Mitig Adapt Strateg Glob Change
DOI 10.1007/s11027-010-9243-0

ORIGINAL ARTICLE

Assessing risk and adaptation options to fires and windstorms in European forestry

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Received: 13 August 2009 / Accepted: 27 June 2010

Abstract Risks can generally be described as the combination of hazard, exposure and vulnerability. Using this framework, we evaluated the historical and future development of risk of fire and wind damage in European forestry at the national level. Fire risk is expected to increase, mainly as a consequence of an increase in fire hazard, defined as the Fire Weather Index in summer. Exposure, defined as forest area, is expected to increase slightly as a consequence of active afforestation and abandonment of marginal agricultural areas. Adaptation options to fire risk should therefore aim to decrease the vulnerability, where a change in tree species from conifers to broadleaves had most effect. Risk for wind damage in forests is expected to increase mainly as a consequence of increase in exposure (total growing stock) and vulnerability (defined by age class and tree species distribution). Projections of future wind climate indicate an increase in hazard (storminess) mainly over Western Europe. Adaptation options should aim to limit the increase in exposure and vulnerability. Only an increase in harvest level can stop the current build-up of growing stock, while at the same time it will lower vulnerability through the reduction of the share of old and vulnerable stands. Changing species from conifers to broadleaves helps to reduce vulnerability as well. Lowering vulnerability by decreasing the rotation length is only

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Published online: 10 July 2010

effective in combination with a high demand for wood. Due to data limitations, no forecast of future fire area or damaged timber amount by storms was possible.

Keywords Adaptation · Climate change · Forest fire · Forestry · Natural disturbance · Windstorm · EFISCEN

1 Introduction

European forests are among the most intensively managed forests in the world. As a result, although only 5% of the global forest area is located in Europe (193 million hectares, excluding the Russian Federation), European forests account for 23% of the global round wood removals (FAO 2007). Meanwhile, other forest functions are also becoming more important, such as: nature conservation, protection of soil, water, air and infrastructure, recreation and carbon storage. Despite their intensive use, the forest resources in Europe are growing. The forest area is currently increasing by about 760 thousand ha per year (0.4%; FAO 2007) and the average growing stock volume increased from 124 $m^3 ha^{-1}$ in 1990 to 141 $m^3 ha^{-1}$ in 2005 (FAO 2007). These trends are projected to continue for at least several decades to come (Schelhaas et al. 2006a). Although these are positive trends, there are other developments that are cause for concern. One of these worrying developments is the apparent increase in occurrence of natural disturbances (FAO 2007). Several severe storms hit the European forests over the last decade, causing unprecedented damage (Schelhaas et al. 2003). In the Mediterranean basin, fire is the major disturbance factor. Annually (average 1980–2007) more than 50 thousand fires burn an area of almost 0.5 million ha (JRC 2008). Damage due to disturbance agents like storms and fire seems to be increasing over Europe over the last decades (Schelhaas et al. 2003). Changes in the state of the forest, changes in the way forests are managed and changes in the climate are thought to have contributed to this increase (Schelhaas et al. 2003). Climate models project worsening fire weather conditions for the future and possibly more frequent and more intensive storms (Alcamo et al. 2007). Combined with expected increases in forest area and standing wood volumes in the forest (Schelhaas et al. 2006a; Nabuurs et al. 2007), a future increase in damage due to these disturbance agents seems inevitable. One way to limit the impact of climate change is to adapt forest management. Management measures to decrease fire and wind risk are usually studied at the stand to landscape scale. Fire management is mostly aiming at reducing fuel build-up and reducing continuity of fuels (Finney 2001; Graham et al. 2004; Agee and Skinner 2005). Management measures to reduce wind risk are aimed at promoting higher stability of individual stands (Quine et al. 1995), or structuring landscapes to minimize exposed edges (Zeng et al. 2007). Schelhaas et al. (2003) mentioned changes in the state of the forest and increases in forest area and timber stock as factors that likely contributed to the increase in disturbances in European forest. An additional set of adaptation measures could therefore aim to influence these trends. Such changes are typically monitored at the national level, which is the focus of this study. This paper aims to evaluate the historic (1950–2005) evolution of possible drivers and indicators of risks of fire and windstorm damage in forests and to asses how adaptation measures in forestry could contribute to reduction of adverse consequences of future (2005–2100) climate change. We selected a few country case studies in Europe over a north–south and an east–west gradient. Reasons for doing so are the general similarity of neighbouring countries in terms of species and age class structure and the fact that only few countries have historic inventory data.

2 Theoretical framework

Risks, such as the risk for natural disturbances, can theoretically be described by the combination of hazard, exposure and vulnerability (Kron 2002). Any change to one of these components will lead to a corresponding change in risk level. Hazard is defined as the probability that a certain disturbance agent will occur and how severe the event will be. Exposure is the amount or value of the goods (or services) that can be damaged, including for example the number of people present in the area. Vulnerability expresses the resistance of the subject under study to the damaging agent, i.e. how easily damage will occur. For each of the risk components we defined indicators, for fire and wind risk separately. Risk is defined here as the probability of large-scale events that cause major economic damage. Due to shortcomings in the historic data sources, risks could not be quantified, but are described in qualitative terms.

3 Data and methods

3.1 Indicators

In case of forest fires, the hazard is mainly dependent on weather conditions; high temperature, lack of precipitation and presence of wind all increase the fire hazard. This effect of weather conditions can be summarised in an index e.g., the Fire Weather Index (FWI) that was developed by the Canadian Forest Service (Van Wagner 1987). It is a daily meteorology-based index, used worldwide to estimate fire danger in a generalized fuel type. FWI consists of six standard components each measuring a different aspect of fire danger (Van Wagner 1987). Three components represent daily changes in the moisture contents of three classes of forest fuel with different drying rates (light, intermediate and heavy fuels). The other three components are related to the fire behaviour representing the rate of spread, fuel weight consumed and fire intensity. The system depends solely on weather readings taken each day at noon: temperature, relative humidity, wind speed and rainfall in the previous 24 h. In addition, the current month must be specified. Several studies showed that the FWI system and its components correlated well with observed fire patterns in the Mediterranean basin (Aguado et al. 2003; Viegas et al. 1999; Viegas et al. 2001; Sol 1999) and concluded that the system is well suited for the estimation of fire hazard for this area. We therefore take the FWI value in June, July and August as an indication for the fire hazard.

The hazard of wind is entirely related to the wind climate. European countries with Atlantic coastlines generally experience higher wind speeds, with Ireland and the United Kingdom in particular having a rather severe wind climate. Also, mountainous regions generally experience a more severe wind climate due to topographical influences. Wind speeds are usually presented as hourly average (ECMWF 2009; KNMI 2009). Since wind damage to forests generally occurs during events with high wind speeds, we take the maximum observed average hourly wind speed in a year as indicator for the wind climate.

Fires and storms can influence all forest functions and services, like timber production, water and soil protection, biodiversity and landscape amenity. Exposure is defined as the value of all these functions. However, many of these are difficult to quantify. The easiest quantifiable variables are forest area and timber volume. Since forest fires are usually expressed in terms of area affected, we take total forest area as a proxy for exposure to fire risk. Similarly, wind damage is usually reported in terms of wood volume damaged, so we take total growing stock volume as a proxy for exposure to wind damage.

Vulnerability of a forest to fire greatly depends on fuel characteristics: how much fuel is available, how it is distributed and how flammable it is (Fernandes et al. 2000). Fuel sources are live biomass like foliage, branches, stems, lichens and shrubs and dead biomass like litter and humus. An even horizontal distribution of fuel will facilitate a fast fire spread, both at the stand scale (Agee and Skinner 2005) as well as on the landscape scale (Fernandes and Botelho 2003). A continuous presence of easily ignitable fuel in the vertical direction (ladder fuel, like shrubs, dead branches and lichens) greatly contributes to the risk that a ground fire will develop into a crown fire (Agee and Skinner 2005). Flammability of fuel partly depends on its size: the smaller the fuel, the more easily it is ignited. In general, such conditions are found especially in young stands (Vélez 1985; Brown and Smith 2000). With increasing age, tree height and crown base increase and fire risk generally decreases. The chemical composition of the fuel is also important. Generally, coniferous species burn more easily than broadleaved species (Meyer 2003), with Pinus pinaster, P. halepensis and P. radiata regarded as highly flammable species (Fernandes et al. 2008). Within the broadleaved tree species, sclerophyllous oak forest or coppice (mostly *Quercus ilex* and *Q. suber*) are reported to burn more frequently than could be expected from their share in the forest area (Le Houérou 1981).

Tree species composition is also important for vulnerability to wind. Coniferous species are considered more vulnerable to wind damage than broadleaved species, with Norway spruce (*Picea abies* (L.) Karst) being regarded as particularly vulnerable (Schütz et al. 2006). Though rooting depth is an important factor in vulnerability to wind, many other factors play a role as well. The tree and stand variables most important with regard to tree stability are tree height and the ratio of tree height to stem diameter at breast height (h/d ratio). Taller trees are more exposed to the wind than shorter ones, for example. Because stand or tree age is highly correlated with tree height, age is often used as a proxy for height. For both wind and fire, age and tree species composition are found to be important indicators of vulnerability. These two can usually be extracted from historic inventory data for a range of European countries, and from model simulations for the future. For the purpose of this study, we developed the following vulnerability indicator:

$$V_i = \sum_j \left(a_{j,young} \times b_{j,young} + \left(1 - a_{j,young}\right) \times b_{j,mature}\right)$$

where V is the vulnerability, i is the type of disturbance (wind or fire), $a_{j,young}$ is the area share (relative to total forest area) of tree species group j below a certain threshold age, $b_{j,young}$ is the relative vulnerability of young stands of tree species group j and $b_{j,mature}$ is the relative vulnerability of mature stands of tree species group j. Table 1 gives an overview of the groupings of tree species, relative vulnerability scores and threshold ages used. Threshold ages for fire are averaged from Meyer (2003). Threshold ages for wind vulnerability are derived from observed onset of wind damage. These are obtained for broadleaves from Winterhoff et al. (1995), for Norway and Sitka spruce from Schmid-Haas and Bachofen (1991), and for poplar from OBV (2009). For other conifers, the same onset age as spruce is assumed. Relative fire vulnerabilities are a combination of relative insurance premiums in different risk classes of forest fire insurance in the Netherlands (OBV 2009) and the rating of Meyer (2003). Relative wind vulnerabilities are a combination of relative insurance premiums in different risk classes of windfall insurance in the Netherlands (OBV 2009) and observed differences in share of damaged area in relation to total forest area after a number of storms (Grayson 1989; Lüpke and Spellmann 1997; Jalkanen and Mattila 2000). The relative vulnerabilities for both fire and wind range

Table 1 Vulnerability scoring of tree species with regard to fire and wind disturbance

Disturbance type (*i*)	Tree species group (*j*)	$b_{j,young}$	$b_{j,mature}$	Threshold age
Fire	Broadleaves except Q ilex and Q suber	2	1	50
	Douglas, fir, spruce	3	1	50
	Coppice	2	2	50
	P sylvestris and other pines	4	2	50
	Q ilex and Q suber	6	4	50
	P nigra, P halepensis, P pinaster	6	4	50
Wind	Broadleaves except poplar	1	3	80
	Poplar	1	4	10
	Conifers other than Norway and Sitka spruce	1	4	40
	Norway and Sitka spruce	1	6	40

from 1 (low vulnerability) to 6 (high vulnerability), and thus also the calculated total vulnerability score can range between 1 and 6.

3.2 Country case studies

The selection of country case studies was based on finding a balance between having a north–south and west–east gradient in Europe, availability of historical data and importance of the disturbance agent in a country. For fire, we selected Finland, the United Kingdom, Denmark, Poland and Italy. For wind we selected Finland, the United Kingdom, Denmark and the Czech Republic. No Mediterranean country was included, since data on wind damage for these countries are lacking.

3.3 History

We assessed historical exposure for 1950 and 2000 respectively from Kuusela (1994) and MCPFE (2007). Vulnerabilities were calculated from relevant national inventory reports as close as possible to these dates. Historical data on forest fire area and damaged volume by wind were taken from the Database on Forest Disturbances in Europe (Schelhaas et al. 2001), for the period since 1948 whenever available. Historical wind hazard was calculated from the Re-Analysis data at ECMWF (2009), including data for the period 1948–2007 (the ERA-40 dataset, Uppala et al. 2005). These data include six-hour observations of temperature, wind speed and precipitation, with a spatial resolution of about 250 by 250 km. For each grid cell, the maximum observed wind speed (hourly average) per year was extracted. From this series, also the average maximum annual wind speed was calculated, giving an indication of the severity of the wind climate. Historical fire hazard (FWI) in the months June, July and August was calculated from the Re-Analysis data at the ECMWF, with a resolution of 50 by 50 km, including data for the period 1975–2005. For both wind and fire hazard, a GIS was used to calculate national averages.

3.4 Future

For the development of future exposure and vulnerability under various adaptation measures, the European Forest Information Scenario model (EFISCEN V3.1.3) was applied. EFISCEN is a model that simulates the development of forest resources at scales from provincial to European level (Schelhaas et al. 2007b). The core of the EFISCEN model was developed by Sallnäs (1990). EFISCEN is mostly used as a tool to evaluate and compare different scenarios. Scenarios can be defined in terms of changes in forest area, changes in increment level due to changing environmental conditions, management regime and expected wood demand. Principal outputs are species and age class distributions, growing stock volumes, harvesting levels and increment at 5-year intervals.

Initialisation data were taken from the forest resources part of the European Forest Sector Outlook Studies of the UN-ECE (Schelhaas et al. 2006a, b). Small deviations between the forest area covered in the database and the area of Forest Available for Wood Supply (FAWS) according to UN-ECE/FAO (2000) exist, due to the fact that country correspondents were not always able to provide the detailed data for the whole FAWS area. These differences were accounted for by scaling the area in the input data to the corresponding area in UN-ECE/FAO (2000). For the baseline scenario, wood demand was assumed to increase slightly. It was calculated as the 5-year moving average of the fellings in the period 2000–2005 projected into the future. Baseline management regimes were adopted from Nabuurs et al. (2007). Total European forest area expansion was calculated from the total forest area expansion according to the IMAGE/CLUE model framework (Image Team 2001; Verburg et al. 2006) under the SRES A1 scenario (Nakicenovic and Swart 2000) for the period 2000–2030. This area expansion was allocated to each European country relative to the reported area expansion in the period 1990–2005. After 2030 no area expansion was assumed. Climate change is expected to influence forest growth in future due to changes in atmospheric CO_2 level, changes in precipitation and higher temperatures (IPCC 2007). However, quantification of changes in growth level over a century are still very uncertain (Kramer et al. 2002). We therefore applied no changes to the growth level in the adaptation scenarios, but examined the impact of future forest growth changes separately for the baseline scenario. Important factors that will influence future growth are climate change and nitrogen deposition. The methodology of Veroustraete et al. (2002) was used to calculate Net Ecosystem Production (NEP) under baseline (1980) and future climate conditions (see for climate scenarios below). However, we decided not to include a CO_2 fertilization effect on forest production: some authors claim substantial effects of increased atmospheric CO_2 concentration on NEP (e.g. (Hyvönen et al. 2007), while others strongly doubt whether there are any effects at all, especially for mature trees (Tognetti et al. 2000; Körner et al. 2005; Körner 2006)). Changes in future nitrogen deposition over Europe were translated to growth changes using the results of Solberg et al. (2009). The nitrogen deposition scenario was derived from (Amann et al. 2007) and was assumed to be independent from the climate change scenario. The relative change in NEP and the nitrogen effect where multiplied and fed into the EFISCEN model.

The main risk component that forest management can influence when considering fire is vulnerability. Lowering fire vulnerability can be achieved by decreasing the share of young forest, and by decreasing the share of flammable species. The following four adaptation scenarios were considered:

1. Rotation length increase (rotinc): For all species, the earliest age of possible harvest was increased by 10 years. At the same time, the period when thinnings are possible was increased by 10 years.
2. Tree species change (sp_change): Regeneration of coniferous area was for 50% done by broadleaved species, equally distributed over the available tree species.
3. A combination of the above, aimed at obtaining older stands (base_rotinc_sp_change): An increase in rotation length, combined with a tree species change towards broadleaves.

4. A combination of the above, aimed at fast conversion to broadleaves (max_rotinc_sp_change): An increase in rotation length and harvest level, combined with a tree species change towards broadleaves.

For adaptation to wind, forest management can aim at decreasing exposure, or at decreasing vulnerability. Decreasing exposure can be achieved by increased harvest levels, and decreasing vulnerability by decreasing the share of old forest and by changing tree species towards more stable species, like broadleaves. The following four adaptation scenarios were considered:

5. Increased harvest level (max): The demand was increased by 10% each 5-year time step, to reflect institutional and economic constraints on increases of the harvest level.
6. Rotation length decrease (rotdec): For all species, the earliest age of possible harvest was decreased by 10 years. At the same time, the period when thinnings are possible was decreased by 10 years.
7. Tree species change (sp_change): Regeneration of coniferous area was for 50% done by broadleaved species, equally distributed over the available tree species.
8. A combination of the above (max_rotdec_sp_change): A decrease in rotation length, an increase in harvest level, and a tree species change towards broadleaves.

