Fire effects on forest resource development in the French Mediterranean region – projections with a large-scale forest scenario model

Jeannette Meyer

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Meyer, Jeannette

Publisher: European Forest Institute
Torikatu 34, FI-80100 Joensuu Finland
Tel. + 358 13 252 020
Fax. + 358 13 124393
Email: publications@efi.fi
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Abstract

In this study, the effects of fire on forest resource development under current climate and climate change conditions were assessed using a large-scale forest scenario model (European Forest Information Scenario model, EFISCEN). The natural disturbances module of EFISCEN was adapted and parameterised in order to include fire disturbances into the projection of forest resources in the French Mediterranean region. Two different approaches for modelling fire within EFISCEN were tested, one for a current climate scenario, and another one for incorporating climate change. For the current climate approach, a statistical distribution, which was fitted to observed fire damages, was used to project the burnt forest area into the future. In the climate change approach, the impact of changed precipitation patterns on fire damage was modelled with the help of a regression model, based on the relationship between the amount of summer precipitation and burnt forest area. The impact of a changed climate on tree growth was implemented with a linear regression function, taking into account the influence of temperature and summer drought. The development of forest resources in the French Mediterranean region was projected until 2060 under one current climate and two climate change scenarios, each with and without the fire module. The results demonstrate that growing stock increases more slowly and potential harvest levels are smaller when fire is included, while there are only slight changes in increment. The burnt volume increases over time due to the increase in growing stock. The climate change model runs indicate that an increase in summer drought would probably result in rising fire damages.

1. Introduction

Forests in Europe are intensely managed and fulfil many functions besides wood supply. Both forest area and growing stock increase in Europe (Kuusela 1994; UN-ECE/FAO 2000). There is also evidence of accelerated tree growth in European forests (Karjalainen et al. 1999). Large-scale forest scenario models are used to gain insight in the development of forest resources and the implications of different management regimes (Nabuurs and Päivinen 1996). Such models are useful for forest managers and policy makers, who need to plan ahead on a long-term basis and make complex decisions. The European Forest Information Scenario Model (EFISCEN) is used to make long-term projections of the development of European forest resources. The EFISCEN model was validated by Nabuurs et al. (2000). They concluded that EFISCEN is capable of making reliable large-scale projections of forest resources for periods of 50–60 years. However, until recently the model did not explicitly include the effect of natural disturbances. Natural disturbances play an important role in forest development. In the past decades, heavy storms have caused huge timber losses in the whole of Europe. After storms, insect outbreaks often kill weakened stands and cause even more severe damages. In southern Europe, forest fires burnt on average half a million hectares of wooded land per year over the period 1980–2000 (European Commission 2001b). In the summer of 2003, forest fires have devastated much larger areas than the average recorded over the past decade in some European countries (UN-ECE 2003). In large areas forestry is not profitable in Europe (Kuusela 1994), which has led to a decrease in thinnings and overlong rotation periods. Kuusela (1994) concludes that if growing stock, stand density and age increase even further, the risk for insect, fungi, wind and other damages will also increase, due to the deteriorating biological stability of the forests. Several studies suggest an increase in disturbance frequency and damage with a changing climate, although in some regions the risk for fire, wind or insect disturbances may decrease (e.g. Badeck et al. 2003; Flannigan et al. 2000; Gerstengarbe et al. 1999; Kellomäki et al. 2000; McCarthy et al. 2001; Piñol et al. 1998).

In order to improve the simulation of volume and increment development, a module dealing with natural disturbances was recently developed for EFISCEN (Schelhaas et al. 2002). This module has been tested for Swiss and German forests, concentrating on wind and insect disturbances, as these disturbance types prevail in both countries (Dolstra 2002; Schelhaas et al. 2002). The aim of this thesis is to parameterise and run the European Forest Scenario Model

(EFISCEN) with the natural disturbance module for a fire prone test region, in order to test and possibly improve the implementation of forest fires within EFISCEN. Another objective was to analyse how fire affects forest resource development in that test region.

The Mediterranean part of France was chosen as a test region because forest fires play an important role in forest development there, and because data were available for the parameterisation of both EFISCEN and the natural disturbance module. Fire is the dominant disturbance factor in regions with a Mediterranean climate, destroying many more trees than all other natural calamities (Alexandrian et al. 1999). Forest fires cause considerable damage, both in terms of loss of life and environmental damages through the destruction of flora and fauna, the loss of habitats and the promotion of soil erosion. Fires also have considerable economic implications, e.g. due to the damage on both wood and properties, and fire fighting costs. Many Mediterranean ecosystems are highly susceptible to fire, mainly due to the climate, characterised by prolonged summer droughts and strong winds, and because that climate has evolved a xerophilous vegetation, which is resistant to drought and highly flammable (Chandler et al. 1983). In the Mediterranean region of France, more than 4 million hectares of forest are estimated to be exposed to fire risk (Branka 2001). Socio-economic changes in the Mediterranean region have led to a decrease in agricultural and forestry activities and uncontrolled growth of forest on abandoned areas (Badia et al. 2002). This development has resulted in considerable fuel build-up, increasing the danger of forest fires (Vélez 1990). In 2003, more than 580,000 hectares of forest and other wooded land have been lost to the flames in the French Mediterranean region, about five times as much as the average of the previous ten years (Prométhée 2003).

It is very likely that climate change will have an impact on the fire regime (Flannigan et al. 2000). Although there is considerable uncertainty about how global changes will affect the Mediterranean climate and environment, some atmospheric warming is likely to occur, and rainfall patterns will probably not remain unchanged (Pereira and Chaves 1995). The available predictions for the rainfall regime in the Mediterranean area agree on the accentuation of seasonality in rainfall (Loustau et al. 2000; McCarthy et al. 2001). Drier and warmer summers will probably increase the risk for forest fires (Kellomäki et al. 2000; McCarthy et al. 2001), which might inflict more damages than today due to the increase in forest area and volume. An increase in summer drought would also have adverse effects on tree growth and natural regeneration (Kellomäki et al. 2000), which may be partly counteracted by an elevated CO_2 concentration in the atmosphere (Rathgeber et al. 2003; Sabaté et al. 2002).

Climate and weather conditions are crucial in determining both the probability of fire ignition and spread, and fire intensity (Brown and Smith 2000; Chandler et al. 1983; Rothermel 1983). By controlling primary productivity, climate also controls fuel quality and distribution (Vázquez and Moreno 1995, and references therein), which in turn influence the severity and spread rate of forest fires (Viegas and Viegas 1994). Global warming, possibly coupled with changing precipitation patterns, may lengthen the growing season in the Mediterranean area, which now is restricted to spring, as winter is too cold, summer too dry and autumn is needed to restore water reserves in the soil. A longer growing season may favour the occurrence of fire as it increases fuel availability.

According to Brown and Smith (2000), an increase in temperature does not affect fire potentials directly very much, but has impacts on several other changes that will influence fire potential. For example, decreased relative humidity will presumably result in lower fine fuel moisture and more rapid fire spread. Hence, if summer drought becomes more frequent and more severe, coupled with a prolonged fire season, then fire severity and fuel consumption will increase.

Various studies have been done on the prediction of forest fires based on meteorological fire hazard indices. Piñol et al. (1998) compared the incidence of forest fires with two meteorological fire hazard indices, using observed data. They found an exponential relationship between the number of very high risk days per fire season, and the area burnt. However, fire risk indices are usually computed on a daily basis and require detailed meteorological data, e.g. daily values of soil water content, wind velocity, dew point temperature, air temperature and relative humidity (see e.g. Sol 1990; Viegas et al. 1999 for a comparison of some daily dryness indices). The use of such a detailed index was not feasible within the scope of this study.

Few studies investigated the relationship between meteorological variables and area burnt by wildfire on a broader temporal scale. Flannigan and Harrington (1988) used monthly averages of meteorological variables such as temperature, dew-point, relative humidity and wind speed, and related them to monthly provincial area burnt in Canada. They found that bad fire months were independent of rainfall amount but significantly dependent on rainfall frequency, temperature, and relative humidity. However, meteorological conditions and fire regime in the Mediterranean region are quite different from those in Canada, so that the applicability of these results seems doubtful. Viegas and Viegas (1994) analysed the relationship between rainfall and the burnt area for Portugal. They found a strong relationship between a summer precipitation index (sum of the precipitation between the beginning of June and the 20th of September plus precipitation in May if greater than 100 mm) and burnt area, which could be described by an exponential function. A third objective of the current study was to analyse the relationship between climate parameters and fire in the Mediterranean part of France, in order to facilitate the explicit implementation of the impact of climate change on the fire regime within the natural disturbances module. Using climate scenarios, the likely effects of climate change on the fire regime and on the development of forest resources might then be assessed within EFISCEN.

This study will analyse the potentials of implementing fire disturbances into a large-scale forest resources modelling approach. It is structured as follows:

Chapter 2 presents a description of the study area and the employed methods. EFISCEN and the natural disturbance module are described, and the parameterisation of the disturbance module with regard to fire disturbances is presented in detail. Furthermore it is outlined how the model was tested in order to evaluate the realisation of the model set-up. The relationship between climate variables and the occurrence of forest fires is then analysed, and the methods for the implementation of climate change into the model simulations are explained.

Chapter 3 details the results of the EFISCEN model runs for current climate and climate change conditions, comparing the findings of the simulations with and without the implementation of fire. The results are examined in Chapter 4 in the context of findings of past studies. Chapter 4 also discusses the methodology and the involved uncertainties.

Finally, the Appendix lists a numerical example of the fire module, the applied EFISCEN scenario file and the raw fire data used in this study.

2. Methods and Models

2.1. Study area

In France, forestry is of great importance to the national economy (Kuusela 1994). The forest resources of France are the third largest in Europe with regard to forest area (after Sweden and Finland), and second largest with regard to growing stock and increment.

More than 25% (15.2 million hectares) of the land area is forested (over-seas regions and territories unaccounted for). The forest area has been increasing markedly since the early 19th century (Ministry of Agriculture and Fisheries - Countryside and Forestry Department and Inventaire Forestier National 2000). This increase is essentially caused by natural colonisation of heathland and fallow land, associated with agricultural abandonment. Most of the forests, about 70%, are privately owned. Deciduous stands dominate in French forests, accounting for two thirds of the forest area. Coppice and mixed coppice / high forest stands represent two thirds of all hardwood stands (Ministry of Agriculture and Fisheries - Countryside and Forestry Department and Inventaire Forestier National 2000). French forests are the most diverse in Europe, comprising 136 tree species (Ministère de l'agriculture de l'alimentation de la peche et des affaires rurales 2003). The main species are pedunculate and sessile oak (*Quercus robur* and *Q. petraea*), Maritime pine (*Pinus pinaster*), beech (*Fagus sylvatica*), Scots pine (*Pinus sylvestris*), pubescent oak (*Quercus pubescens*) and Norway spruce (*Picea abies*). There are two main forest types in France: temperate forests and Mediterranean forests.

Temperate forests are made up by mainly broadleaved species in maritime regions, coniferous species in mountainous areas and mixed forests in the inland plains of mainland France.

Mediterranean forests consist of a mixture of both evergreen and deciduous broadleaves and conifers, maquis scrublands, and wooded garrigue scrublands (Ministère de l'agriculture de l'alimentation de la peche et des affaires rurales 2003).

Storms are the main type of natural disturbances in France, but forest fires also play an important role. According to Branka (2001), about 7 million hectares of forest are estimated to be exposed to fire risk in France, representing 13% of the territory and almost half of the total forest area. Most of the fires occur in the Mediterranean region of France, where more than 4 million hectares of forest are exposed to fire risk. Therefore this study focuses on the Mediterranean part of France. The administrative regions concerned are Languedoc-Roussillon, Provence Alpes-Côte d'Azur and Corsica, situated in the south-east of the country, as shown in Figure 2.1. The topography, climate and vegetation of these three regions are briefly described in the following sections.

Figure 2.1.: Study area: The French Mediterranean regions Languedoc-Roussillon, Provence-Alpes-Côte d'Azur and Corsica.

2.1.1. Topography

Much of the French Mediterranean area is mountainous. The land rises continuously from the coastal lowlands to heights well above 2000 m. Some elevation parameters for each of the three Mediterranean regions are listed in Table 2.1. They were derived from the GTOPO30 Digital Terrain Model of the US Geological Survey (2003), with a grid resolution of approximately 1000 m.

The highest elevations can be found in Provence-Alpes-Côte d'Azur, with maximal heights of about 3640 m above sea level (a.s.l.). Mean elevation is also highest in Provence-Alpes-Côte d'Azur, 834 m, compared with 510 m in Languedoc-Roussillon and 575 m in Corsica. Half of the land area in Provence-Alpes-Côte d'Azur is higher than 624 m. The respective values are 312 m in Languedoc-Roussillon and 462 m in Corsica. Hence, although its maximal elevation is higher than the one of Corsica (2812 m compared to 2405 m), Languedoc-Roussillon has the greatest proportion of lowlands of the three French Mediterranean regions.

Table 2.1.: Elevation parameters [meter a.s.l.].

Region	Min	Max	Mean	Median
Languedoc-Roussillon	0	2812	510	312
Provence-Alpes-Côte d'Azur	0	3640	834	627
Corsica	0	2405	575	462

Table 2.2.: Climate parameters, averages from the years 1971–2000.

	Languedoc-Roussillon	Provence-Alpes-Côte d'Azur	Corsica
Average annual temperature	11.5	10.7	12.7
Average temperature of the warmest month	20.2	19.5	20.8
Average temperature of the coldest month	4.3	3.4	6.4
Annual precipitation sum	836.3	895.3	771.6
Summer precipitation sum (May–September)	329.7	338.8	201.7

(Climate data from the ATEAM climate data-set (Mitchell et al. 2003), compare Section 2.4.3)

2.1.2. Climate

The Mediterranean climate is characterised by hot and dry summers and mild, wet winters. Precipitation is very much concentrated in the winter half-year (November to April). Winter precipitation frequently comes down in the form of torrential rainfalls, which are important agents of soil erosion (Tomaselli 1977). Additionally, strong, hot and dry summer winds ("mistral") are frequent.

Table 2.2 presents some climate parameters for the three Mediterranean regions. They only give an approximate picture, as these are average values for the entire regions. The relief varies considerably in each of the regions, and temperature and precipitation ranges differ substantially between the coastal lowlands and the mountains. Provence-Alpes-Côte d'Azur is, on average, the region with the lowest temperatures and highest precipitation values, closely followed by Languedoc-Roussillon. Corsica is the hottest and driest of the three regions. July is the warmest and January the coldest month in Languedoc-Roussillon and Provence-Alpes-Côte d'Azur. In Corsica, August and February are the warmest and coldest months, respectively.

2.1.3. Vegetation and land use

Productive forests cover about one quarter of the land area in Corsica, and about one third in Languedoc-Roussillon and Provence-Alpes-Côte d'Azur (see Table 2.3). The remaining area is mostly agricultural land and heathland, in varying proportions. In Corsica, almost half of the territory is classified as heathland, this is much more than in the other two regions (almost 20%

in Languedoc-Roussillon and 13% in Provence-Alpes-Côte d'Azur). Built-up areas and bare land, included in the "other" land use class, cover around 10% in Languedoc-Roussillon and Corsica, and as much as 18% in Provence-Alpes-Côte d'Azur.

Table 2.3.: Land use in the French Mediterranean regions.

	Languedoc-Roussillon		Prov.-Alpes-Côte d'Azur		Corsica	
	Area (1000 ha)	Percent (%)	Area (1000 ha)	Percent (%)	Area (1000 ha)	Percent (%)
Productive Forest	910.6	32.8	1161.9	36.5	228.4	26.2
Other wooded land	63.9	2.3	146.6	4.6	23.9	2.7
Heathland	544.6	19.6	414.8	13.0	432.4	49.7
Agricultural land[1]	957.2	34.5	810.2	25.5	81.3	9.3
Other	242.2	8.7	573.4	18.0	98.5	11.3
Water	58.0	2.1	76.1	2.4	6.2	0.7
Total	2776.4	100.0	3183.0	100.0	870.7	100.0

[1] includes poplar plantations

Data source: Inventaire Forestier National (IFN), 2003

The Mediterranean vegetation is very diverse (both in terms of species and genetic diversity) and complex, and has a long history of intense human influence and degradation (Le Houérou 1981). Many of the dominant plants are evergreen and have sclerophyllous leaves, often containing resins, waxes and volatile oils. These characteristics make plants resistant to drought, but also highly flammable.

In southern France, water supply is the most important factor limiting forest growth, followed by nutrient supply. An additional abiotic limitation of forest growth is fire, especially in South-Eastern France (Kellomäki et al. 2000). Soil erosion as a result of fires reduces both the amount of water available for plants, and soil fertility, since the nutrient elements mobilised in ash are mostly carried away by run-off and are thus lost to terrestrial vegetation (Le Houérou 1981). Fire and degradation caused by human activities have turned much of the once vast Mediterranean forests into shrubland over the last four millenia (Quezel 1977).

Quezel (1977) characterises the Mediterranean forests in the following way:

Deciduous forests are generally found in cooler and more humid zones of the Mediterranean climate. They are characteristic of the upper Mediterranean zone, from approximately 200 to 1000 m. They are composed of numerous species, predominantly of the *Quercus* genus. Forests of *Quercus pubescens* (pubescent oak) are the most common.

Coniferous forests grow at altitudes higher than the *Quercus* forests, but they are also found at much lower altitudes. They are predominantly composed of the *Pinus* genus.

Mediterranean type shrublands (garrigue and maquis) constitute a vast part of the wooded

Table 2.4.: Forest distribution over elevation classes.

Elevation class	Languedoc-Roussillon	Provence-Alpes-Côte d'Azur	Corsica
> 0 – 250 m	24.3%	21.8%	23.5%
> 250 – 500 m	19.7%	19.4%	22.9%
> 500 – 1000 m	30.9%	25.8%	35.2%
> 1000 – 2000 m	23.8%	32.4%	18.0%
> 2000 m	1.3%	0.6%	0.4%

land in the Mediterranean area. Evergreen sclerophyllous oak species (mainly *Quercus ilex* and *Q. suber*) are usually dominant in these ecosystems. Garrigue is often a result of the degradation of deciduous forests, due to e.g. overgrazing or fire (Le Houérou 1981).

The main forest species in the Mediterranean area are pubescent oak (*Quercus pubescens*, 17.8% of the total forest area), Scots pine (*Pinus sylvestris*, 16.0%), holm oak (*Quercus ilex*, 17.3%), and Aleppo pine (*Pinus halepensis*, 9.8%) (Ministry of Agriculture and Fisheries - Countryside and Forestry Department and Inventaire Forestier National 2000).

A considerable part of the forest in the French Mediterranean area is upland or mountain forest. Table 2.4 shows how the forest is distributed over five elevation classes. This information was derived by spatially combining the European Forest Map (Päivinen et al. 2001; Schuck et al. 2002) and the GTOPO30 Digital Terrain Model of the US Geological Survey (2003). One third of the forest in Provence-Alpes-Côte d'Azur grows at elevations greater than 1000 m, in Languedoc-Roussillon and Corsica only one fourth and one fifth, respectively.

2.2. The European Forest Information Scenario Model (EFISCEN)

The core of the European forest information scenario model (EFISCEN) was developed for even-aged forests by Prof. O. Sallnäs from the Swedish University of Agricultural Sciences in the late 1980s (Sallnäs 1990). It has been used to project the development of forest resources in Europe (Nilsson et al. 1992). Nowadays EFISCEN is in use and under further development at the European Forest Institute (EFI), where it has been used for new analyses of the future development of forest resources on European, national or regional scale (e.g. Karjalainen et al. 2002; Nabuurs et al. 2001, 1998; Päivinen and Nabuurs 1997; Päivinen et al. 1999). Nabuurs et al. (2000) validated EFISCEN with historical data for Finnish forests and improved the model based on this validation. They concluded that EFISCEN is capable of making reliable large-scale projections of forest resources for periods up to 50–60 years.

The following description of EFISCEN is largely based on Pussinen et al. (2001). EFISCEN is a statistical, non-spatially explicit model, applicable for large-scale forest resource projections, on a national or regional level, operating on a five year time step. The forest area is distributed over a volume and age matrix. For each forest type, such a matrix is established. Forest types can be distinguished by region, tree species, ownership and site class. Wood increment for each age class and tree species is calculated based on empirical growth functions that are derived from national forest inventories. Management is controlled at two levels. First, the basic management regime defines which thinnings and final fellings can be carried out, according to handbooks or expert knowledge of forest management in the region or country concerned. Second, the total volume that is required from harvests (both thinnings and final fellings) can be defined for each time step, as well as possible afforestation or deforestation, the success of reforestation after clearcut, and possible tree species changes after final fellings. For each forest type, thinning regimes can be defined on a cellular basis in the matrix, i.e. by volume and age class. Thinning is a fraction of the increment. When the forest area in a cell is thinned, it does not grow during the period in which it is thinned, and therefore does not move to the next volume class. A part of the thinned area will be subject to “growth boost”, i.e. it will grow one volume class extra in the second period after the thinning. Final felling regime depends on stand age, and/or standing volume. The clearcut area is transfered out of the matrix into the bare forest land class and may move back into the matrix in the next time step. How much of the area in the bare forest land class moves back to the first volume and age class of the matrix is regulated by a parameter that expresses the intensity and success of regeneration.

National forest inventory data are used as model input. The quality and resolution of the input data determines how many regions, tree species and site classes can be distinguished in that country. The model output consists of the state of the forest after each time step, in terms of e.g. increment, growing stock, harvest levels and age class distribution.

2.3. The natural disturbances module

A module was developed for EFISCEN dealing with disturbances caused by storm, fire and insects (Schelhaas et al. 2002). As EFISCEN is a statistical, non-spatially explicit model, the disturbance module has to use a statistical approach, in contrast to large-scale mechanistic models (e.g. Thonicke et al. 2001; Venevsky et al. 2002) or small-scale models that require detailed input data (e.g. Keane et al. 1996; Malanson and Trabaud 1988). The natural disturbances module is based on the statistical distributions of damages caused by the disturbances. Storm and fire are assumed to be stochastic in character, while insect damage is directly linked to the amount of storm damage, expressing the dependence of insect outbreaks on the availability of dead wood or dying trees, and thus breeding material. The performance of this module regarding storm and insect disturbances has already been tested in two previous studies (Dolstra 2002; Schelhaas et al. 2002). The focus of the current study is on fire disturbances, wind and insect disturbances are neglected. The following description of the natural disturbance module in EFISCEN, based on Schelhaas et al. (2002), is therefore focused on the implementation of fire disturbances.

The fire module is based on two components:

1. the *statistical distribution* of the damaged area, which is based on damage amounts in the past (see Section 2.3.1) and
2. a *susceptibility matrix* for each forest type, expressing the varying sensitivity to fire depending on various characteristics, such as tree species, age etc. (see Section 2.3.2).

The statistical distribution defines *how much* is burnt, the susceptibility matrix defines *what* is burnt, i.e. which forest types burn more frequently than others.

2.3.1. The statistical distribution

Observed data on past burnt area were used to define a statistical distribution which describes the annual occurrence of forest fires in the study area. The expected value E of the chosen distribution corresponds to the annual percentage of area that is disturbed. Parameters needed to calculate the expected value were estimated from the observed time series on burnt area. A log-normal distribution was chosen for this study, for reasons discussed in Section 2.5.2. The expected value of a log-normal distribution is defined by equation 2.1:

$$E = e^{(\bar{x}+\frac{s^2}{2})} \tag{2.1}$$

where E is the expected value, $\bar{x}$ the average and s the standard deviation of the distribution.

Every time step, five random draws are made from the log-normal distribution. The actual hazard ratio is generated by comparing the sum of the random draws with the expected value of the distribution (equation 2.2):

$$A_t = \frac{\sum_{i=1}^{i=5} RND_i}{E \times 5} \tag{2.2}$$

where A_t stands for the actual hazard ratio for time step t, RND_i for the random draws, and E for the expected value of the log-normal distribution. If $A_t < 1$, the fire hazard is lower than the average for the corresponding five year period, if $A_t > 1$, the fire hazard is greater.

2.3.2. The susceptibility matrix

In the susceptibility matrix, the sensitivity for fire disturbances is defined per cell, depending on tree species, age, and ownership (private or public), relative to other cells. Regional dependencies were also included in the susceptibility matrix, in order to express the regionally varying fire regime, which was derived from the statistical data. For each EFISCEN cell, all the individual sensitivities are combined to one susceptibility value (equation 2.3):

$$S_{h,i,j,k} = h \times i \times j \times k \tag{2.3}$$

where $S_{h,i,j,k}$ is the susceptibility value, depending on the forest region (h), tree species (i), stand age (j) and forest ownership (k).

Furthermore, a distinction is made between stand-replacing and non-stand replacing fires. The susceptibility value for a non-stand-replacing fire is calculated with equation 2.4:

$$S_{h,i,j,k,l} = S_{h,i,j,k} \times m \qquad \text{where } l = 1 \text{ and } 0 \leq m \leq 1 \tag{2.4}$$

where m stands for the proportion of low-severity, non-lethal fires, where the fire kills few or no canopy trees and a variable number of understory trees. The remainder of the fires are considered to be stand-replacing fires (equation 2.5):

$$S_{h,i,j,k,l} = S_{h,i,j,k} \times (1 - m) \qquad \text{where } l = 2 \text{ and } 0 \leq m \leq 1 \tag{2.5}$$

Stand-replacing disturbances are caused by lethal, high-severity fires, which kill most or all of the canopy as well as understory trees. The proportion of stand-replacing versus non-stand replacing fires depends on the forest type, i.e. tree species and stand age.

In EFISCEN, non-stand-replacing disturbances are handled similar to thinnings in the normal management, i.e. as a decrease in volume of the areas that were subjected to a non-stand-replacing fire. However, as a non-stand-replacing fire may weaken the surviving trees and does not necessarily kill those trees that would have been removed in a thinning, the disturbed areas do not show an increased increment after the fire, in contrast to normal thinnings. Stand-replacing fires are regarded as a complete harvest (final felling). The affected areas are transfered to the bare forest land class and may enter the matrix again in the next time step, either due to afforestation or natural regeneration.

Using the initial area per cell, the weighted average of the susceptibilities W is calculated:

$$W = \frac{(E \times \sum_h \sum_i \sum_j \sum_k X_{h,i,j,k})}{\sum_h \sum_i \sum_j \sum_k \sum_l (X_{h,i,j,k} \times S_{h,i,j,k,l})} \tag{2.6}$$

where E is the expected value of the frequency distribution, $X_{h,i,j,k}$ is the initial area in cell h, i, j, k, while $l = 1$ denotes a stand-replacing fire and $l = 2$ a non-stand-replacing fire.

For each time step, the weighted average of the susceptibilities is then multiplied with the hazard ratio and the current area per cell, resulting in the area F per cell that will be subject to either stand-replacing or non-stand-replacing damages (equation 2.7):

$$F_{h,i,j,k,l,t} = S_{h,i,j,k,l} \times 5 \times W \times A_t \times X_{h,i,j,k,t} \tag{2.7}$$

$F_{h,i,j,k,l,t}$ is the area that will be subject to stand-replacing ($l = 1$) or non-stand-replacing ($l = 2$) fires in cell h,i,j,k in time step t. A_t is the actual hazard ratio (see equation 2.2) for that time step and $X_{h,i,j,k,t}$ is the current area in cell h,i,j,k. A numerical example can be found in the Appendix.

$F_{h,i,j,k,l,t}$ is calculated for each time step (5 years), W only once in the beginning, remaining constant in the following time steps. Therefore, as the EFISCEN matrix (age and volume class distribution) and thus also the overall susceptibility change, the average burnt area changes, too. For example, as trees grow older, they become less susceptible to fire and so the overall susceptibility and the burnt area would decrease over time.

The natural disturbances module of EFISCEN had to be adapted to the characteristics of the Mediterranean part of France. Parameters needed for the set-up module were retrieved from literature review and observed data on fire occurrences. The parametrisation of the EFISCEN model and the natural disturbances module is specified in Section 2.5. In particular, 2.5.2 describes the set-up of the applied statistical distribution, and 2.5.3 illustrates the set-up of the susceptibility matrix for forest fires.

Additionally, the influence of climatic variables on fire was analysed and a regression function between summer precipitation and burnt area was implemented in the module for this study, in order to take into account possible changes of fire disturbances due to climate change. This process is described in Section 2.7. Figure 2.2 presents the way the fire module is organised, both for the current climate and the climate change runs.

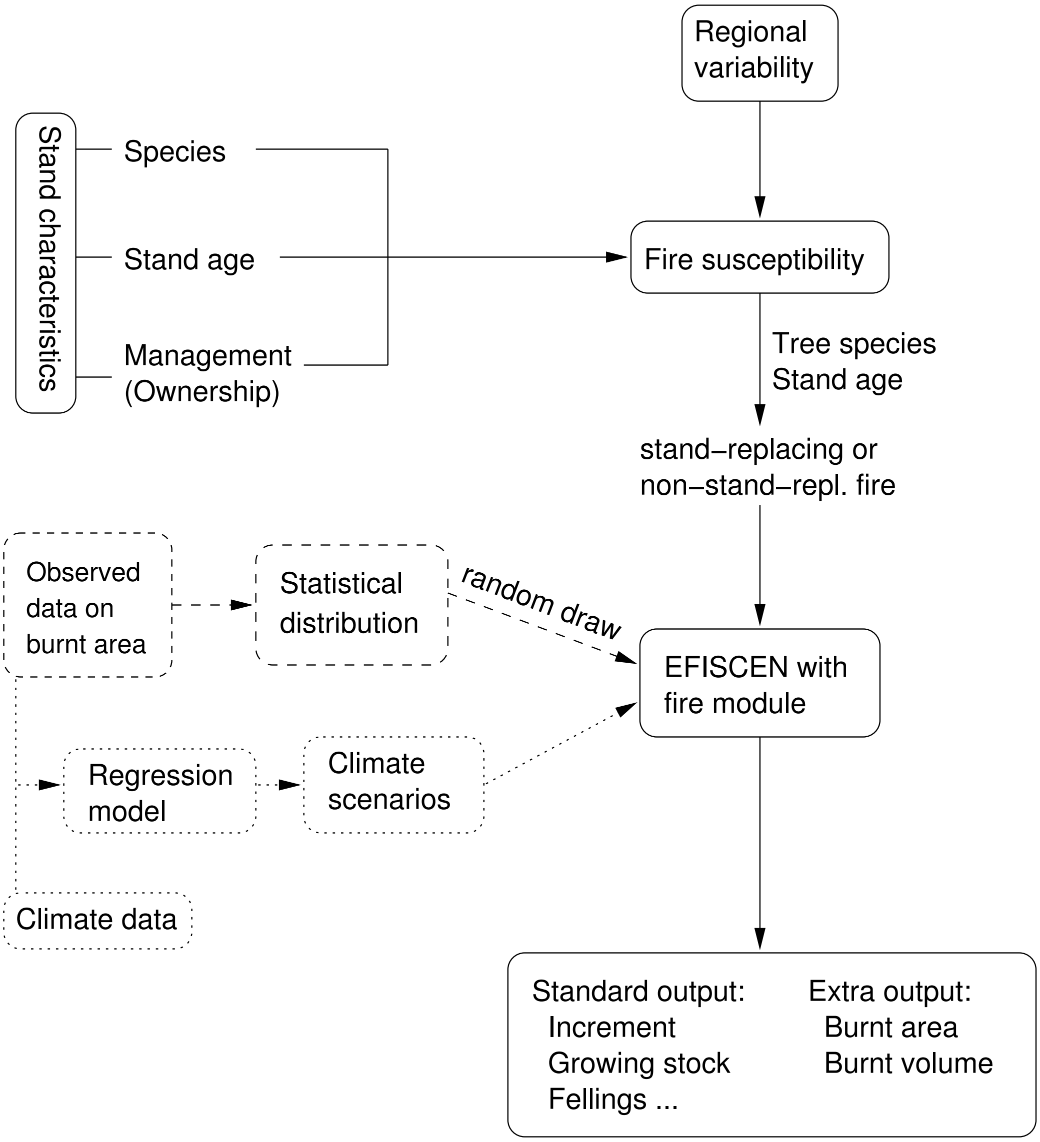


Figure 2.2.: Flow chart of the fire module. Dashed lines represent the current climate run, dotted lines the climate change runs. Solid lines apply to both current climate and climate change runs.

2.4. Input data and data preparation

2.4.1. EFISCEN input data

In France, the Inventaire Forestier National (IFN) is responsible for the national forest inventory. The forest inventory is designed in a continuous way: the whole country is surveyed in 12 years, and each year there is new data for several departments. The mean year of inventory of the French input data for EFISCEN was 1994. In France, 22 regions are distinguished in EFISCEN, representing the administrative regions. The input data comprise ten tree species or tree species groups and three ownership classes. The tree species (groups) are oak, beech, chestnut, other broadleaved species, Maritime pine, Scots pine, fir and spruce, Douglas fir, other conifers and poplar (plantations). The ownership classes are state forest, other public forest, and private forest. No differentiation is made between site classes.

In this study, only the three Mediterranean regions of Languedoc-Roussillon, Provence-Alpes-Côte d'Azur and Corsica were modelled. Table 2.5 presents the distribution of tree species or tree species groups in those regions. Other broadleaved species (including pubescent, holm and cork oak), pines and other coniferous species (including Aleppo pine) are dominant in all three regions, but to various extents. Languedoc-Roussillon shows the greatest variety in tree species distribution, while in Corsica and Provence-Alpes-Côte d'Azur some of the EFISCEN tree species groups are missing entirely (no Douglas fir in both regions, no oak and Scots pine in Corsica) or are very rare (e.g. fir & spruce in both regions, oak and chestnut in Provence-Alpes-Côte d'Azur).

Table 2.5.: Tree species distribution in the Mediterranean regions Languedoc-Roussillon (L-R), Provence-Alpes-Côte d'Azur (PACA) and Corsica, given as percent of the forest area in each region

	Oak	Beech	Chestnut	Other broadl.	Marit. Pine	Scots pine	Fir & Spruce	Douglas fir	Other conif.
L-R	2.6	8.3	8.3	35.7	3.4	14.6	8.1	1.4	17.6
PACA	0.1	3.5	0.5	35.3	3.4	22.7	2.5	0.0	32.1
Corsica	0.0	7.3	13.6	50.0	15.2	0.0	0.2	0.0	13.7

Data source: EFISCEN input inventory data (made available by the Inventaire Forestier National, IFN)

2.4.2. Fire data

The Prométhée database (Prométhée 2003) on forest fires includes information on the number of fires and area burnt in the 15 Mediterranean departments of France, starting in 1973. These departments fully cover three regions (Languedoc-Roussillon, Provence-Alpes-Côte d'Azur and

Corsica). Of a fourth region (Rhône-Alpes) only two departments are covered. These were not included in the analysis as fire activity in the two departments was negligible throughout the observed period, and because no data was available for the remaining departments in this region.

From the Prométhée database, information on burnt forest area per year and department was retrieved and aggregated on regional level. Burnt forest area in the Prométhée data includes fire on Mediterranean-type shrublands, i.e. maquis and garrigue. No distinction is made in the data between fire on forest and other wooded land. In the input data for EFISCEN – the French inventory data – only productive forests are included. Thus the Prométhée had to be split up with the help of other data.

Data on burnt area, distinguishing between area burnt in forests and in other wooded land, were only available for the years 1991–2001 (Agreste 1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2003; European Commission 2001a). The data are presented on departmental level for the whole of France. But only in 1998 and 1999 the differentiation between forest and other wooded land is made for the burnt area in the Mediterranean regions. From those two years the percentage of area burnt in forest only was calculated (see Table 2.6). This ratio varies considerably between the regions: almost 50% of the total area burnt was forest land in Languedoc-Roussillon, while the respective proportion was less then 10% in Corsica, and around one third in Provence-Alpes-Côte d'Azur. The inter-annual variation was relatively small: almost negligible in Languedoc-Roussillon and only a few percent in Provence-Alpes-Côte d'Azur and Corsica. To derive estimates of the forest area burnt for the remaining years, the average of the ratios for 1998 and 1999 was calculated and applied to the Prométhée data.

Table 2.6.: Proportion of burnt forest in the Mediterranean regions in 1998 and 1999.

Region	Proportion of burnt forest (as percent of total wooded land burnt)		
	1998[1]	1999 [2]	Average
Languedoc-Roussillon	46.7%	46.9%	46.8%
Provence-Alpes-Côte d'Azur	32%	39.3%	35.8%
Corsica	8.7%	5.3%	7.0%

[1] Source: Agreste (2000)

[2] Source: European Commission (2001a)

This method gives only a very rough estimate, as the ratio between the area burnt in forest and in forest and other wooded land probably varies substantially over the years. However, it was the only way to derive a complete time series as input for the statistical analysis of the burnt forest area, which was required to set up the model (see Section 2.3). Figure 2.3 illustrates the results of this estimation for the years 1973 to 2002. According to the assumptions made, other wooded land constitutes the majority (about 74%) of the burnt area. The original data (aggregated on regional level) and the derived forest area burnt can be found in the Appendix, Table A.1.

For the time span 1991–2000, Schelhaas and Schuck (2002) reported that approximately 0.3% of the forest land burnt annually in the European Mediterranean region. According to the estimates presented in the current study, about 0.11% of the forest area burnt annually in the same period in the Mediterranean part of France, but about 0.3% in the period from 1973 to 2002.

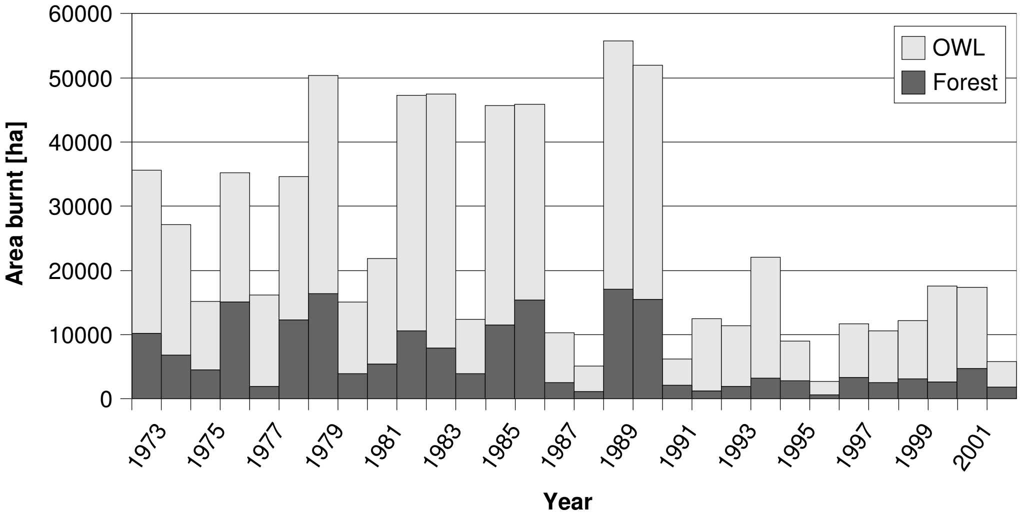


Figure 2.3.: Development of the burnt area [ha] of forest and other wooded land (OWL) in the Mediterranean regions of France (sum of Languedoc-Roussillon, Provence-Alpes-Côte d'Azur, Corsica) between 1973 and 2002. The forest area burnt is partly derived from the area of forest and other wooded land (FOWL) and the ratio between FOWL and forest .

Since 1991 the burnt forest area in Mediterranean France has been below average (see Figure 2.3). This is mainly attributed to favourable, i.e. relatively wet climate conditions in the 1990s as well as effective fire prevention and control measures (Ministry of Agriculture and Fisheries - Countryside and Forestry Department and Inventaire Forestier National 2000). Because fire control measures are becoming more efficient, the mean area per fire is decreasing, while the number of small fires is rising (see Table 2.7).

Table 2.7.: Fires on forest and other wooded land in Mediterranean France.

Reference period	Mean area burnt per annum [ha]	Mean area per fire [ha]	Mean number of fires per year	Data source
1960–1971	38000	30.0	1260	Le Houérou (1981)
1973–1989	32660	11.2	2900	Prométhée (2003)
1990–2002	15400	5.7	2550	Prométhée (2003)

This development gives rise to concern. The amount of combustible material in forests and in formerly agricultural land is rising due to reduced fire occurrences and a decline in agricultural and forestry activities. Marginal agricultural areas are abandoned and shrubs and trees quickly invade these sites, generating the most dangerous types of fine fuel accumulation that favour high intensity fires (Vélez 2002). Fuel accumulation in forests is hardly counteracted anymore be the collection of fuelwood and fodder. In 2003, extreme weather conditions have favoured forest fires throughout Europe. In the Mediterranean part of France, 3344 fires have burnt more than 58000 ha of forest and other wooded land (Prométhée 2003). The mean area per fire, 17.4 ha, was therefore relatively high in 2003.

2.4.3. Climate data

Climate data were available from the ATEAM project (Advanced Terrestrial Ecosystem Analysis and Modelling). The data, as described in Mitchell et al. (2003), are supplied on a 10' grid, with monthly time-steps for 1901–2000 (observed) and 2001–2100 (a total of 16 climate change scenarios). The climate change scenarios are made up of all possible combinations of four state-of-the art general circulation models (GCMs) and four emission scenarios. For each variable in the climate change scenarios, the 1901–2000 anomalies relative to 1961–90 were detrended against global temperature. The anomalies were then superimposed with the trend projected by each particular climate scenario (the combination of a GCM and an emission scenario). Therefore the variability of the 20th century is conserved in all climate change scenarios, and all scenarios show the same pattern.

For this study, the data were aggregated for the 22 French administrative regions which also represent the EFISCEN regions (see Section 2.2). Of the 16 climate scenarios, two were selected for usage in this study: the combination of two GCMs (HadCM3 and PCM) with one emission scenario (A2). HadCM3 (Hadley Centre Climate Model), a coupled atmosphere-ocean model, was developed at the Hadley Centre and PCM (Parallel Climate Model) at the National Center for Atmospheric Research (NCAR). The A2 emission scenario (Nakicenovic and Swart 2000) emphasises the strengthening of regional and local cultures with diversifying social and political structures. Environmental concerns are relatively weak, with just some attention being paid at bringing local pollution under control. The use of energy and carbon is high, thus also the corresponding greenhouse gas emissions. The CO_2emissions in the A2 scenario are relatively high, they will have doubled by 2040 compared to 2000 levels, and will continue to rise steadily.

Table 2.8 presents 30-year averages of mean annual temperature, annual and summer precipitation sum for the observed climate data, as well as for the PCM-A2 and HadCM3-A2 climate scenarios. Both scenarios project rising temperatures, but the increase is more moderate for PCM-A2 than for HadCM3-A2. Annual precipitation is expected to decrease slightly under the HadCM3-A2 scenario. According to the PCM-A2 scenario, annual precipitation decreases slightly in the period 2001–2030, and rises afterwards in Languedoc-Roussillon and Provence-Alpes-Côte d'Azur, but remains almost constant in Corsica. Both climate scenarios project changes in intra-annual precipitation patterns, with a strong decrease in summer precipitation, especially for the HadCM3-A2 scenario. Only in Languedoc-Roussillon the PCM-A2 scenario suggests a higher increase in summer precipitation compared to annual precipitation during the period 2031–2060. However, even an increase in summer precipitation may be not be enough to compensate the increase in potential evapotranspiration, caused by rising temperatures. Therefore water stress and summer drought can be expected to increase in both scenarios, but more so in the HadCM3-A2 scenario.

Table 2.8.: Mean annual temperature (T_m), annual precipitation sum ($Prec_a$) and summer precipitation sum ($Prec_s$, May-September), averaged over three 30-year periods: 1971–2000 (observed), 2001–2030 and 2031–2060 (climate scenarios HadCM3-A2 and PCM-A2)$^{\mathbf{1}}$.

	1971–2000	2001–2030		2031–2060	
	(=100%)	HadCM3-A2	PCM-A2	HadCM3-A2	PCM-A2
Languedoc-Roussillon					
T_m (°C)	11.5	12.1 (+4.6)	11.7 (+1.7)	13.1 (+13.4)	12.4 (+7.4)
$Prec_a$ (mm)	836	805 (-3.8)	823 (-1.6)	804 (-3.8)	842 (+0.7)
$Prec_s$ (mm)	330	289(-12.4)	310 (-5.8)	290 (-12.1)	336 (+1.8)
Provence-Alpes-Côte d'Azur					
T_m (°C)	10.7	11.4 (+6.0)	10.9 (+2.0)	12.5 (+16.9)	11.6 (+8.4)
$Prec_a$ (mm)	895	840 (-6.2)	863 (-3.6)	863 (-3.6)	911 (+1.8)
$Prec_s$ (mm)	339	287 (-15.2)	311 (-8.1)	282 (-16.9)	331 (-2.2)
Corsica					
T_m (°C)	12.7	13.4 (+5.4)	13.1 (+3.0)	14.4 (+13.4)	13.7 (+8.2)
$Prec_a$ (mm)	772	744 (-3.5)	764 (-0.9)	729 (-5.5)	770 (-0.3)
$Prec_s$ (mm)	202	163 (-19.0)	171 (-15.2)	159 (-21.0)	174 (-13.5)

[1] The values shown in parenthesis represent the change with respect to the average of 1971–2000 (in percent)

2.5. Model parametrisation

2.5.1. Set-up of the EFISCEN model

The EFISCEN model was run only for the three French Mediterranean regions (Languedoc-Roussillon, Provence-Alpes-Côte d'Azur and Corsica). A business-as-usual harvest scenario was used for all model runs, i.e. felling levels remained constant throughout the whole modelling period. The management regime was based on analysis carried out for the European

Forest Sector Outlook Study (Schelhaas et al. in press). As felling levels in the EFSOS study refer to the whole of France, they had to be adapted to the Mediterranean regions. This was done based on the relative proportion of current total increment (m^3 ha^{-1}) felled, for conifers and broadleaves. Felling levels are about 60% of the increment at the beginning of the simulation. An annual total felling level of 5.04 million m^3 (overbark) was applied, of which thinnings make up 30%. The tree species distribution was kept as it was in 1994, by regenerating a final cut area with the same species as there was before the final cut. No forest expansion was implemented.

2.5.2. Specification of the frequency distribution

In this approach, fire disturbances were modelled with the help of their statistical distribution, based on fire occurrences in the past. Armstrong (1999) found that the annual burnt area in a boreal mixedwood forest in Canada was well described by a log-normal distribution. Franklin et al. (2001) used a log-normal distribution function for describing the fire size in the Landscape Disturbance and Succession model (LANDIS). In another study the assumption was made that the area burnt per year in Switzerland is log-normally distributed (Schelhaas et al. 2002, based on Mandallaz and Ye 1997). In order to check whether this assumption also applies to France, the fire data was analysed statistically. The log-normal distribution is asymmetrical with a positive skewness. This means that the probability for relatively small values is greater than for large values, but there is a broad range of values. If a distribution is log-normal, the natural logarithm (ln) of its values follows a normal distribution. Therefore the ln values of the observed data on burnt area for the years 1973 to 2002 were analysed using the Shapiro-Wilk normality test and by examining the histograms visually.

The Shapiro-Wilk test calculates a W statistic that tests whether a random sample, $x_1, x_2, ..., x_n$ comes from a normal distribution. The Shapiro-Wilk W statistic ranges from zero to one. Small values of W are evidence of departure from normality (NIST/SEMATECH, 2003). If the W statistic is significant ($p < 0.05$), then the hypothesis that the respective distribution is normal should be rejected. The Shapiro-Wilk's W test is very effective for small samples (Lozán and Kausch 1998). According to Shapiro et al. (1968, in: StatSoft 2003) it is the preferred test of normality because of its good power properties as compared to a wide range of alternative tests.

Table 2.9 presents the values for the W statistic and its significance for Languedoc-Roussillon, Provence-Alpes-Côte d'Azur and Corsica. The W statistic, with values close to one, was not significant in any of the three regions ($p > 0.05$). These findings indicate that the distribution is normal.

Visual examination of the histograms (see Figure 2.4) confirmed the assumption of normality. Thus a log-normal distribution could be used to describe the time series on burnt area. The

Table 2.9.: Results of the Shapiro-Wilk normality test.

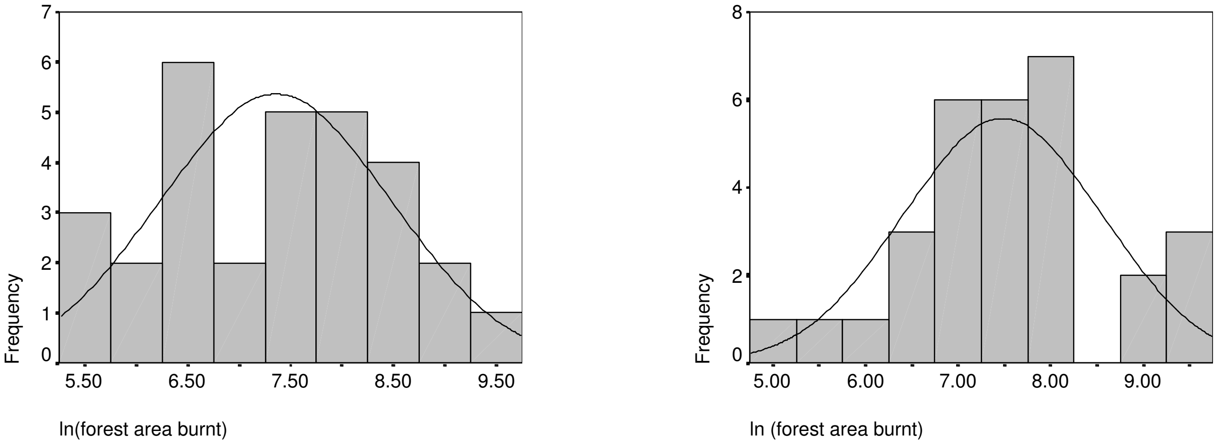
Region	df	W statistic	Significance (p)
Languedoc-Roussillon	30	0.969	0.516
Provence-Alpes-Côte d'Azur	30	0.963	0.371
Corsica	30	0.971	0.572

parameters mean ($\overline{x}$) and standard deviation (s) of the log-normal distribution were calculated from the data and used as model input.

2.5.3. Set-up of the susceptibility matrix

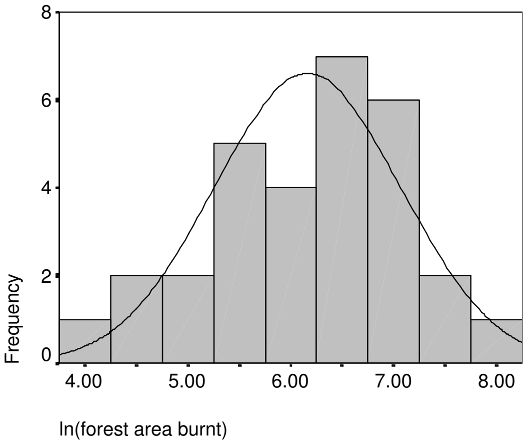
Forest fires vary in intensity (the rate at which fuel is consumed and heat generated) and severity (the damage to both abiotic and biotic forest components). Most fires in the French Mediterranean regions are human-induced, so they start on the surface layer of the forest. The intensity and severity of the evolving fire depends, among other things, on species composition, available fuel, fuel arrangement, fuel moisture content, weather and the physical setting (Graham et al. 1999). These and other factors (like fire suppression activities) determine whether a fire remains a surface fire, killing only a relatively small percentage of the trees (non-stand-replacing fire), or turns into a crown fire, killing most trees (stand-replacing fire). Due to the large-scale modelling approach of EFISCEN, only the effect of tree species composition, forest ownership (which affects management and thus fuel loads) and regional variability on the occurrence and severity of fire could be taken into account. The influence of climatic variables on forest fires is analysed in Section 2.7.

Volume classes were not considered in the susceptibility matrix, because no reasonable assumptions could be made about the influence of stand volume on fire behaviour. Related studies vary in their conclusions. Silva et al. (1999) examined the effect of thinning on surface fuels and fire behaviour in a *Pinus pinaster* stand in central Portugal. They found no significant differences between three tested treatments (no thinning, removal of 15 and 30 percent of the trees) concerning fire behaviour characteristics. These results are contradictory to several other studies, which demonstrated a temporal fire severity increase due to the accumulation of slash from thinning operations (Bilgili 2003), followed by a decrease in fire severity due to the reduced probability of crowning (Graham et al. 1999; Pollet and Omi 2002). None of these studies were performed in the Mediterranean regions, where, according to Silva et al. (1999), the shrub component is of crucial importance. Thinning favours the growth of heliophyte herbs and shrubs, which often are a major component of forest fuels in Mediterranean conditions (Dreyfus 1990, in Silva et al. 1999). Nevertheless, the influence of forest management on fire behaviour was indirectly included by considering the ownership dependencies: fires are more frequent in poorly



(a) Languedoc-Roussillon

(b) Provence-Alpes-Côte-d'Azur



(c) Corsica

Figure 2.4.: Histograms of the ln values of the burnt forest area the three Mediterranean regions (1973–2002). Parameters for the normal curve were estimated from the data.

managed privately owned forests than in public forests.

The following sections illustrate how the impact of tree species composition (2.5.3.1), forest ownership (2.5.3.2) and regional variation (2.5.3.3) on fire occurrence were taken into account in the set-up of the susceptibility matrix. The differentiation between stand-replacing and non-stand-replacing fires, based on tree species and age class, is described in Section 2.5.3.4.

2.5.3.1. Fire and tree species

Mediterranean forests are very diverse. Each forest type has distinct characteristics in regard to flammability and post-fire regeneration. Flammability determines whether a species or forest type is easily ignited and contains enough fuel to sustain and spread a fire. Flammability reaches a maximum in young forest stands, where the whole stand is formed by light fuels, easily accessible by flames, as the stems are still thin and branches close to the ground (Vélez 1985). Furthermore, dead but easily burnable stems from previous fires may still remain standing, increasing both fuel load and flammability of the young stands. Vélez (1985) found that fire hazard is two to three times higher in young *Pinus halepensis* stands than in the mature ones. Flammability typically decreases as the stand ages, because the height to the base of the tree crown increases, either from self-pruning or from removal of basal branches by surface fires (Brown and Smith 2000). The combustible material (branches, leaves or needles) is accumulated in the tree crown, while the stems do not burn easily. High fuel loads, dry weather conditions and wind promote fire intensity and spread. Most fires start at the forest floor, but under extreme weather conditions, flames can reach tree crowns and the resulting crown fire causes considerably more damage than the initial surface fire.

The tree species susceptibility to fire depends not only on tree species flammability and stand structure, but also on the geographic distribution of the species, including site characteristics like elevation and the amount and distribution of precipitation throughout the year. A forest stand growing in a relatively humid climate with a short dry period will rarely burn even if it is highly flammable. Fire risk is also influenced by population density and attractiveness for tourists, especially as humans are the main cause for fires in the Mediterranean area (Alexandrian et al. 1999). Because of the large-scale, non-spatially explicit approach of EFISCEN, no elevation or climate parameters could be included directly into the susceptibility matrix. However, the site characteristics where each tree species or tree species group typically grows was considered in the set-up of the matrix, in addition to the flammability characteristics.

In EFISCEN, ten tree species or tree species groups are differentiated in France: oak, beech, chestnut, other broadleaves, Maritime pine, Scots pine, fire & spruce, Douglas fir, other conifers and poplar (plantations). Table 2.10 shows how the Mediterranean tree species are classified in EFISCEN. Various Mediterranean tree species are aggregated in one EFISCEN forest class

Table 2.10.: Main tree species in the Mediterranean area of France.

EFISCEN group	Percent of forest area [%] [1]	Main tree species [2]	
Oak	1.1	Sessile oak	*Quercus petraea*
Beech	5.6	Beech	*Fagus spp.*
Chestnut	4.4	Chestnut	*Castanea spp.*
Other broadleaves	36.5	Pubescent Oak	*Quercus pubescens*
		Holm oak	*Quercus ilex*
		Cork oak	*Quercus suber*
Maritime pine	4.2	Maritime pine	*Pinus pinaster*
Scots pine	17.9	Scots pine	*Pinus sylvestris*
Fir & spruce	4.5	Silver Fir	*Abies alba*
		Norway spruce	*Picea abies*
Douglas fir	0.6	Douglas fir	*Pseudotsuga menziesii*
Other conifers	25.2	Aleppo pine	*Pinus halepensis*
		European larch	*Larix decidua*
		Austrian pine	*Pinus nigra nigra*
		Mountain pine	*Pinus uncinata*
		Corsican pine	*Pinus nigra laricio corsicana*
Poplar plantations	0.0		

[1] Derived from the EFISCEN inventory data, sum of Languedoc-Roussillon, Provence-Alpes-Côte d'Azur and Corsica

[2] Source: Ministry of Agriculture et al. (2000)

(especially in the other broadleaves and other conifers class), so the fire regime characteristics of those species had to be combined.

The Prométhée database does not provide information about the type of the forests that were subject to fire. Various literature sources were used to compile data on tree species flammability, as there are Le Houérou (1981), Valette (1990), Xanthopoulus (2000), Sullivan (1993, 1994a,b) and Mediaforest (2003).

The fire susceptibility values used in the susceptibility matrix are presented in Table 2.11. The values range from 1 (very low susceptibility) to 6 (very high susceptibility) and are relative. Thus a mature Maritime pine forest, for example, is three times as susceptible to fire as mature oak, beech or chestnut stands.

Le Houérou (1981) states that it is mostly *Pinus halepensis* (around one third of the area burnt) and sclerophyllous oak forest or coppice (*Quercus ilex, Q. suber* and others) (about 50% of the area burnt) that burn in the Mediterranean, although they constitute only 10% and 20% of the forest area, respectively. The EFISCEN forest classes that include these forest types are other

Table 2.11.: Fire susceptibility values and assumed maturity ages of the tree species groups.

Tree species in EFISCEN	Susceptibility Sapling[1]	Susceptibility Mature tree	Maturity age	Reference (Maturity age)
Oak	1	1	70	Bisch (1969)
Beech	1	1	70	Bianchi (1981); Gualdi (1974)
Chestnut	1	1	70	estimated
Other broadleaves	6	4	70	estimated
Maritime pine	4	3	28	Lemoine and Decourt (1969)
Scots pine	4	3	50	Garcia Abejon and Tella Ferreiro (1986)
Fir & spruce	2	2	50	Giurgiu et al. (1972)
Douglas fir	2	2	30	Madrigal Collazo et al. (1999)
Other conifers	6	4	65	Madrigal Collazo et al. (1999)

[1] from 0 years – maturity age

conifers and other broadleaves. The fire risk of these classes is accordingly set to a high value.

Deciduous oak, beech and chestnut forests are little affected by forest fires as they are generally located in the more humid zones of the Mediterranean area (Le Houérou 1981). The fire susceptibility values of these forests are accordingly small. The same is true for fir and spruce forests. Their fire susceptibility value is slightly higher than for the oak, beech and chestnut classes, because, due to their high resin content, coniferous species are generally more flammable than deciduous species.

There is no poplar in the national inventory data of the French Mediterranean regions, so it was left out of consideration.

Most references refer to the age of a tree as seedling, sapling or mature tree. The maturity age certainly varies for different tree species, but is also dependent on site and stand properties. Röhrig and Gussone (1982) speak of saw-timber (“Baumholz”) stands when most of the dominant trees have exceeded a diameter in breast hight of at least 20 cm. This diameter was used as indicator of maturity. To ascertain the age when most trees in a stand exceed this diameter, growth and yield tables were used for medium site classes. Where several species were aggregated in the EFISCEN tree species group (e.g. fir and spruce, other deciduous or coniferous species), the maturity age was averaged based on the area coverage of the individual species in the Mediterranean regions. The maturity ages used in the susceptibility matrix are given in Table 2.11.

2.5.3.2. Fire and forest ownership

French forest is mainly privately owned, with about three quarters of the area in this category. Properties smaller than 25 ha cover about 55% of the private forest area and are not required to have an agreed management plan (Pignard 1996). Susmel (1973, in Le Houérou 1981), stated that in southeastern France fires in private forests are three times as frequent as in state-owned forest. Possible reasons for this were mentioned by Vélez (1990): the socio-economic development of the region has led to a decrease in grazing and in the collection of wood and forest scrub for fuelwood and fodder. This development is more pronounced in privately owned forests, which, due to low returns on labour, tend to be abandoned until they have reached harvestable dimensions. Private forests are therefore assigned a three times higher susceptibility to fire than state-owned forests.

2.5.3.3. Regional variation in fire occurrence

The percentage of the total forest area that is burnt per year varies regionally (see Table 2.12). Although the average annual burnt area is highest in Provence-Alpes-Côte d'Azur (almost 3000 ha), its proportion of forest burnt per year (0.26%) is the lowest of the three Mediterranean regions. The greatest proportion of forest area burns in Corsica, 0.42%. Languedoc-Roussillon, with 0.35%, lies between the two other regions. These regional differences are also included in the susceptibility matrix, where they are combined with the tree species, age and ownership dependencies.

Table 2.12.: Average burnt area as percent of forest area.

Region	forest area [ha]	burnt area [ha][1]	Forest area subject to fire per year [%]
Languedoc-Roussillon	798200	2759	0.35
Provence-Alpes-Côte d'Azur	1162300	2998	0.26
Corsica	156500	662	0.42

[1] average 1973–2002

2.5.3.4. Stand-replacing versus non-stand-replacing fires

In the natural disturbances module, a differentiation is made between stand-replacing and non-stand-replacing disturbances (see Section 2.3). Both disturbance types occur with fires: non-stand-replacing fires can be low to medium intensity surface fires, which do not kill the entire population, while high intensity crown fires usually kill the entire stand and are thus stand-replacing. Whether a fire is stand-replacing or not is determined by fire intensity (which depends on weather conditions, fuel loads, vertical and horizontal fuel arrangement etc.) and tree resistance to fire. Tree resistance to fire depends on the species, but it generally increases with age, because bark thickness and stem diameter increase (Brown and Smith 2000). Younger trees are more susceptible to stem and top-kill than older ones (Trabaud 1987). To realise this situation in the module, the susceptibility to (non-)stand-replacing fires is set up separately for each species and for three age classes (seedling, sapling and mature tree), as demonstrated in Table 2.13. For each tree species and age class, a value m between 0 and 1 is assigned for stand-replacing fires, and $1 - m$ for non-stand-replacing fires. All fires are stand-replacing if $m = 1$ and thus no non-stand-replacing fires occur for that tree species and age class, and vice versa. The susceptibility to stand-replacing fires decreases with age, to reflect the increasing tree resistance to fire. Seedlings (0–5 year old stands) are always subjected to stand-replacing fires, regardless of the tree species, because they are easily killed even by low intensity surface fires.

Table 2.13.: Susceptibility to stand-replacing and non-stand-replacing fires.

	Stand-replacing fires			Non-stand-replacing fires		
Tree species	Seedling[1]	Sapling[2]	Mature tree[3]	Seedling[1]	Sapling[2]	Mature tree[3]
Oak	1	0.3	0.1	0	0.7	0.9
Beech	1	0.3	0.1	0	0.7	0.9
Chestnut	1	0.3	0.1	0	0.7	0.9
Other broadleaves	1	0.3	0.2	0	0.7	0.8
Maritime pine	1	0.8	0.7	0	0.2	0.3
Scots pine	1	0.7	0.5	0	0.3	0.5
Fir & spruce	1	0.8	0.7	0	0.2	0.3
Douglas fir	1	0.6	0.4	0	0.4	0.6
Other conifers	1	0.8	0.7	0	0.2	0.3

[1] 0 – 5 years

[2] > 5 years – maturity age

[3] for maturity age see Table 2.11

Deciduous oak, beech and chestnut forests are little affected by fires, as they grow in more humid zones. The water content of their leaves is higher, the litter of deciduous forests decomposes faster than sclerophyllous leaves or needles and thus does not easily build up to form a readily flammable litter layer. Due to the relatively short dry period in summer, fuel moisture does not decrease as much as in the more arid parts of the Mediterranean area. Hence stand-replacing crown fires are rare and occasionally occurring litter or brush fires do not kill many trees. The susceptibility to stand-replacing fires was thus set to low values for oak, beech and chestnut forests – one out of ten fires was considered to be stand-replacing in mature stands.

The “other broadleaves” class mainly includes holm, pubescent, and cork oak (compare Table 2.10). These forest types burn frequently, but they resist mild fires and recover quickly after more severe fires as they are able to sprout after partial destruction of their aboveground organs (Nasi et al. 2002; Trabaud 1981, 1987; Vélez 1990). However, after repeated fires, the trees are replaced by a woody shrub cover (Vélez 1990). Cork oak withstands fire owing to its thick bark (Trabaud 1987). The susceptibility to stand-replacing fires was accordingly set to a low value for mature trees in the other broadleaves class – only one out of five fires was assumed to be stand-replacing.

According to Vélez (1990), *Pinus halepensis*, *Pinus pinaster* and *Pinus nigra* tend to have a particularly high content of resin or essential oils, which makes them extremely inflammable. Regeneration of these species depends on fire – their cones only open when exposed to intense heat. Thanos (1997) states that a typical Mediterranean wildfire usually kills the entire pine (*Pinus halepensis* and *P. brutia*) population. Hence it was assumed that the *Pinus* genus in the Mediterranean area is generally very susceptible to stand-replacing fires and accordingly both the Maritime pine and the other conifers class (which mainly contains *P. halepensis* and *P. nigra*) were assigned a high susceptibility value for stand-replacing fires.

Young Scots pine trees are easily killed by fire due to their thin bark and shallow roots, but mature trees are better able to withstand fire (Sullivan 1993). Their susceptibility to stand-replacing fires was assumed to be lower than for the other *Pinus spp.*

Norway spruce and silver fir grow in more humid zones and do seldom burn. If they do burn, however, they are easily destroyed by fire. Norway spruce is easily damaged or killed by fire and its crown canopy is often totally destroyed by even minor surface fires (Sullivan 1994b). Silver fir is also assumed to be highly sensitive to fire due to its thin bark and its high resin content. The fir & spruce class was assigned the same high susceptibility to stand-replacing fires as the Maritime pine and other conifers classes.

Douglas fir is protected from heat damage by thick and corky bark on the lower bole of the tree, so it can survive even moderately intense fires (Uchytil 1991). The susceptibility value for stand-replacing fires for Douglas fir was set to a lower value than for all other coniferous species.

2.6. Testing the fire module

This section describes how the fire module was tested in order to evaluate its set-up and to analyse its sensitivity to regional and temporal variations in fire regime. The realisation of the susceptibility matrix is also assessed.

2.6.1. Regional variation

The fire regime varies regionally, due to variations in e.g. forest type and structure, forest cover, relief and climatic variables. Fire statistics are compiled on the basis of administrative units (e.g. departments or regions), which do not necessarily reflect the differences in vegetation cover, topography and climate. Such structural changes were partly incorporated into the susceptibility matrix by defining the fire sensitivity per tree species and ownership category (see Section 2.5.3). In order to assess whether the model is able to reproduce large-scale regional variations in fire occurrence satisfactorily, a test simulation was carried out for the whole of France. Forest fire data for the Mediterranean regions was available as described in Section 2.4.2. Regional data on burnt forest area in the other regions of France were only available for the years 1991–2001. Therefore only this period was used as input for this test. The corresponding original data are summarised in the Appendix, Table A.2.

Because the tree species distribution and fire susceptibility differ considerably between the Mediterranean region and the rest of France, two separate model simulations were carried out, one for the three Mediterranean regions and one for the remaining 19 regions. The susceptibility matrix for the regions outside the Mediterranean was adapted in order to take into account the different tree species distribution there. In the Aquitaine region, forest fires mostly occur in Maritime pine forest stands, so a high susceptibility value was assigned to this forest type in this region. No fire dependence on forest ownership was found for the non-Mediterranean regions of France, therefore forest ownership was assumed to have no impact on fire occurrence there.

In Figure 2.5 the model results are compared to the average percentage of the forest area burnt per region. The regions most affected by fire are in the Mediterranean area. The highest percentage of forest area burnt in Corsica, annually about 0.3% in the period from 1991 to 2001. But also in the western and south-western part of France the forest area subject to fire was considerable, especially in the Aquitaine region (subfigure 2.5(a)). This pattern was reproduced quite well by the model (subfigure 2.5(b)). The variation between the observed data and the model results (subfigure 2.5(c)) was highest in Northern France, where the burnt area was generally so low that a few hectares difference in the model resulted in a variation of up to 34%. These differences were partly caused by the setup of the model: regional and tree species susceptibilities are multiplied to one general susceptibility value. Thus, regional differences in tree species sensitivity to fire can cause small deviations in the simulation results. For example, if on average the same forest area burnt in two regions according to the observed data, but one of the regions has a higher proportion of fire sensitive tree species, the general susceptibility value will be higher and the model will slightly overestimate the burnt area in that region. This effect has to be kept in mind when analysing the results. To prevent this behaviour, it would be necessary to define one frequency distribution per region, which would result in considerable computational effort, or to run the model separately per region. In both options one would lose the correlation of the burnt area between the regions. However, as it is, the model reproduced the regional variability reasonably well, particularly in the Mediterranean regions, where the forest composition does not vary so much between the regions.

2.6.2. Temporal variation

As mentioned earlier, there was a marked decrease in the burnt forest area in the French Mediterranean region from the beginning of the 1990s. To test the influence of changes in the expected value on the model results, the model was run for the three Mediterranean regions with the statistical input (burnt area) of two different periods, 1980–1990 and 1991–2001. In the first period, the mean annual area burnt was about 3.4 times higher than in the latter period. As can be seen in Figure 2.6, the model reproduced the input statistics quite well, the differences between the observed data and the model results remained below 9%. The forest area burnt tended to be underestimated in Languedoc-Roussillon and Corsica, while in Provence-Alpes-Côte d'Azur it was overestimated slightly. This can be explained with the fact that the overall tree species susceptibility of the forest in Provence-Alpes-Côte d'Azur, as defined in Table 2.11, is higher than in the other two regions, owing to the different tree species distribution in the Mediterranean regions. Furthermore, some deviation may be caused by the fact that the EFISCEN input data (the French national forest inventory data) did no correctly represent the state of the forest in the 1980–1990 period, as the mean year of inventory was 1994.

2.6.3. Assessing the realisation of the susceptibilities

According to the setup of the tree species susceptibility matrix, the tree species groups most heavily affected by fire should be other broadleaves and other conifers, and, to a lesser extent, Maritime and Scots pine. Oak, beech, chestnut, fir and spruce and Douglas fir should hardly burn. To what extent the various forest types burn can also be modified by variations in the age class and ownership distribution between the regions. Figure 2.7 illustrates how the susceptibility setup is mirrored in the results. The proportion of the forest area covered by each tree species or tree species group (given as percentage of the total forest area) is compared to the percentage of the forest area burnt per species or species group. As the tree species distribution varies considerably between the three Mediterranean regions, the comparison between forest area and burnt area is presented separately for each of the three regions.

The tree species group most heavily affected by fire are other broadleaves and, to a lesser extent, other conifers. Other broadleaved species cover about 35% of the forest area in Languedoc-Roussillon and Provence-Alpes-Côte d'Azur, and 50% in Corsica. The proportion of the other

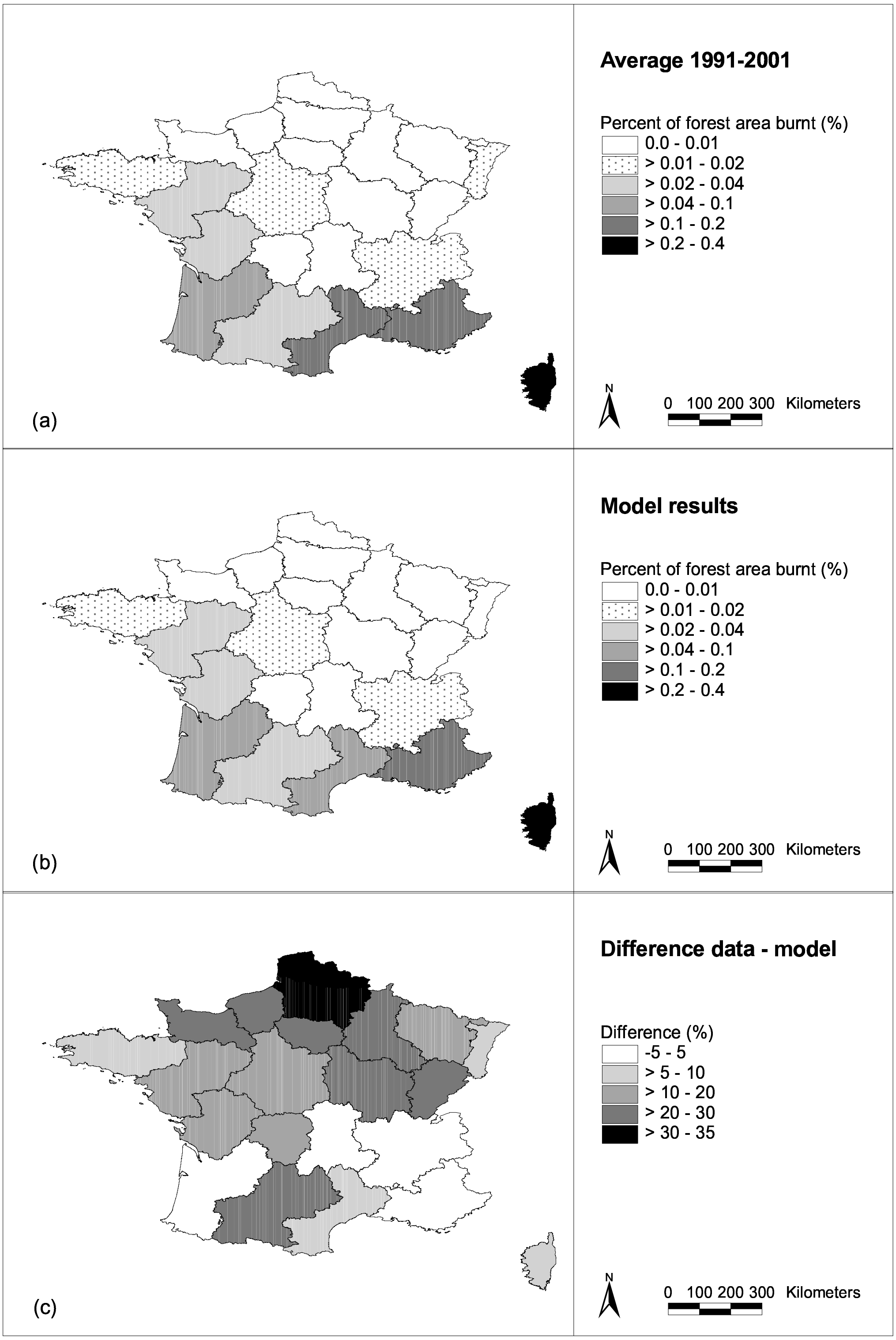


Figure 2.5.: Percent of forest area burnt per region in 1991–2001 (a), as result of the model simulations (b) and the difference (c) between (a) and (b).

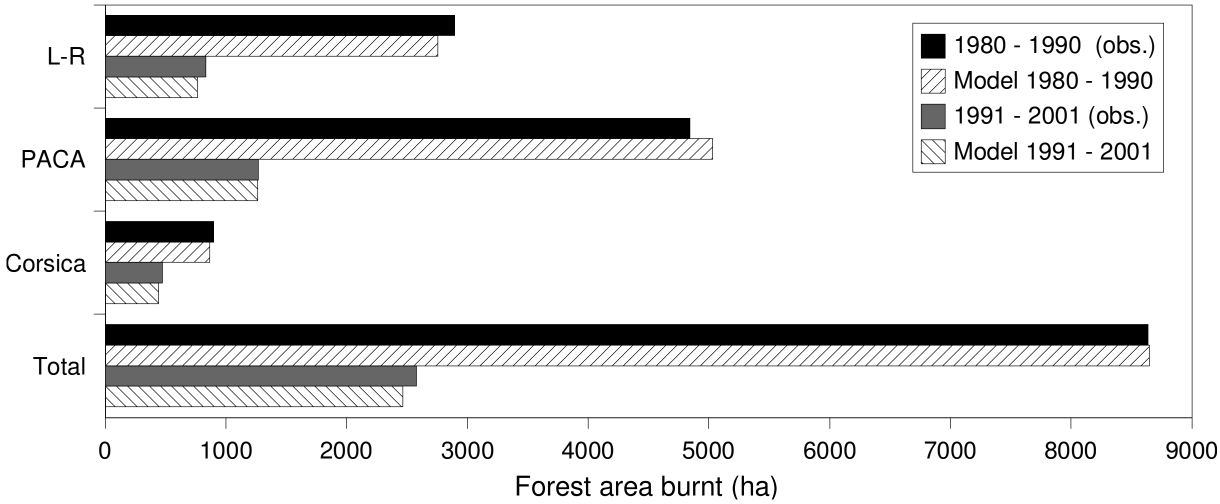
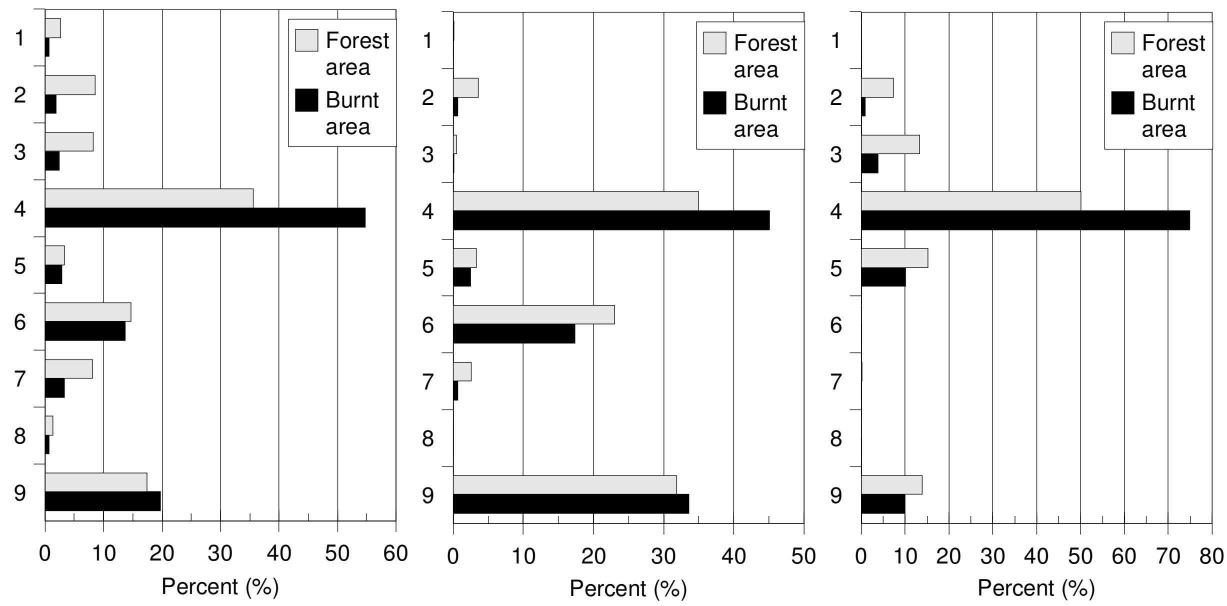


Figure 2.6.: Comparison of the observed burnt forest area with the model results for Languedoc-Roussillon (L-R), Provence-Alpes-Côte d'Azur (PACA), Corsica and the sum of the three regions (total).

broadleaves group on the total burnt area was higher than its relative area coverage: 55% in Languedoc-Roussillon, 45% in Provence-Alpes-Côte d'Azur, and 75% in Corsica. For the other conifers group, the proportion of burnt area was also higher than the relative forest area covered by this tree species group, but only in Languedoc-Roussillon and Provence-Alpes-Côte d'Azur. In Corsica, the proportion of burnt area for other conifers was relatively low because more than 80% of the trees in this group are older than 60 years and are therefore not so flammable, as defined in Table 2.11. Oak, beech, chestnut, fir and spruce and Douglas fir were relatively little affected by fire – the proportion of burnt area compared to forest area is rather small. It can be concluded that the realisation of the susceptibilities is satisfactorily. Therefore no changes to the model setup were made for this study.

2.7. Incorporating climate change

There is considerable uncertainty about how global changes will affect the Mediterranean climate and environment. Climate scenarios indicate that precipitation might increase slightly during the winter, while water availability may decrease during the summer months in Southern Europe (McCarthy et al. 2001). The two climate scenarios used in this study, HadCM3-A2 and PCM2-A2 (see Section 2.4.3), both project rising temperatures for the French Mediterranean area. Summer precipitation decreases in the HadCM3-A2 scenario, and does not change substantially in the PCM-A2 scenario. But even rising summer precipitation might not compensate for increased potential evapotranspiration (PET) caused by a warmer climate. It is very likely that drought will remain a major factor in Mediterranean regions (Pereira and Chaves 1995). An increase in summer drought due to climate change would probably have adverse effects on



(a) Languedoc-Roussillon (b) Prov.-Alpes-Côte d'Azur (c) Corsica

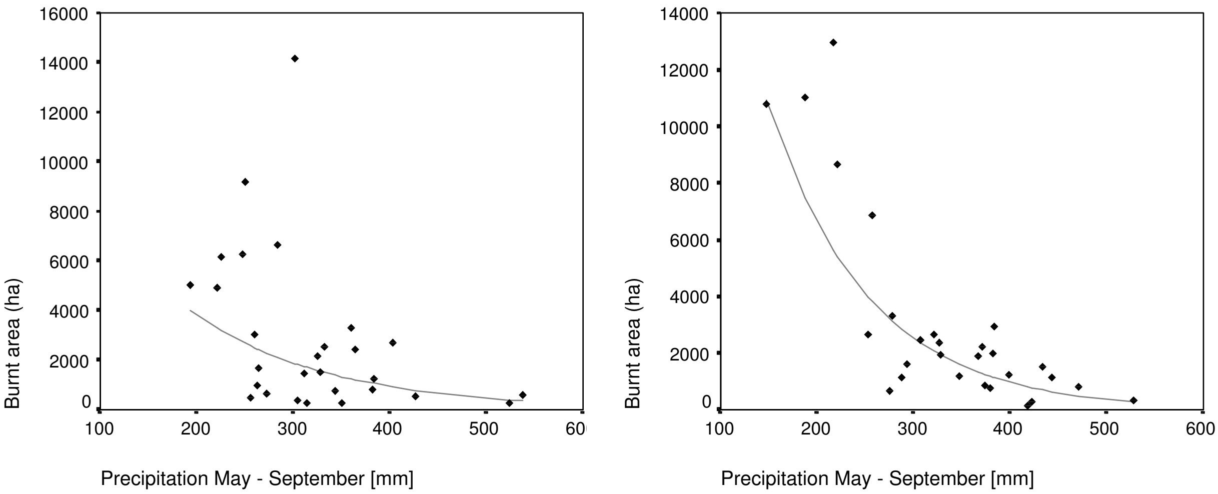
Figure 2.7.: Comparison of forest area and burnt area by tree species (group). For each of the three Mediterranean regions (a, b, c), the proportion of the total forest area covered by each tree species (group) is given, together with the proportion of the burnt area, also by tree species (group).
(1 – oak, 2 – beech. 3 – chestnut, 4 – other broadleaves, 5 – Maritime pine, 6 – Scots pine, 7 – Fir & Spruce, 8 – