases after a short time drop (Sohn et al., 2016).

TABLE 4.1 Examples of short-term, medium-term, and long-term reactive and proactive adaptation options to deal with bark beetle impacts on forests at stand, landscape and policy levels

	Short-term (< 5 years)	
	Reactive	*Proactive*
Stand	Restore economic value (e.g., salvage logging)	Reduce competition (e.g., tending, thinning to increase vitality of remaining trees)
Landscape	Implement spatial and temporal planning of post disturbance management to facilitate joint action (e.g. organization of salvage logging across different ownerships)	Monitor severity and movement of bark beetle infestation and prevent spread of bark beetles (e.g., sanitary fellings)
Policy/governance	Promote pest and disturbance management (e.g., tax reductions for salvaged timber)	Promote access to forests and adaptive forest management (e.g., subsidies for road building, storage places of salvage logged timber)
	Mid-term (5-10 years)	
	Reactive	*Proactive*
Stand	Intensify management (e.g., increased thinning regimes to reduce risk)	Promote mixing of species to reduce the number of susceptible trees (e.g., by fostering in growing trees from other species than the main species)
Landscape	Gain knowledge (e.g., monitoring programs to monitor severity and movement of bark beetle infestation)	Build adaptation experience (e.g., exchange among forest managers)
Policy/governance	Incentivize management actions about how to deal with bark beetle damage (e.g., education campaigns how to clean affected stands)	Transfer seeds (e.g., relax national trading restrictions)
	Long-term (> 10 years)	
	Reactive	*Proactive*
Stand	Intensify management (e.g., plantation economy with short rotations)	Convert forest towards uneven-aged, mixed species to spread infestation risk
Landscape	Develop infrastructure to shorten reaction times to contain bark beetle spread (e.g., road building, storage places of salvage logged timber)	Implement temporal and spatial planning of management actions to increase landscape heterogeneity
Policy/Governance	Fund programmes to increase disaster risk management (e.g., road building, storage places of salvage logged timber)	Fund programmes to enhance resilience, e.g., forest type conversion

Source: Authors' own work

4.3 Adaptation at the stand level

4.3.1 Forest regeneration

Regeneration offers an opportunity to lay the foundation for adaptation. Ideally, the next generation of trees will have potential to deal with future climatic conditions. There is a presumption that if the parent trees performed well, their progeny would perform similarly. Natural regeneration may be considered in management plans as an option for forest regeneration. If the natural regeneration fails to appear, is expected to occur in undesired states (composition, density), or cannot survive future disturbance regimes, planting can possibly compensate. Enrichment plantings can supplement natural regeneration or can replace it. Sometimes. planting or seeding non-native tree species or different origins/provenances may benefit adaptive capacity. Choosing the species, origin/provenance, mixed planting, densities, and planting methods, should be based on information from field experiments, observations and modelling, to minimise maladaptation or failure.

4.3.2 Tending and thinning

Tending and thinning remove individual trees, reduce stand densities and modify species compositions. After a short drop in productivity, the remaining trees compensate for the removal (Dieler et al., 2017). Trees in thinned stands are better able to withstand drought stress and maintain defenses against pests and diseases (Sohn et al., 2016; Bottero et al., 2017). Opening the canopy by thinning may increase short-term susceptibility to storm damage, but once crowns have reconnected, the stand will be more storm-resistant, with better crown depth, improved height-diameter stem ratio, and root growth (Slodicak & Novak, 2006). The additional growing space gives the tree better access to soil nutrients and soil water, reducing the effects of heat and drought (Sohn et al., 2012).

4.3.3 Forest type conversion

Forest conversion gradually transforms the species composition and structure of poorly adapted forest stands so they have better adaptive potential, while minimizing any reduction in provisioning services. The most common conversions change single-species forests into mixed-species forests, and even-aged forests into uneven-aged forests. Techniques include establishing shade-tolerant species under a mature stand before final harvest, by natural regeneration or planting. Low intensity thinning slowly increases light at the forest floor, allowing establishment of more light-demanding species. The process requires time to secure a balanced mix between shade-tolerant and light-demanding species. Achieving an uneven-aged structure requires even more time. Conversions may take up to 80 years and require low intensity management intervention at various times, and at differing scales.

Box 7

Browsing effects on forest regeneration

Artificial and natural regeneration in temperate forests is often damaged by ungulate browsing. It may not be possible to establish trees successfully without the added cost of fencing (Ward et al., 2004). The populations of many wild ungulate species have grown through the 20th century because of reduced food competition with domestic livestock, milder winters, and absence of predators. Forest management too has boosted ungulate survival rates and overall population (Rooney, 2001; Reimoser, et al., 2003). A mosaic of large, even-aged stands provides a better habitat than natural forests where resources tend to be scarcer. In parts of Europe and North American, the decoupling of wildlife management from forest management has resulted in poor population control of grazing wildlife, to the detriment of natural regeneration (Ramirez et al., 2019). Forest managers need to be aware of oversized ungulate populations, which could hamper forest management investment, reducing efforts to promote active climate change adaptation.

4.3.4 Post-disturbance management

Post-disturbance management may include salvage logging after storm or fire damage, sanitation felling following disease or pest outbreaks, and planting to replace losses. Salvage logging is the most common response, with the aim of decreasing economic losses, reducing hazardous conditions, and preventing subsequent problems, like bark beetle outbreaks after a storm.

Salvage logging reduces forest carbon stock through removal of dead or damaged trees, but allows living trees continue to sequester carbon (Molinas-Gonzáles et al., 2017). By removing dead or weakened trees, sanitary felling contains further spread of insects or pathogens. Disturbances arising because of climate change, may even provide an opportunity to plant better-adapted species mixtures. However, large, unplanned volumes of salvage stock can cause roundwood prices to drop, and the fall may be enough to make salvage operations uneconomic. Furthermore, adverse effects of salvage 60
logging on the recovery of biodiversity and ecosystem resilience have recently been discussed (Leverkus et al., 2018). Where salvage is not expected to reduce damage from subsequent disturbances, alternative approaches, such as non-intervention, should be considered (Dobor et al., 2020) and may be a preferred option, promoting natural regeneration and thereby encouraging a more diverse and species-rich forests structure. This in turn may help build heightened resilience to future disturbances (Seidl. et al., 2016).

Intervention following disturbance may benefit from cross-sectoral crisis management. Salvage logging needs access to damaged stands, and logistics to extract and market salvaged timber. Storage facilities may be needed to maintain the timber in good condition so that it goes to market when capacity allows. Access to planting stock in nurseries will allow rapid replanting in situations where natural regeneration is not practicable or where it would be of an unwanted species. Lastly a relaxation of legal constraints (e.g., with regard to the species to be replanted) can further increase the success of post-disturbance management (Hlasny et al., 2019).

4.4 Adaptation beyond the stand level

Forest governance has always been complex but it has become more so in the past three decades, with multiple layers, increasing stakeholder interest, and sometimes conflicting policies impinging on forest management. Responsibility for policies affecting forest management is shared among local, sub-national and national bodies in all UNECE member States, which may limit options for defining and achieving UNECE regional goals.

However, the current system also offers potential to produce flexible and adaptive responses to local circumstances. Adaptation policies and measures can be designed to empower sub-national or national government institutions to take account of local circumstances and forest priorities. Responding to disturbances will often require urgent measures to mitigate economic impacts, and local bodies are often best equipped to respond quickly. Where there is a need for a coordinated, cross-sectoral approach, this may be best led at the national level, guided by national and international policies. Measures available at government level could include long-term arrangements between forest owners and processing industries, tax reductions for salvaged timber, financial assistance for sanitary felling, adaptive management, and temporary easing of legal constraints.

Effective adaptation requires policies and measures that cover the immediate response as well as longer-term proactive/preparatory action. These will differ with location and state of management (Nabuurs et al., 2019). In an intensively managed area, policies promoting a resilient forest sector which can secure long-term raw material supplies may take precedence. In areas that experience hotspots of disturbance, actions that focus on the transition to a long-term resilient forest ecosystem may take priority. Economic and ecological disturbance impacts could be reduced if countries establish a regulatory and managerial environment supporting rapid response at local and sub-national levels, with national leadership that encourages cross-sectoral cooperation.

4.5 National adaptation strategies

Most UNECE member States are signatories to international agreements on forests, recognizing the challenges of climate change, deforestation and forest degradation. The United Nations Strategic Plan for Forests 2017-2030 aims to prevent and reverse forest cover loss and forest degradation through sustainable forest management, protection, restoration, reforestation and afforestation. Measures should explicitly improve forests' adaptive capacity and resilience to meet predicted climate change. The Global Forest Goals refer to climate change mitigation and adaptation. Global Forest Goal 1 states, "Reverse the loss of forest cover worldwide through sustainable forest management, including protection, restoration, afforestation and reforestation, and increase efforts to prevent forest degradation and contribute to the global effort of addressing climate change" (United Nations, 2017). How to achieve this goal is decided by national governments, resulting in widely varied adaptation strategies. National adaptation strategies reflect local circumstances and parameters such as forest extent and condition, historical management and social and governance contexts. Strategies will differ in implementation, and may encompass tax reductions for reactive measures, or financial support for intensified management such as shortening rotation lengths.

Most countries in the UNECE regions have strategic plans for adaptation to climate change, though forests may not be mentioned except in reference to other sectors on cross-sectoral matters. Detailed descriptions and assessments of national adaptation strategies have been published for pan-Europe (Forest Europe, 2020); the Russian Federation (Leskinen et al., 2020); and Canada (Environment and Climate Change Canada, 2016).

In the United States, the USDA Forest Service has worked with other federal agencies on adaptation measures in national forests and national grasslands. State governments and some Native American tribes and communities have taken formal steps to adapt forests to climate change (Vose et al., 2018). However, there is no overall federal policy to guide land managers in what approach to take in adapting forest management to climate change (Keskitalo and Preston, 2019).

The European Union has made several forest-related climate commitments. In particular, the EU strategy "A Clean Planet for All", refers to legislation to maintain the EU land and forest sink (European Commission, 2018). In the Russian Federation, national forestry authorities included climate change in forestry planning in 2017 and added the requirement to develop adaptation measures in forest plans (Leskinen et al., 2020). Examples of three adaptation approaches in Europe are shown below (Box 8).

BOX 8

Examples of national adaptation strategies across Europe

A recent report summarizes the state of forest adaptation in Europe (Forest Europe, 2020). Three examples from the report for Eastern Europe (Czech Republic), central-European mountain regions (Switzerland) and the Mediterranean region (Spain) are described next, including material from additional sources.

Forests in the **Czech Republic** have suffered from a series of storms, severe droughts, and bark beetle infestations, which damaged almost 100 million m^3 between 2010 and 2020, with severe effects on timber markets (Toth et al., 2020). The Czech Republic adopted a cross-sectoral adaptation strategy in 2015, looking ahead to 2030. Though not explicitly enforced by legislation, forest adaptation is a major element of the national forest programme. Propelled by incentives and tax relief, forest management strategies, such as close-to-nature forestry and intensified management are encouraged, with emphases on changing tree species and improving forest water retention capacity. Changes to tree species composition has had government and legislative support since 1996. The Czech Republic actively supports planting species which improve soil condition and stabilize forests, reforestation, stand establishment and follow-up management. Recently, support has been extended to cover reactive measures following disturbances. Since 2000, stand inventories have shown more than a 5% reduction overall in vulnerable conifer species, and more than 15% in stands aged 1–20 years, suggesting that these measures have been effective.

In 2006, **Spain** implemented a cross-sectoral climate change adaptation strategy, introducing action plans for forest adaptation. Financial support has been provided for close-to-nature and intensified management measures; use of good quality genetic stock for replanting and afforestation; improvements to promote water retention, and; agroforestry. Spain recorded the worst wildfires in Europe from 2010 to 2020, affecting more than 100,000 ha/year, and has launched fire prevention measures, including constructing firebreaks; removal cuttings; pruning; prescribed burning; forest debris removal; planting fire-resistant species, and; reducing arson. During the winter of 2018, in a programme of controlled burning coordinated by the Integral Forest Fire Prevention Teams (EPRIF) in collaboration with farmers, 526 ha of forest were treated with 100 prescribed and controlled fires. Another collaboration between the Preventive Work Brigades (BLP) from the Ministry of Agriculture and the autonomous administrations, applied preventive silvicultural measures on over 1300 hectares. Measures included thinning, pruning, and underbrush removal, carried out in 11 months by more than 400 workers.

Switzerland adopted its adaptation strategy in 2012. It includes a 2020–2025 Action Plan supported by federal legislation, as well as financial and institutional support. Close-to-nature forestry is practiced in almost all forests. Switzerland uses a combination of advanced technologies to guide forest adaption, among which is an automated warning system to map forest fire risk at local, regional and federal levels. To guide climate-change-oriented decision-making, the national research programme, "Forests and Climate Change" supported development of the "Tree-App". which projects future development of Swiss forests and provides users with a system to select tree species ecologically suited to local circumstances. In 2018, the Federal Office for the Environment (FOEN) and the Swiss Federal Institute for Forest and Landscape Research (WSL), launched a project to investigate how tree species suited to Switzerland might perform during climate change. The trial tested seven provenances of 18 species across 57 regionally distributed sites. The Swiss adaptation strategy also acknowledges the role of "urban-forestry" in reducing heat stress and preventing heat-islands in cities, improving health-enhancing effects and benefiting biodiversity.

5

Summary - Balancing impacts, mitigation and adaptation

Forests across the UNECE region are likely to be impacted by changes in average growing conditions and extreme events brought about by climate change. The effects of climate change on the processes that underpin forest growth and productivity are complex and uncertain. An extended growing season, warmer temperatures and higher atmospheric CO_2 levels might increase productivity in some countries and subregions but might also increase the risk of drought and the risk of disruption from fire, disease and insect outbreaks. These changes may have a more profound effect on productivity than assumed in current models.

Changes in productivity and species distribution will be highly variable and may affect forest products' markets, giving rise to changes in comparative advantages among subregions. Underlying uncertainty about forest growth changes and market implications mean that modelling results need to be viewed with a degree of caution. For instance, if projected growth increases do not arise – because actual physiological adaption to higher levels of CO_2 differs from assumptions built into the vegetation models underlying these projections – the projected changes in forest product prices may not occur.

Natural disturbances are a challenge for forest management and wood processing. Salvage logging and sanitary cutting produce unexpected and temporary workloads. This may drive down timber prices, disrupting management plans and operations like harvesting and regeneration. Delaying thinning or final felling could affect stand stability, generating a negative loop that makes forests susceptible to subsequent disturbance. Over the longer term, this could threaten ecosystem services. The models used in this Outlook study do not typically include a full-depth analysis of such effects on forest products and forest productivity. This leaves questions, such as: will more frequent events, like heat waves and persistent drought, cancel out climate-induced productivity gains? What are the exact implications for the global timber market of frequent, large-scale disturbances?

Forests play an important role in mitigating climate change. The mitigation effect is influenced by the carbon stored in biomass, litter, soil, deadwood and wood products, and changes brought about by climate change, plus the contribution of emissions avoided when wood products substitute carbon-intensive products and fossil energy (TABLE 5.1).

TABLE 5.1 Current carbon stocks and future fluxes in the reference scenario and different mitigation strategies in the UNECE region.

	All values in billions							
	Overview reference scenario (SSP2)						**Mitigation**	
	Fossil fuel emissions (as flux) 2018***	Biomass stock 2015	Biomass flux 2015-2040	HWP stock 2015	HWP flux 2015-2040	Disturbance flux	Forest management	Afforestation
	tCO_2e per year	*tCO_2e*	*tCO_2e per year*	*tCO_2e*	*tCO_2e per year*	*tCO_2e per year*	*tCO_2e per year*	*tCO_2e per year*
Europe-EU	-3.2	35.5	0.5	5.1	0.1	-0.185*	0-0.21	0.8
Europe-Other	-0.5	7.5	0.1	0.5	0.0		0-0.04	NA
North America	-5.9	130.1	0.7	5.9	0.0	-0.7**	0-0.5	0.61 - 0.83
EECCA	-0.7	8.4	0.1	0.4	0.0	n.a.	n.a.	n.a.
Russian Federation	-1.6	121.4	0.1	2.4	0.0	-0.3	n.a.	0.5
UNECE	-11.9	302.9	1.5	14.3	0.2	-1.2	0.8	2.0
Rest of the world	-21.6	1,046.7	-0.3	10.0	0.3	n.a.	0-1.3	3.9
Global	**-33.5**	**1,349.6**	**1.2**	**24.3**	**0.5**	**n.a.**	**0.4-2.1**	**5.9**

Notes: Stocks and flux for biomass and harvested wood products (HWP) are based on the modelling with GFPM in this Outlook, effects of disturbance (section 3.2.1), forest management (section 3.2.1) and afforestation (section 3.2.2) are based on the literature review presented in this Outlook and GFPM results. Values marked n.a. are not available; *for 2021-2030 from Seidl et al., 2014; ** for recent period; *** energyatlas.iea.org

Based on a literature review, the current disturbance effects on carbon may be as large as the net carbon sink of forests in the UNECE region (TABLE 5.1). Although forest management measures may increase the forest carbon sink in the UNECE region by 50-100% over the period 2020-2040, research suggests that increased disturbance frequency and intensity may offset part or all of these additional carbon gains. Forest management strategies for climate change mitigation must account for forest disturbances, and adaptation and mitigation measures should be considered together (Box 9).

The carbon stock in forest biomass is large, and the sink (the annual net absorption of CO_2) is only a fraction of that. The average annual projected increase in forest biomass carbon storage (net carbon sink expressed as % of the biomass stock) in this Outlook was 0.5% in North America, 1.3% in Europe-EU, 1.8% in Europe-Other, 1.7% in ECCCA, and 0.1% in the Russian Federation. This equates to 0.5% in the UNECE region as a whole from 2015 until 2040. The Russian Federation had a small biomass sink compared with the wide range of values reported in the literature. In 2015, harvested wood products (HWP) stored a small fraction of carbon: 5% of forest biomass stock in the UNECE region as a whole, although this increased to 15% in Europe, which is a main producer of HWP.

Increasing global forest area by 10% by 2040 would sequester 1.95 billion tCO_2e per year in the UNECE region as opposed to the 1.5 billion tCO_2e per year of the baseline scenario.

Scenarios aimed at increased production of wood to substitute fossil-based alternatives were projected to be nearly carbon neutral, both for textiles and wood construction until 2040. Longer time-horizons could produce different results. There is considerable variation, especially around the substitution factors, which is due to differences in assumptions, data and methods used to estimate such factors. Substitution effects depend, for example, on assumptions of the type of non-wood product that is substituted and its operating life, as well as the end-of-life management of wood and non-wood products. The greatest changes in net carbon emissions would be obtained by substituting wood and wood fibres for the most fossil energy-intensive non-wood materials. Furthermore, these scenarios show effects in other regions or subregions, as wood is partly produced outside of the region or subregion where it is consumed. The effect of the substitution option can be further increased by increasing wood product production efficiency and by minimizing forest and production losses. Overall, large uncertainties still revolve around the quantification of carbon storage in HWP and its substitution effects. While results depend very much on the approach and data used (e.g., Box 4), in summary, this assessment finds that material substitution can have a positive contribution to climate change mitigation but that successfully achieving positive substitution effects depends on many factors that require careful attention. Forests and forest management will need to adapt to a changing climate to maintain ecosystem services. Adaptation may occur naturally or may require forest management to be adapted. Changing management would require a qualified workforce and might require investment in monitoring, research and forest management. While the impacts of climate change itself may result in some level of adaptation through natural processes, the impacts of climate change may also create limited-time opportunities to implement managed adaptation measures. For example, disturbances may allow silviculture to adjust species composition more quickly than would otherwise be possible.

Ideally, adaptation and mitigation would be considered together when anticipating how best to combine measures to react to changing environmental and socio-economic conditions (see Box 9). Discussion about how to balance trade-offs between sometimes competing management objectives, as well as mitigation and adaptation options, needs to also consider the context of changing demands on the forest. In this regard, it is necessary to make explicit the trade-offs and synergies between 1) nature conservation, 2) carbon sequestration through forest management, 3) carbon sequestration in harvested wood products and 4) emissions reduction by substituting carbon intensive products with low carbon forest products.

Large-scale, disruptive disturbances might influence societal discourse about adaptation options and mitigation potential. Climate-Smart Forestry is a concept designed to explicitly address these issues in an integrated way.

Box 9

Climate-Smart Forestry

The Paris Agreement requires major societal and economic reforms to ensure that global average temperature does not rise beyond 2°C compared to pre-industrial levels. Forests and forestry can play an important part, through a wide set of potential measures, adapted to local circumstances. In addition to mitigating climate change, forestry also needs to adapt to climate change, but mitigation and adaptation are rarely considered together when considering national strategies to implement climate action. Climate-Smart Forestry (CSF) is a holistic approach that connects mitigation with adaptation measures, guiding forest management to enhance the resilience of forest resources and ecosystem services, and meet the needs of a growing population (Nabuurs et al., 2017; Jandl et al., 2018; Yousefpour et al., 2018; Bowditch et al., 2020). CSF builds on the concepts of sustainable forest management, with a strong focus on climate and ecosystem services. It uses three mutually reinforcing components:

- Increasing carbon storage in forests and wood products, in conjunction with provisioning of other ecosystem services.
- Enhancing forest health and resilience through adaptive management.
- Using wood resources sustainably to substitute non-renewable, carbon-intensive materials.

CSF aims at a mix of these by developing spatially diverse forest management strategies that acknowledge all carbon pools, emissions and removals simultaneously to provide longer-term and larger mitigation benefits, while supporting biodiversity and other ecosystem services. Such strategies should combine measures to maintain or increase carbon stocks in forest ecosystems and wood products, and maximise substitution benefits, while taking regional conditions into account. (Nabuurs et al., 2017; Verkerk et al., 2020).

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Annexes

ANNEX A: COUNTRIES IN THE UNECE REGION AND ITS SUBREGIONS

Eastern Europe, Caucasus and Central Asia
Armenia
Azerbaijan
Belarus
Georgia
Kazakhstan
Kyrgyzstan
Republic of Moldova
Russian Federation
Tajikistan
Turkmenistan
Ukraine
Uzbekistan

North America
Canada
United States of America

European Union		Europe other countries
Austria	Italy	Albania
Belgium	Latvia	Andorra
Bulgaria	Lithuania	Bosnia and Herzegovina
Croatia	Luxembourg	Iceland
Cyprus	Malta	Israel
Czech Republic	Netherlands	Liechtenstein
Denmark	Poland	Monaco
Estonia	Portugal	Montenegro
Finland	Romania	North Macedonia
France	Slovakia	Norway
Germany	Slovenia	San Marino
Greece	Spain	Serbia
Hungary	Sweden	Switzerland
Ireland		Türkiye
		United Kingdom of Great Britain and Northern Ireland

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ANNEX C: SOME FACTS ABOUT THE COMMITTEE ON FORESTS AND THE FOREST INDUSTRY

The UNECE Committee on Forests and the Forest Industry (COFFI) is a principal subsidiary body of the UNECE based in Geneva. It constitutes a forum for cooperation and consultation between member countries on forestry, the forest industry and forest product matters. All countries of Europe and the EECCA, as well as the United States, Canada and Israel, are members of the UNECE and participate in its work.

The UNECE Committee on Forests and the Forest Industry shall, within the context of sustainable development, provide member countries with the information and services needed for policymaking and decision-making with regard to their forest and forest industry sectors, including the trade and use of forest products and, where appropriate, it will formulate recommendations addressed to member governments and interested organizations. To this end, it shall:

1. with the active participation of member countries, undertake short-, medium- and long-term analyses of developments in, and having an impact on, the sector, including those developments offering possibilities for facilitating international trade and for enhancing the protection of the environment;
2. in support of these analyses, collect, store and disseminate statistics relating to the sector, and carry out activities to improve their quality and comparability;
3. provide a framework for cooperation, for example by organizing seminars, workshops and ad hoc meetings and setting up time-limited ad hoc groups, for the exchange of economic, environmental and technical information between governments and other institutions of member countries required for the development and implementation of policies leading to the sustainable development of the sector and the protection of the environment in their respective countries;
4. carry out tasks identified by the UNECE or the Committee on Forests and the Forest Industry as being of priority, including the facilitation of subregional cooperation and activities in support of the economies in transition of central and eastern Europe and of the countries of the region that are developing from an economic perspective; and
5. keep under review its structure and priorities and cooperate with other international and intergovernmental organizations active in the sector, particularly FAO and its European Forestry Commission and the International Labour Organization, in order to ensure complementarity and avoid duplication, thereby optimizing the use of resources.

ANNEX D: SOME FACTS ABOUT THE EUROPEAN FORESTRY COMMISSION

The European Forestry Commission (EFC), which was created in 1947, is one of six regional forestry commissions established by FAO to provide a policy and technical forum for countries to discuss and address forest issues on a regional basis.

The purpose of the EFC is to advise on the formulation of forest policies and to review and coordinate their implementation at the regional level; exchange information; advise on suitable practices and actions to address technical and economic problems (generally through special subsidiary bodies); and make appropriate recommendations in relation to the foregoing. The EFC meets every two years and its official languages are English, French and Spanish.

The EFC has a number of associated subsidiary bodies, including the Working Party on the Management of Mountain Watersheds; the UNECE/FAO Working Party on Forest Statistics, Economics and Management; and seven UNECE/FAO Teams of Specialists. The Committee on Mediterranean Forestry Issues (Silva Mediterranea) informs the EFC.

FAO encourages the wide participation of government officials from forestry and other sectors as well as representatives of international, regional and subregional organizations that deal with forest-related issues in the region, including non-governmental organizations and the private sector. Accordingly, the EFC is open to all members and associate members whose territories are situated wholly or in part in the European Region or who are responsible for the international relations of any non-self-governing territory in that region. Membership comprises such eligible member nations as have notified the Director-General of their desire to be considered as members.

The EFC is one of the technical commissions serving the FAO Regional Office for Europe and Central Asia (REU), and the EFC Secretary is based in Geneva. EFC work is regulated by its Rules of Procedures, which were adopted by the FAO Conference in 1961 and amended at the Eighteenth Session of the EFC in 1977.

More information about the work of the EFC and COFFI may be obtained by contacting:

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ANNEX E: UNECE/FAO PUBLICATIONS

Geneva Timber and Forest Study Papers

Forest Products Annual Market Review 2021-2022	ECE/TIM/SP/54
Reporting on Forests and Sustainable Forest Management in the Caucasus and Central Asia	ECE/TIM/SP/53
Forest Products Annual Market Review 2020-2021	ECE/TIM/SP/52
Forest Sector Outlook Study 2020-2040	ECE/TIM/SP/51
Forest Products Annual Market Review 2019-2020	ECE/TIM/SP/50
Forests in a Circular Economy	ECE/TIM/SP/49
Forest Products Annual Market Review 2018-2019	ECE/TIM/SP/48
State of Forests of the Caucasus and Central Asia	ECE/TIM/SP/47
Forest Products Annual Market Review 2017-2018	ECE/TIM/SP/46
Forests and Water	ECE/TIM/SP/44
Forest Ownership in the ECE Region	ECE/TIM/SP/43
Wood Energy in the ECE Region	ECE/TIM/SP/42
Forest Products Annual Market Review 2016-2017	ECE/TIM/SP/41
Forest Products Annual Market Review 2015-2016	ECE/TIM/SP/40
Forest Products Annual Market Review 2014-2015	ECE/TIM/SP/39
Promoting sustainable building materials and the implications on the use of wood in buildings	ECE/TIM/SP/38
Forests in the ECE Region: Trends and Challenges in Achieving the Global Objectives on Forests	ECE/TIM/SP/37
Forest Products Annual Market Review 2013-2014	ECE/TIM/SP/36
Rovaniemi Action Plan for the Forest Sector in a Green Economy	ECE/TIM/SP/35
The Value of Forests: Payments for Ecosystem Services in a Green Economy	ECE/TIM/SP/34
Forest Products Annual Market Review 2012-2013	ECE/TIM/SP/33
The Lviv Forum on Forests in a Green Economy	ECE/TIM/SP/32
Forests and Economic Development: A Driver for the Green Economy in the ECE Region	ECE/TIM/SP/31
Forest Products Annual Market Review 2011-2012	ECE/TIM/SP/30
The North American Forest Sector Outlook Study 2006-2030	ECE/TIM/SP/29
European Forest Sector Outlook Study 2010-2030	ECE/TIM/SP/28
Forest Products Annual Market Review 2010-2011	ECE/TIM/SP/27
Private Forest Ownership in Europe	ECE/TIM/SP/26
Forest Products Annual Market Review 2009-2010	ECE/TIM/SP/25
Forest Products Annual Market Review 2008-2009	ECE/TIM/SP/24
Forest Products Annual Market Review 2007-2008	ECE/TIM/SP/23
Forest Products Annual Market Review 2006-2007	ECE/TIM/SP/22
Forest Products Annual Market Review, 2005-2006	ECE/TIM/SP/21
European Forest Sector Outlook Study: 1960 – 2000 – 2020, Main Report	ECE/TIM/SP/20
Forest policies and institutions of Europe, 1998-2000	ECE/TIM/SP/19
Forest and Forest Products Country Profile: Russian Federation	ECE/TIM/SP/18
(Country profiles also exist on Albania, Armenia, Belarus, Bulgaria, former Czech and Slovak Federal Republic, Estonia, Georgia, Hungary, Lithuania, Poland, Romania, Republic of Moldova, Slovenia and Ukraine)	
Forest resources of Europe, CIS, North America, Australia, Japan and New Zealand	ECE/TIM/SP/17

Note: *Additional market-related information is available in electronic format at* **www.unece.org/forests**.

Geneva Timber and Forest Discussion Papers (original language only)

The Outlook for the UNECE Forest Sector in a Changing Climate	*ECE/TIM/DP/93
Structural changes in the forest sector and their long-term consequences for the forest sector	*ECE/TIM/DP/92
Catalogue of Wood Waste Classifications in the UNECE Region	ECE/TIM/DP/91
Detailed Methodology for the Preparation of the Forest Sector Outlook Study 2020-2040	*ECE/TIM/DP/90
COVID-19 Impacts on the Forest Sector in Countries in countries in the Western Balkans	*ECE/TIM/DP/89
COVID-19 Impacts on the Forest Sector in Countries in countries Eastern Europe, Caucasus and Central Asia	*ECE/TIM/DP/88
Forest Landscape Restoration in Eastern and South-East Europe	ECE/TIM/DP/87
Overview of the State of Forests and Forest Management in Uzbekistan	ECE/TIM/DP/85
Overview of the State of Forests and Forest Management in Turkmenistan	ECE/TIM/DP/84
Overview of the State of Forests and Forest Management in Tajikistan	ECE/TIM/DP/83
Overview of the State of Forests and Forest Management in Kyrgyzstan	ECE/TIM/DP/82
Overview of the State of Forests and Forest Management in Kazakhstan	ECE/TIM/DP/81
Overview of the State of Forests and Forest Management in Georgia	ECE/TIM/DP/80
Overview of the State of Forests and Forest Management in Azerbaijan	ECE/TIM/DP/79
Overview of the State of Forests and Forest Management in Armenia	ECE/TIM/DP/78
Guidelines on the Promotion of Green Jobs in Forestry	ECE/TIM/DP/77
Forest Sector Workforce in the UNECE Region	ECE/TIM/DP/76
Rovaniemi Action Plan for the Forest Sector in a Green Economy: Mid-term Review	ECE/TIM/DP/75
Trends in green jobs in the forest sector in the UNECE region	ECE/TIM/DP/74
Guidelines for the Development of a Criteria and Indicator Set for Sustainable Forest Management	ECE/TIM/DP/73
Forest Landscape Restoration in the Caucasus and Central Asia	ECE/TIM/DP/72
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Comparative assessment of wood biomass for energy in Europe	*ECE/TIM/DP/65
Forecast of the Committee on Forests and the Forest Industry: Forest Products Production and Trade 2014-2016	ECE/TIM/DP/64
Forecast of the Committee on Forests and the Forest Industry: Forest Products Production and Trade 2013-2015	ECE/TIM/DP/63
Competitiveness of the European Forest Sector	ECE/TIM/DP/62
Forecast of the Committee on Forests and the Forest Industry: Forest Products Production and Trade 2012-2014	ECE/TIM/DP/61
Forecast of the Committee on Forests and the Forest Industry: Forest Products Production and Trade 2011-2013	ECE/TIM/DP/60

Econometric Modelling and Projections of Wood Products Demand, Supply and Trade in Europe	ECE/TIM/DP/59
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THE OUTLOOK FOR THE UNECE FOREST SECTOR IN A CHANGING CLIMATE

A CONTRIBUTION TO THE FOREST SECTOR OUTLOOK STUDY 2020-2040

The Forest Sector Outlook Study 2020-2040 (FSOS) for the UNECE region provides information that supports decision-making by showing the possible medium- and long-term consequences of specific policy choices and structural changes, using scenario analyses whenever possible. The study is the first to cover the entire UNECE region and provides results for the main UNECE subregions of Europe, North America and the Russian Federation.

Together with this Discussion Paper and other supporting publications, the FSOS 2020-2040 provides insight on six priority questions which were identified through a transparent and participatory process: (i) *How would different demand changes affect the UNECE forest products' markets?* (ii) *How would different supply changes affect the UNECE region forest products' markets?* (iii) *How would significant trade restrictions affect the UNECE region forest products' markets?* (iv) *How will UNECE forests be affected by climate change?* (v) *How could UNECE region forests and the forest sector contribute to climate change mitigation?* (vi) *How could UNECE forests adapt to climate change?*

The FSOS 2020-2040 main report and the supporting Discussion Papers contain information on the possible impacts of future trends regarding the future forest carbon sink in tonnes of CO_2 equivalents, and on harvest, production, consumption, net exports, and prices of wood products by 2040.The study takes a pragmatic, transparent and objective approach to answering these key questions, sometimes using a modelling approach. It enables stakeholders to evaluate the long-term consequences of policy choices.

The FSOS 2020-2040 contributes to evidence-based policy formulation and decision making. It is not a forecast of what will happen in the future. Rather, it sheds light on the possible consequences of policy choices and of factors external to the forest sector, most notably anthropogenic climate change. The study draws attention to the following issues emerging from the analysis in the study, and asks questions which policy makers and stakeholders might consider: (i) *Disturbances and the forest sink*; (ii) *Demand for land for increased carbon sequestration by forests*; (iii) *Putting substitution in a wider context*; (iv) *Trade measures*, and; (v) *Need for a system-wide, holistic approach to strategies and policies*

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