3.5 Climate scenarios

The Regional Circulation Model (RCM) of the Hadley Centre (HadRM3P, Jones et al. 2004) was used to simulate fire hazard both in present and future period according to the approach used in Moriondo et al. (2006). HadRM3P is the result of a GCM dynamical downscaling procedure at a spatial resolution of 0.44° Lat×0.44° Lon. This RCM takes boundary conditions from coarser resolution global model and provides a higher spatial resolution of local topography and more realistic simulations of fine-scale weather features. In particular, the outputs of the coupled ocean-atmosphere HadCM3 (2.5° Lat×3.75° Lon) experiments provide the boundary conditions to drive a high-resolution (~120 Km) model of the global atmosphere (HadAM3H) which in turn provide the boundary conditions to drive the HadRM3P. HadCM3 model runs were forced between 1860–1990 including observed changes in greenhouses gases and aerosols to simulate changes in climate to date. For the period 1990–2100, the SRES A2 and B2 emission scenarios (Nakicenovic and Swart 2000) were applied. These two scenarios are characterised by respectively medium-high and medium-low greenhouse gas emissions, coming close to the 4 degrees and 2 degrees scenarios of the ADAM project. The average FWI values over the summer months for the periods 1960–1990 and 2070–2100 were calculated as an indication for the change in fire hazard under changing climate. We were not able to obtain reliable wind speed projections for the prediction of future wind hazard. Therefore we chose to assume no change in future wind climate and to discuss possible future changes in a qualitative way.

4 Results

4.1 Fire

The summer FWI clearly shows a north–south gradient, with the highest values in the Mediterranean Basin (Fig. 1). In the period 1975–2005, the average FWI in summer for

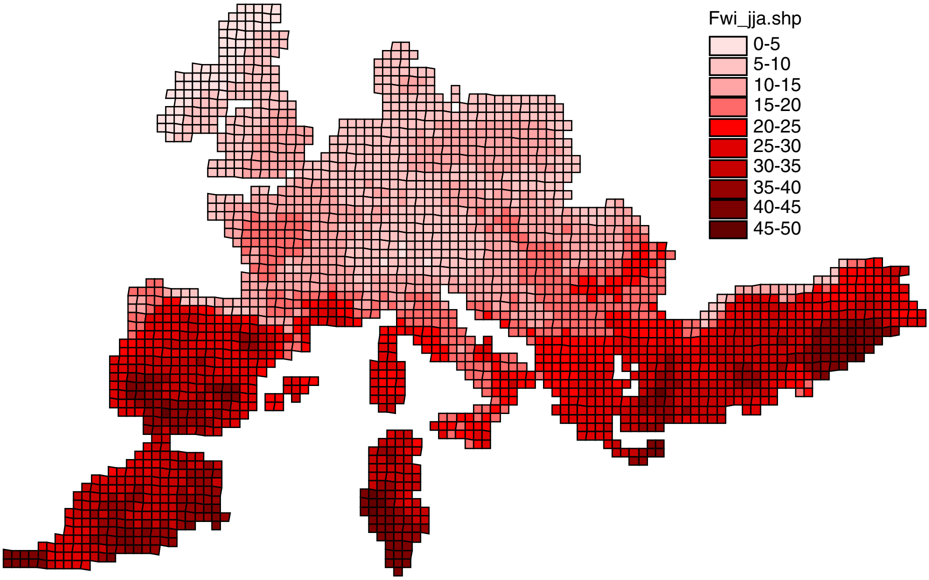

Fig. 1 Mean FWI index for the months June, July and August over the period 1975–2005 (Moriondo et al. 2006)

Finland was 1.8, while in Italy it was 15.3 (Table 2). The United Kingdom, Denmark and Poland showed intermediate values in the range from 8.5 to 10.0. The RCM simulations for the period 1960–1990 reproduced the same pattern, but absolute numbers did not match well in all cases. RCM simulations showed lower values for Denmark (−1.9) and the United Kingdom (−3.6), and higher values for Poland (+1.8) and especially Italy (+5.8). Under the climate change scenarios A2 and B2, the FWI values increased drastically. In Finland and the United Kingdom the increase was rather moderate with 3–6 points. In Denmark the FWI index increased by 8–12 points. In Italy and Poland FWI values increased by 12–16 points, resulting in a summer FWI value in Italy of 33.3 under the B2 scenario and 37.1 under the A2 scenario. If we express the annual burned forest area as a percentage of the forest area in 2000, we see more or less the same pattern as in the distribution of the FWI. Annual fire area in Finland is very low (0.00%), in Denmark and the United Kingdom it is 0.02%, in Poland 0.13% and in Italy 0.72%.

All countries showed an increase in exposure in the period 1950–2000, and in all countries the forest area is projected to increase further in future. Regarding the vulnerability, different countries showed different patterns. Poland had large afforestations after the Second World War, mainly with conifers, leading to high vulnerabilities around 1950. As these plantations got older, a lower vulnerability resulted in 2000. Under the baseline scenario, the vulnerability was expected to remain at the same level. For all other scenarios, vulnerability decreased. In Denmark and the United Kingdom the expansion of forest area continued longer, leading to a stable vulnerability between 1950 and 2000. Under all scenarios, vulnerability is expected to decrease in future. Finland showed an increase in vulnerability between 1950 and 2000, probably due to the regeneration of many old stands and the focus on coniferous species. Under all scenarios, the vulnerability was expected to decrease towards 2100. For Italy, no information on age class structure prior to 1985 was available. Between 1985 and 2000, vulnerability was constant, and under all

Table 2 Indicator values for hazard, vulnerability and exposure to fire, and burned area

		Finland		Denmark		United Kingdom		Poland		Italy	
FWI	historic (observed)	1975–2005	–	1975–2005	8.5	1975–2005	9.1	1975–2005	10.0	1975–2005	15.3
	historic (RCM output)	1960–1990	1.8	1960–1990	6.6	1960–1990	5.4	1960–1990	11.8	1960–1990	21.1
	A2 (RCM output)	2070–2100	5.0	2070–2100	15.1	2070–2100	11.8	2070–2100	27.3	2070–2100	37.1
	B2 (RCM output)	2070–2100	4.7	2070–2100	13.9	2070–2100	10.9	2070–2100	25.7	2070–2100	33.3
Vulnerability	historic	1952	2.0	1951	2.3	1980	2.6	1968	2.8	1985	2.1
	historic	2000	2.4	2000	2.3	2000	2.6	2000	2.4	2000	2.1
	baseline	2100	2.2	2100	1.6	2100	1.6	2100	2.4	2100	1.8
	rotation increase	2100	2.2	2100	1.5	2100	1.6	2100	2.3	2100	1.8
	species change	2100	1.9	2100	1.4	2100	1.5	2100	2.0	2100	1.8
	max_rotinc_sp_change	2100	2.0	2100	1.8	2100	1.9	2100	2.0	2100	1.9
	base_rotinc_sp_change	2100	1.8	2100	1.4	2100	1.5	2100	1.9	2100	1.8
Exposure (Mha)	historic	1952	17.4	1951	0.37	1950	1.5	1956	7.4	1950	5.6
	historic	2000	20.3	2000	0.49	2000	2.2	2000	8.4	2000	6.4
	baseline	2100	20.4	2100	0.58	2100	2.6	2100	8.9	2100	9.5
Fire area	historic (ha/yr)	1975–2006	556	1974–1997	173	1990–2001	495	1990–2005	6780	1975–2002	46688
	historic (% relative to 2000)		0.00		0.02		0.02		0.13		0.72

scenarios it decreased in future. Increasing rotation length had only a small positive effect in all countries, as compared to the baseline scenario. Changing the species distribution towards conifers reduced the vulnerability to fire by 0–0.39 points. Combining species change with an increase in rotation length only had a slightly more positive effect than changing tree species alone. Increasing the harvest level to speed up changes in tree species distribution had a negative effect up to 0.2 points in three cases and a positive effect up to 0.33 points in two cases. Figure 2 summarises the development of hazard, vulnerability and exposure between 1950 and 2100 (baseline), relative to the situation in 2000. Poland, Italy and Finland show an increase in fire risk, because all components are unchanged or increasing in future. For Denmark and UK, exposure and hazard are increasing, but vulnerability is decreasing at the same time. However, it is not clear how far the decrease in vulnerability can counteract the increase in the other two components.

4.2 Wind

The maximum annual wind speed that can be expected above land is clearly linked to distance to the Atlantic Ocean and other seas (Fig. 3). The United Kingdom is fully exposed to depressions coming from the Atlantic and on average experiences an annual maximum wind speed of 19.4 m/s (Table 3). Denmark is a bit more sheltered with values of 18.1 m/s. In Finland the average annual maximum is 10.4, while in the Czech Republic it is 12.2 m/s. The Czech Republic reported the highest amount of damaged timber in the period 1948–2007 with 107.7 million m^3 (Table 3). Damage in the other three ranged from 16.0 in Poland to 19.7 million m^3 in Finland.

Due to its skewed age class distribution, the United Kingdom shows the lowest vulnerability of the countries under study. It increased from 1.6 in 1980 to 1.7 in 2000, but was projected to increase to 3.6 by 2100 under the baseline scenario. Denmark showed a similar development, with little change between 1951 (2.0) and 2000 (2.2), but a drastic increase to 3.6 in 2100 under the baseline scenario. Due to the harvest of older stands in Finland, vulnerability decreased from 3.9 in 1952 to 3.0 in 2000. Under the baseline scenario, it is expected to increase to 3.2. Vulnerability in Czech Republic was stable over the last half a century at 3.5 and is hardly expected to change over the coming century. Decreasing rotation lengths had in all countries only a very minor effect on the vulnerability. Increasing the harvest level had not much effect in the Czech Republic (−0.1 point), but a high effect in Denmark (−1.5) and the United Kingdom (−1.9). Changing the species distribution towards broadleaves resulted in a decrease of the vulnerability in the range of 0.5 (Untied Kingdom) to 0.8 (Czech Republic). The combination of these three scenarios gave the highest reductions of vulnerability, with a reduction just below 1 point for the Czech Republic to a reduction of 2.4 in the United Kingdom.

Exposure, expressed as the total timber volume in a country, is strongly related to the forest area in a country. Denmark only has little timber volume (74 million m^3 in 2000) in comparison with Finland (over 2 billion m^3 in 2000). All countries showed a huge increase in timber volume over the period 1950–2000, and this increase is projected to continue towards 2100. Climate change effects could even exacerbate this trend, with especially in Finland a huge effect. Decreasing the rotation age or changing the tree species composition only had a minor effect on the exposure. Increasing the harvest level had a strong effect, but could in many cases not avoid an increase in exposure in 2100 as compared to 2000. The combination of the three scenarios yielded an exposure in 2100 comparable to the increasing harvest scenario, only in Finland was the reduction of exposure more pronounced. Figure 4 summarises the development of hazard, vulnerability and exposure

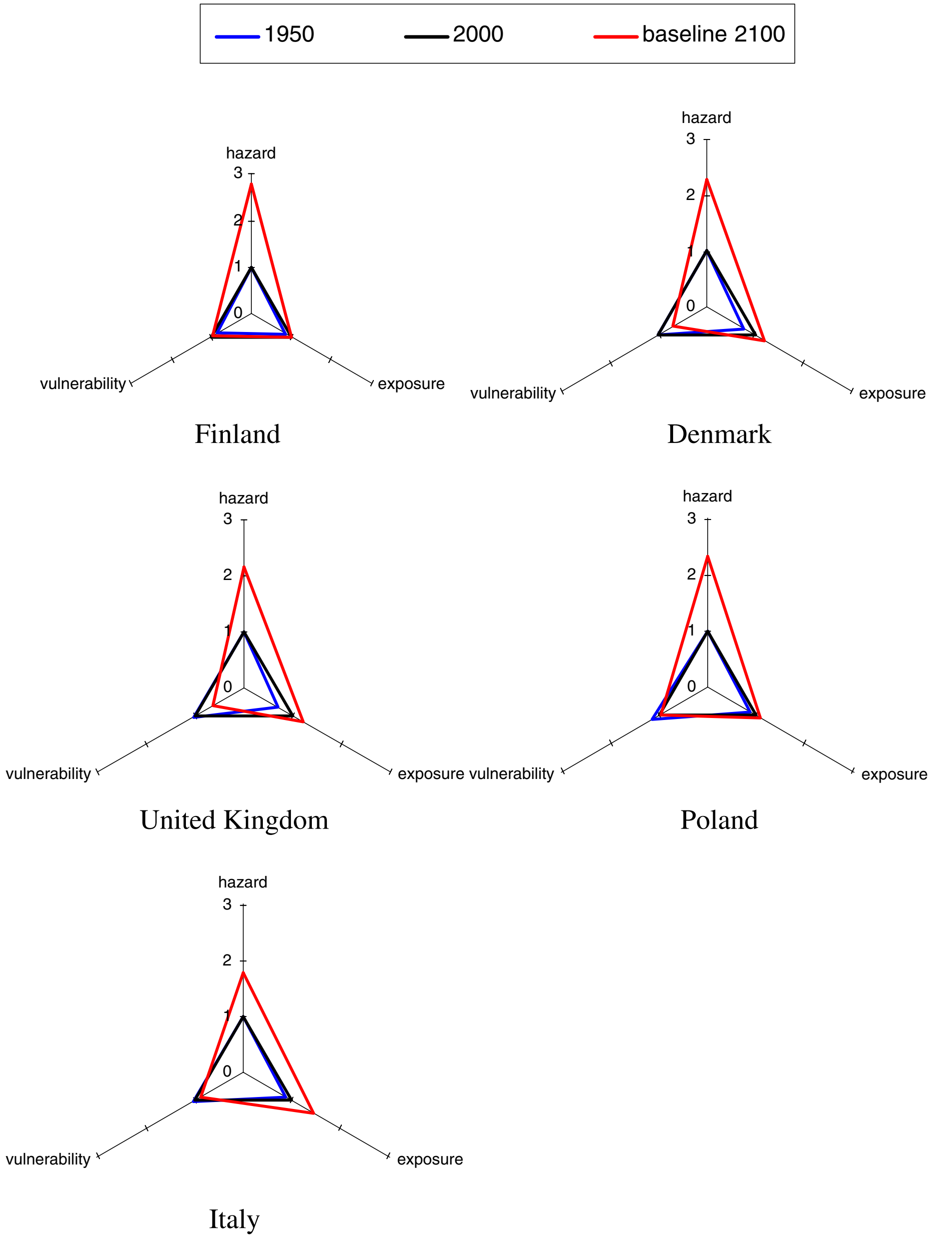

Fig. 2 Change in hazard, exposure and vulnerability to fire for 1950, 2000 and 2100 (climate: A2 scenario; vulnerability: baseline scenario), relative to the situation in 2000 (for which the value of 1 is assumed), for Finland, Denmark, the United Kingdom, the Netherlands, Poland and Italy. For absolute values see Table 2

between 1950 and 2100 (baseline scenario), relative to the situation in 2000. Under the assumption that the wind climate will not change, risk will increase considerably in Denmark and the UK, due to higher exposure and higher vulnerability. The risk in Finland and Czech Republic will also increase, but only due to an increase in the exposure.

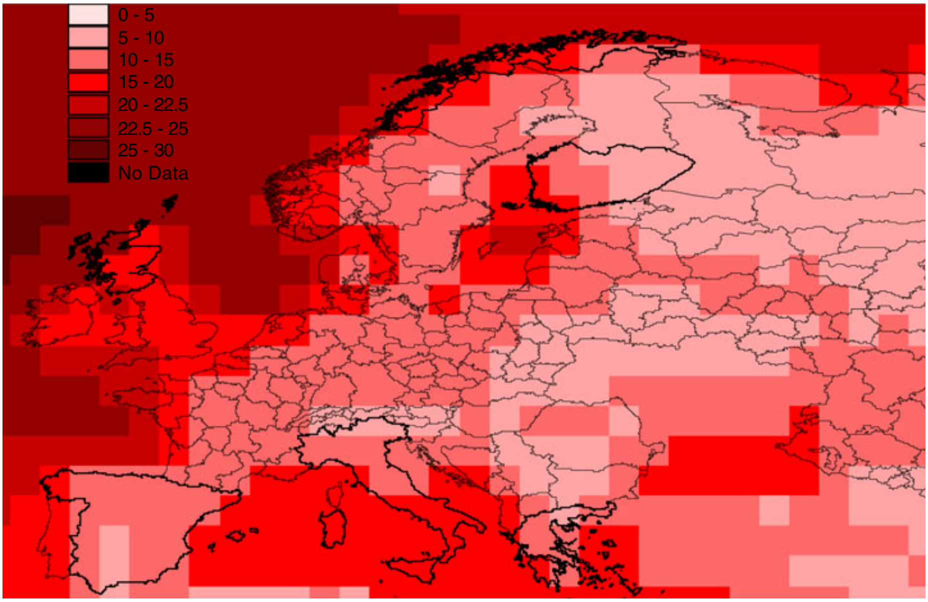

Fig. 3 Maximum annual wind speed (in m/s; average per hour), averaged over the period 1948–2007

5 Discussion

5.1 Fire

Our hazard indicator, the FWI in the summer months, shows a good agreement with the fire pattern over Europe (Table 2). High FWI values, caused by warm and dry summers, correlate with greater fire areas. Observed FWI values from the ERA dataset and the simulated FWI from the RCM do not totally agree, in particular in southern countries. This is probably caused by an overestimation of summer temperatures in the RCM when the soil dries out, as discussed by Moberg and Jones (2004). This RCM bias might cause an overestimation of future FWI, also in more northern regions. However, it is clear that FWI is expected to increase considerably under a warmer climate (Table 2, Fig. 2). Higher FWI will inevitably lead to a larger fire area in most of the countries if other conditions remain the same. Forest area has been increasing over the last 50 years and is expected to increase further in future (Fig. 2). Major drivers for forest area expansion are active afforestation policies and abandonment of agricultural lands. Policies at different levels (EU, national and local) can influence these drivers, but forest fire prevention through reduction of exposure is unlikely to play a large role in formulating such policies. Reduction of future exposure to counteract the increase in hazard therefore does not seem to be a very promising option. Ageing of the forest has caused the vulnerability to decrease in most countries. Also the trend towards more broadleaved forest in large parts of the EU has contributed to the decrease in vulnerability. Even if no more conversion of coniferous forests to broadleaves takes place, the vulnerability is projected to decrease due to further ageing of the forest. We explored some scenarios to see to what degree the vulnerability can be influenced by forest management. Increasing the rotation length by 10 years hardly had an effect on the overall vulnerability. This is because stands over 50 years of age have a low

Table 3 Indicator values for hazard, vulnerability and exposure to wind, and wind-affected volume

		Finland		Denmark		United Kingdom		Czech Republic	
Wind speed	historic	1948–2007	10.4	1948–2007	18.1	1948–2007	19.4	1948–2007	12.2
Vulnerability	historic	1952	3.9	1951	2.0	1980	1.6	1950	3.5
	historic	2000	3.0	2000	2.2	2000	1.7	1994	3.5
	baseline	2100	3.2	2100	3.6	2100	3.6	2100	3.6
	maximum harvest	2100	2.8	2100	2.1	2100	1.7	2100	3.5
	rotation decrease	2100	3.1	2100	3.5	2100	3.5	2100	3.5
	species change	2100	2.5	2100	2.8	2100	3.1	2100	2.8
	max_rotdec_sp_change	2100	1.8	2100	1.6	2100	1.2	2100	2.8
Exposure (Mm^3)	historic	1952	1538	1950	39	1950	110	1950	322
	historic	2000	2091	2000	74	2000	267	2000	631
	baseline	2100	3237	2100	272	2100	1168	2100	1103
	baseline_A2	2100	5345	2100	280	2100	1241	2100	1379
	baseline_B2	2100	5027	2100	279	2100	1220	2100	1322
	maximum harvest	2100	1998	2100	146	2100	355	2100	899
	rotation decrease	2100	3033	2100	265	2100	1134	2100	1021
	species change	2100	2779	2100	242	2100	1073	2100	925
	max_rotdec_sp_change	2100	1247	2100	150	2100	334	2100	870
Damage	historic (Mm^3, total in period)	1948–2007	19.7	1948–2007	16.0	1948–2007	17.9	1948–2007	107.7
	historic (total compared to 2000)		0.9		21.5		6.7		17.1

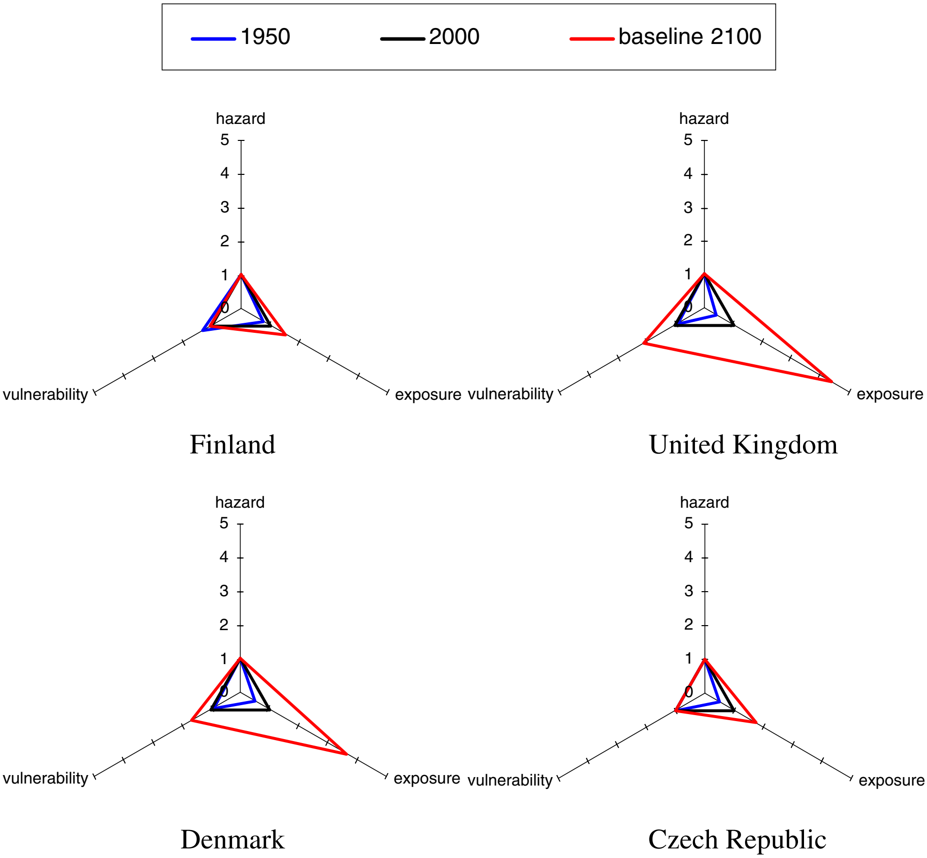

Fig. 4 Change in hazard, exposure and vulnerability to wind for 1950, 2000 and 2100 (baseline scenario), relative to the situation in 2000 (for which the value of 1 is assumed), for Finland, Denmark, the United Kingdom and the Czech Republic. For absolute values see Table 3

vulnerability. For the overall score, it does not matter if a stand is of age 80 or 90. The standing volume in these stands does not change much, so more or less the same area of clearfelling is needed to find the required harvest level. Thus the area of young stands with high vulnerability will be of similar magnitude. Changing the species distribution had a larger effect, because broadleaves, even if young, have lower vulnerabilities. However, in most countries it took about 50 years before differences between the baseline and the species-change scenario became apparent. Vulnerability decreased by up to 0.4 points in 2100 compared to the baseline. Effects of species change and rotation increase are additive, and their combination was therefore not much different from the species-change scenario alone. By increasing the harvest level, the rate at which conifers are replaced can be increased. This effect is however counteracted by the increase of vulnerable regeneration area, which results in a net increase of vulnerability in most cases as compared to the baseline scenario.

Converting conifers to broadleaves was the most effective option to decrease future forest vulnerability to fires. However, we are not able to predict how much this decrease in vulnerability could contribute to a decrease in overall risk. A thorough statistical analysis of the relationship between observed fire area and the indicators (of hazard, exposure and vulnerability) was not possible due to difficulties with availability of reliable long term series on hazard and observed fire area. Furthermore, the vulnerability and exposure indices changed only slowly over time, leading to low explanative power. For future projections on fire area, we would have to extrapolate far outside the historic range.

We defined vulnerability as an index of the combined age class distribution and the tree species distribution. The major reason for this definition was the availability of data to calculate this index both for the past and for the future. However, much more factors play a role in vulnerability, like fuel build-up within the stands, the spatial arrangement of stands, accessibility to the forest, distance to water sources, etc. It is virtually impossible to combine these factors in one vulnerability index, and even then the required data would probably be not available over large areas. Despite the shortcomings of our way to calculate it, decreasing the vulnerability of the forest seems the only way to combat the effects of expected increases in FWI. At a large scale, changing the tree species distribution could be part of a forest management strategy towards lower vulnerability, but this should be combined with more local options of fuel management and spatial arrangements of forest stands and non-forest areas.

5.2 Wind

The wind speed pattern as shown in Fig. 3 largely corresponds with the damage pattern in Table 3. However, the Czech Republic showed a high damage amount at a rather low maximum wind speed. A likely reason is that wind speed data do not take into account influences of the topography. Also the alpine region shows low wind speed maxima, although it has been exposed to very high wind speeds by several storms in recent history (Schütz et al. 2006). Although the general pattern in Fig. 3 seems very plausible, the quality of the dataset can be questioned. In most country cases, annual damage data did not correlate very well with the country-specific anomalies of the wind speed data set. Smits et al. (2005) found opposing trends in storminess for the Netherlands, using a high-quality wind speed dataset with long term observation series for a couple of stations in the Netherlands and the same reanalysis dataset as we used. Discrepancies were thought to be caused by inhomogeneities in the reanalysis dataset. High-quality long-term datasets would be most ideal for our analysis, but such datasets are very rare (Smits et al. 2005).

In large parts of Europe, increment has increased over the last decades, while the harvest level has remained rather stable (Nabuurs et al. 2003). This difference has lead to an increasing growing stock and a higher share of older forest, leading to an increased exposure and an increased vulnerability in most countries. Under the baseline scenario, these trends are expected to continue in future, leading to very high growing stocks and a high vulnerability (Fig. 4). Growth changes due to climate change effects could increase the future exposure even more. This effect is relatively modest in the UK, Denmark and Czech Republic, but very apparent in Finland. A drastic increase in harvest level could curb this trend, keeping future vulnerability and exposure more or less at the current level. Decreasing the rotation age hardly had an effect on vulnerability and exposure. Although it is possible to harvest at an earlier age, the model will not do so if there is no demand for the wood. Changing the species distribution mainly affected the vulnerability, through replacement of vulnerable conifers with less vulnerable broadleaves. In most cases the growth rate of broadleaves is lower than conifers, leading to somewhat lower exposure under this scenario. The most intensive scenario was a combination of these measures, and showed a considerable decrease in both vulnerability and exposure as compared to the baseline. The increase in harvest level limited the occurrence of old and vulnerable stands. The decrease in rotation age was more effective, since these stands were indeed harvested due to a high demand for wood. Finally, the conversion to broadleaves occurred much faster, since more stands were regenerated due to the high wood demand.

The apparent increase in winter storms and damage by winter storms has triggered many research projects, aimed at identifying historical and future trends in storminess. Ulbrich et al. (2009) provides a review of the literature on tracking of extra-tropical cyclones under future climate conditions. For Europe, most models agree on a lower number of cyclones in total, but an increase in the occurrence of intense cyclones in winter. The increase in intense cyclones is limited to certain regions, notably over the Northeast Atlantic and the British Isles (see references in Ulbrich et al. 2009). Beniston et al. (2007) find an increase of 2.5–10% in the 90th percentile of daily winter wind speed in Western Europe (North Sea countries, France, northern Switzerland, Germany) and a small decrease to the north and south of this area. Fink et al. (2009) state that storms in future might penetrate deeper into Europe, also causing an increase in storminess in eastern parts of Central Europe. They find an increase in the 98th percentile of daily surface maximum wind speed of 5–15% over most of Europe, except for Northern Scandinavia and the Mediterranean. From this overview, an increased storminess for Denmark and the UK seems likely. Finland seems to be largely safe, while the picture for Czech Republic is not clear.

For all countries, we can expect an increasing risk for wind damage in forests due to the expected large increase in exposure and vulnerability under the baseline scenario. Climate change effects in the form of increased storminess might increase the risk in the UK and Denmark, while a positive growth effect especially in Finland could lead to an even larger increase in exposure. Adaptation measures should be aiming at reducing the vulnerability and exposure. Changing the species distribution helps to reduce the future vulnerability, while only an increase in harvest level could reduce the future exposure. Furthermore, increasing the harvest level increases the efficiency of species change and a reduction of the rotation age.

Vulnerability to wind damage of a particular forest stand can be modified by many factors, like thinning regime, regeneration method, species mixture and occurrence of openings in the forest at the windward side (Quine et al. 1995). These were not included in our study, but must be taken into account in studies at the landscape and stand level scale. For example, Schelhaas (2008) modelled vulnerability of forest stands induced by changes in thinning regime and species mixture, while Zeng et al. (2007) tried to reduce vulnerability at the landscape level by minimising the length of freshly exposed forest edges through the spatial arrangement of clearcuts.

Unfortunately we were not able to fit a regression model on the data, so we cannot make predictions on future risks. The quality of the wind speed dataset can be questioned, but also the quality and completeness of the damage dataset. Only the Czech Republic had a more or less complete coverage of annual wind damage for the period 1948–2007. In the other countries, only major events were reported. For example, Holmsgaard (1986) estimated that although a good overview exists for Denmark for the major storm damage to forest in the 20th century, only half of the total damage was included in his overview, the rest consisting of smaller windthrows. If a year when no damage is reported is considered as a year with no damage, the regression results are heavily influenced by these data points, since they are many. This would lead to an underestimation of the risk in severe events. If these years are excluded, only little data remains.

There is a clearly nonlinear linkage between temperature rise and the increase in wind and fire hazards. According to orientative assessment reported in Mills et al. (2001), a

2.2°C mean temperature increase leads to 5–10% increase in hurricane wind speed, while a 1°C mean summer temperature increase may correspond to 17–28% increase in wildfires. Storm damage to infrastructure is over-proportionally related to the wind speed. Mills et al. (2001) proposed a quadratic relationship, while a cubic relationship has been postulated as well (cf. Hitz and Smith 2004). Grace (2009) cited Insurance Australia Group's experience, showing that an increase in peak wind gust strength from 40–50 to 50–60 knots can generate a 6.5 fold increase in building claims.

In this study, the EFISCEN model is used to project the future development of exposure and vulnerability to wind and fire under a range of scenarios. One drawback of this approach is that occurrence of these disturbance events will influence the further development of the projections. Exposure and vulnerability to wind are projected to reach very high values under the baseline scenario. In reality storms will cause major damage long before these values are reached, leading to a natural reduction in exposure and vulnerability through regeneration of old stands. Similarly, stand-replacing fires will influence the projected decrease in fire vulnerability. In a study by Schelhaas et al. (2002), a natural disturbances module was added to the EFISCEN model. This enables a dynamic simulation of disturbances in relation to exposure and vulnerability, not only allowing a more realistic projection of exposure and vulnerability itself, but also a direct projection of future damage. However, a prerequisite to parameterise this module is a known relationship between hazard index and the occurrence of disturbance events, and a projection of future hazard. From experiences in our study it is clear that a lack of reliable datasets would inhibit that approach. Furthermore, climate change will have an influence on forest growth as well. Although it is possible within EFISCEN to take this into account (see for example Nabuurs et al. 2002), we did not incorporate this aspect. The underlying projections of changes in increment remain very uncertain, but would not change much of the general picture as sketched here.

This study gives insight in some trends that influence the future risk to fire and wind damage in forests. Unfortunately we were not able to exactly quantify the risk and give a prediction of expected damage under different scenarios. However, the direction and magnitude of these trends give a general idea of the consequences of certain scenarios. Although the methodology can be much improved, it can serve as a tool to evaluate the risk of other scenarios projections as well. Schelhaas et al. (2007a) used the EFISCEN model to evaluate mitigation options in forestry. Especially the optimisation of carbon storage in the forest could lead to situations comparable to our baseline scenario, with high exposure and vulnerability to wind damage. In situations with high annual wind speeds, this would be a risky option. Similarly, a focus on biomass production with short rotations could lead to risky situations in areas where fire hazard is or will become high.

Each component of the framework has its associated uncertainties, like those associated with data sources (inhomogeneities, interpolations, missing data), model assumptions and scenario assumptions. When evaluating the outcomes of the risk analysis, these uncertainties should be kept in mind. Possible changes in forest policy or management should not be aimed at reacting to one scenario only, but should be favourable or at least not be worsening the situation under a range of plausible scenarios. The direction and approximate magnitude of change is more important than the absolute value.

The baseline scenario projected an increase in exposure and vulnerability to wind for some countries. Adaptation scenarios were most effective under a drastic increase in harvest level (Table 3). Such an increase might mean that in some future periods the harvest would exceed increment. This might conflict with current views on sustainability and implementing such a policy would need a very good communication strategy. In Switzerland, a similar policy has already been formulated (SAEFL 1999). However, adaptation to wind risk will and should never be the only goal. A proper policy should try to find a balance between the various functions of the forest and the associated risks.

6 Conclusions

Over the last 50 years, the European forests have changed considerably. In most parts of Europe the forest area expanded, the growing stock increased and the forest has become older. Under the baseline scenario, these trends are expected to continue until 2100. Due to climate change, the fire weather is expected to become much worse, leading to a considerable increase in fire risk. The most effective scenario at the national scale was to reduce the vulnerability by promoting the conversion of conifers to broadleaves. It seems more and more likely that climate change will increase the storminess in some parts of Europe. Also the projected increase in exposure and vulnerability will increase the risk considerably. Only an increase in harvest level can stop the current build-up of growing stock, while at the same time it will lower vulnerability through the reduction of the share of old and vulnerable stands. Changing species from conifers to broadleaves helps to reduce vulnerability as well. Lowering vulnerability by decreasing the rotation length is only effective in combination with a high demand of wood.

Acknowledgements This study was financed by the European Commission through the ADAM project (Adaptation and Mitigation: Supporting European climate policy, FP7-018476). The research is part of the strategic research programmes "Sustainable spatial development of ecosystems, landscapes, seas and regions" and "Climate change", funded by the Dutch Ministry of Agriculture, Nature Conservation and Food Quality, and carried out by Wageningen University Research centre. Furthermore we would like to thank Emil Cienciala and Zuzanna Exnerová from IFER for their help in obtaining historical forest inventory data for the Czech Republic.

References

Agee JK, Skinner CN (2005) Basic principles of forest fuel reduction treatments. For Ecol Manage 211:83–96

Aguado I, Chuvieco E, Martín P, Salas FJ (2003) Assessment of forest fire danger conditions in southern Spain from NOAA images and meteorological indices. Int J Remote Sens 24:1653–1668

Alcamo J, Moreno JM, Nováky B, Bindi M, Corobov R, Devoy RJN, Giannakopoulos C, Martin E, Olesen JE, Shvidenko A (2007) Europe. Climate Change 2007: Impacts, adaptation and vulnerability. Contribution of working group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Parry ML, Canziani OF, Palutikof JP, van der Linden PJ and Hanson CE (Eds), Cambridge University Press, Cambridge, UK, 541–580

Amann M, Asman W, Bertok I, Cofala J, Heyes C, Klimont Z, Schöpp W, Wagner F (2007) Cost-effective emission reductions to meet the environmental targets of the Thematic Strategy on Air Pollution under different greenhouse gas constraints, NEC Scenario Analysis Report Nr. 5. IIASA, Laxenburg, Austria

Beniston M, Stephenson D, Christensen O, Ferro C, Frei C, Goyette S, Halsnaes K, Holt T, Jylhä K, Koffi B, Palutikof J, Schöll R, Semmler T, Woth K (2007) Future extreme events in European climate: an exploration of regional climate model projections. Clim Change 81:71–95

Brown JK, Smith JK (2000) Wildland fire in ecosystems: effects of fire on flora. Gen. tech. rep. rmrs-gtr-42-vol. 2, U.S. Department of Agriculture, Forest Service. Available: http://www.fs.fed.us/rm/pubs/rmrs_gtr42_2.html

ECMWF (2009) European Centre for Medium-Range Weather Forecasts, www.ecmwf.int. Cited 2 February 2009

FAO (2007) State of the World's Forests 2007. Food and Agricultural Organization of the United Nations, Rome

Fernandes PM, Botelho H, Loureiro C (2000) Fire hazard implications of alternative fuel management techniques—case studies from northern Portugal. In: Proceedings from The Joint Fire Science Conference and Workshop, Idaho, 1999

Fernandes PM, Botelho HS (2003) A review of prescribed burning effectiveness in fire hazard reduction. Int J Wildland Fire 12(2):117–128

Fernandes PM, Vega JA, Jiménez E, Rigolot E (2008) Fire resistance of European pines. For Ecol Manage 256:246–255

Fink A, Brücher T, Ermert V, Krüger A, Pinto JG (2009) The European storm Kyrill in January 2007: synoptic evolution, meteorological impacts and some considerations with respect to climate change. Nat Hazards Earth Syst Sci 9:405–423

Finney MA (2001) Design of regular landscape fuel treatment patterns for modifying fire growth and behavior. For Sci 47:219–228

Grace E (2009) Dangerous climate change and extreme weather events in Australia (in press)

Graham RT, McCaffrey S, Jain TB (2004) Science basis for changing forest structure to modify wildfire behavior and severity. Gen. Tech. Rep. RMRS-GTR-120. U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station, Fort Collins

Grayson AJ (ed) (1989) The 1987 Storm: impacts and responses. Forestry Commission Bulletin 87

Hitz S, Smith J (2004) Estimating global impacts from climate change. Global Env Change 14(3):201–218

Holmsgaard E (1986) Historical development of wind damage in conifers in Denmark. In: Communities, CotE (ed) Minimizing wind damage to coniferous stands. Lövenholm Castle, Denmark, pp 2–4

Hyvönen R, Ågren GI, Linder S, Persson T, Cotrufo MF, Ekblad A, Freeman M, Grelle A, Janssens IA, Jarvis PG, Kellomäki S, Lindroth A, Loustau D, Lundmark T, Norby RJ, Oren R, Pilegaard K, Ryan MG, Sigurdsson BD, Strömgren M, Van Oijen M, Wallin G (2007) The likely impact of elevated [CO2], nitrogen deposition, increased temperature and management on carbon sequestration in temperate and boreal forest ecosystems: a literature review. New Phytol 173(3):463–480

Image Team (2001) The IMAGE 2.2 implementation of the SRES scenarios: A comprehensive analysis of emissions, climate change and impacts in the 21st century. Main disc, National Institute for Public Health and the Environment, Bilthoven, the Netherlands. RIVM CD-ROM publication 481508018

IPCC (2007) Climate Change 2007: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. [Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds.)]. Cambridge University Press, Cambridge, United Kingdom

Jalkanen A, Mattila U (2000) Logistic regression models for wind and snow damage in northern Finland based on the National Forest Inventory data. For Ecol Manage 135:315–330

Jones RG, Noguer M, Hassell D, Hudson D, Wilson S, Jenkins G, Mitchell J (2004) Generating high resolution climate change scenarios using PRECIS, report, Met Off. Hadley Centre, Exeter, UK

JRC (2008) Forest Fires in Europe 2007. JRC Scientific and Technical Reports, Report No. 8. Joint Research Centre, Ispra, Italy. http://www.fire.uni-freiburg.de/programmes/eu-comission/EU-Forest-Fires-in-Europe-2007.pdf

KNMI (2009) Koninklijk Nederlands Meteorologisch Instituut, www.knmi.nl. Cited 2 February 2009

Körner C (2006) Plant CO2 responses: an issue of definition, time and resource supply. New Phytol 172 (3):393–411

Körner C, Asshoff R, Bignucolo O, Hättenschwiler S, Keel SG, Pelaez-Riedl S, Pepin S, Siegwolf RTW, Zotz G (2005) Carbon flux and growth in mature deciduous forest trees exposed to elevated CO2. Science 309:1360–1362

Kramer K, Leinonen I, Bartelink HH, Berbigier P, Borghetti M, Bernhofer C, Cienciala E, Dolman AJ, Froer O, Gracia CA, Granier A, Grünwald T, Hari P, Jans W, Kellomäki S, Loustau D, Magnani F, Markkanen T, Matteucci G, Mohren GMJ, Moors E, Nissinen A, Peltola H, Sabaté S, Sanchez A, Sonntag M, Valentini R, Vesala T (2002) Evaluation of six process-based forest growth models using eddy-covariance measurements of CO_2 and H_2O fluxes at six forest sites in Europe. Glob Chang Biol 8(3):213–230

Kron W (2002) Flood risk=hazard x exposure x vulnerability. In: Wu M et al (eds) Flood defence. Science, New York

Kuusela K (1994) Forest Resources in Europe 1950–1990. Research Report 1, European Forest Institute. Cambridge University Press

Le Houérou HN (1981) Impact of man and his animals on Mediterranean vegetation. In: Di Castri F, Goodall D, Specht RL (eds) Mediterranean-type shrublands, ecosystems of the world vol 11. Elsevier Scientific Publishing Company, Amsterdam, pp 479–521

Lüpke B, Spellmann H (1997) Aspekte der Stabilität und des Wachstums von Mischbestanden aus Fichte und Buche als Grundlage für waldbauliche entscheidungen. Forstarchiv 68:167–179

MCPFE (2007) State of Europe's forests 2007. The MCPFE Report on Sustainable Forest Management in Europe. Ministerial Conference on the Protection of Forests in Europe, Liaison Unit Warsaw, Poland

Meyer J (2003) Fire effects on forest resource development in the French Mediterranean region—projections with a large-scale forest scenario model. Technical Report 16. European Forest Institute

Mills E, Lecomte E, Peara A (2001) U.S. Insurance Industry perspectives on global climate change. Lawrence Berkeley National Laboratory, MS 90-4000, U.S. Department of Energy, University of California, Berkeley, California, February 2001, p. 72

Moberg A, Jones PD (2004) Regional climate model simulations of daily maximum and minimum near-surface temperatures across Europe compared with observed station data 1961–1990. Clim Dyn 23:695–715

Moriondo M, Good P, Durao R, Bindi M, Giannakopoulos C, Corte-Real J (2006) Potential impact of climate change on fire risk in the Mediterranean area. Clim Res 31:85–95

Nabuurs GJ, Pussinen A, Karjalainen T, Erhard M, Kramer K (2002) Stemwood volume increment changes in European forests due to climate change-a simulation study with the EFISCEN model. Glob Chang Biol 8:304–316

Nabuurs GJ, Schelhaas MJ, Mohren GMJ, Field CB (2003) Temporal evolution of the European Forest carbon sink from 1950 to 1999. Glob Chang Biol 9(2):152–160

Nabuurs GJ, Pussinen A, van Brusselen J, Schelhaas MJ (2007) Future harvesting pressure on European forests. Eur J For Res 126:391–400

Nakicenovic N, Swart R (eds) (2000) IPCC Special Report on Emission Scenarios, Cambridge University Press, Cambridge, United Kingdom

OBV (2009) Onderlinge Bossen Verzekering http://www.bossenverzekering.nl/ Cited 2 February 2009

Quine C, Coutts M, Gardiner B, Pyatt G (1995) Forests and wind: management to minimize damage, Forestry Commission Bulletin 114. HMSO, London

SAEFL (1999) The Swiss forest—taking stock. Interpretation of the Second National Forest Inventory in terms of forestry policy

Sallnäs O (1990) A matrix growth model of the Swedish forest. Studia Forestalia Suecica 183, Swedish University of Agricultural Sciences, Faculty of Forestry. Uppsala, Sweden

Schelhaas MJ (2008) The wind stability of different silvicultural systems for Douglas-fir in The Netherlands: a model-based approach. Forestry 81(3):399–414

Schelhaas MJ, Varis S, Schuck A (2001) Database on Forest Disturbances in Europe (DFDE), European Forest Institute, Joensuu, Finland. http://www.efi.fi/projects/dfde/. Cited 2 February 2009

Schelhaas MJ, Nabuurs GJ, Sonntag M, Pussinen A (2002) Adding natural disturbances to a large-scale forest scenario model and a case study for Switzerland. For Ecol Manage 167:13–26

Schelhaas MJ, Nabuurs GJ, Schuck A (2003) Natural disturbances in the European forests in the 19th and 20th centuries. Glob Chang Biol 9(11):1620–1633

Schelhaas MJ, van Brusselen J, Pussinen A, Pesonen E, Schuck A, Nabuurs GJ Sasse V (2006a) Outlook for the Development of European Forest Resources. A study prepared for the European Forest Sector Outlook Study (EFSOS). Geneva Timber and Forest Discussion Paper, ECE/TIM/DP/41. UN-ECE, Geneva

Schelhaas MJ, Varis S, Schuck A, Nabuurs GJ (2006b) EFISCEN Inventory Database, European Forest Institute, Joensuu, Finland, http://www.efi.int/portal/virtual_library/databases/efiscen/ Cited 2 February 2009

Schelhaas MJ, Cienciala E, Lindner M, Nabuurs GJ, Zianchi G (2007a) Selection and quantification of forestry measures targeted at the Kyoto Protocol and the Convention on Biodiversity. Alterra report 1508

Schelhaas MJ, Eggers J, Lindner M, Nabuurs GJ, Pussinen A, Päivinen R, Schuck A, Verkerk PJ, van der Werf DC, Zudin S (2007b) Model documentation for the European Forest Information Scenario model (EFISCEN 3.1). Wageningen, Alterra, Alterra report 1559, EFI Technical Report 26, Joensuu, Finland

Schmid-Haas P, Bachofen H (1991) Die Sturmgefährdung von Einzelbäumen und Beständen. Schweizerische Zeitschrift für Forstwesen 142:477–504

Schütz JP, Götz M, Schmid W, Mandallaz D (2006) Vulnerability of spruce (Picea abies) and beech (Fagus sylvatica) forest stands to storms and consequences for silviculture. Eur J For Res 125:291–302

Smits A, Klein Tank AMG, Können GP (2005) Trends in storminess over the Netherlands, 1962–2002. Int J Climatol 25:1331–1344

Sol B (1999) A European program improves the operational fight against forest fires: MINERVE Program and meteorological fire danger in southeastern France. In DELFI Proceedings, Athens

Solberg S, Dobbertin M, Reinds GJ, Lange H, Andreassen K, Fernandez PG, Hildingsson A, De Vries W (2009) Analyses of the impact of changes in atmospheric deposition and climate on forest growth in European monitoring plots: a stand growth approach. For Ecol Manage 258:1735–1750

Tognetti R, Cherubini P, Innes JL (2000) Comparative stem-growth rates of Mediterranean trees under background and naturally enhanced ambient CO_2 concentrations. New Phytol 146(1):59–74

Ulbrich U, Leckebusch G, Pinto J (2009) Extra-tropical cyclones in the present and future climate: a review. Theor Appl Climatol 96:117–131

UN-ECE/FAO (2000) Forest resources of Europe, CIS, North America, Australia, Japan and New Zealand In: Geneva Timber and Forest Study papers No. 17

Uppala SM, Kållberg PW, Simmons AJ, Andrae U, Bechtold VDC, Fiorino M, Gibson JK, Haseler J, Hernandez A, Kelly GA, Li X, Onogi K, Saarinen S, Sokka N, Allan RP, Andersson E, Arpe K, Balmaseda MA, Beljaars ACM, Berg LVD, Bidlot J, Bormann N, Caires S, Chevallier F, Dethof A, Dragosavac M, Fisher M, Fuentes M, Hagemann S, Hólm E, Hoskins BJ, Isaksen L, Janssen PAEM, Jenne R, Mcnally AP, Mahfouf J-F, Morcrette J-J, Rayner NA, Saunders RW, Simon P, Sterl A, Trenberth KE, Untch A, Vasiljevic D, Viterbo P, Woollen J (2005) The ERA-40 re-analysis. Q J R Meteorol Soc 131:2961–3012

Van Wagner CE (1987) Development and structure of a Canadian forest fire weather index system, Forestry Technical Report 35. Canadian Forestry Service, Ottawa

Vélez R (1985) Fire prevention in Aleppo pine forests. In: Le pin d'Alep et le pin brutia dans la sylviculture méditerranéenne, volume 1986 of Options Mediterraneennes. CIHEAM, 167–178. Available: http://ressources.ciheam.org/om/pdf/s10/CI010861.pdf

Verburg PH, Schulp CJE, Witte N, Veldkamp A (2006) Downscaling of land use change scenarios to assess the dynamics of European landscapes. Agric Ecosyst Environ 114(1):39–56

Veroustraete F, Sabbe H, Eerens H (2002) Estimation of carbon mass fluxes over Europe using the C-Fix model and Euroflux data. Remote Sens Environ 83(3):376–399

Viegas DX, Biovio G, Ferreira A, Nosenzo A, Sol B (1999) Comparative study of various methods of fire danger evaluation in southern Europe. Int J Wildland Fire 10:235–246

Viegas DX, Piñol J, Viegas MT, Ogaya R (2001) Estimating live fine fuels moisture content using meteorologically-based indices. Int J Wildland Fire 10:223–240

Winterhoff B, Schönfelder E, Heiligmann-Brauer G (1995) Sturmschäden des Frühjahrs 1990 in Hessen—Analyse nach Standorts-Bestandes-und Behandlungsmerkmalen. Forch. Ber. Hess. Landesanst. Forsteinrichtung, Waldforch. Und Waldökologie, Hannover Münden 20

Zeng H, Pukkala T, Peltola H (2007) The use of heuristic optimization in risk management of wind damage in forest planning. For Ecol Manage 241:189–199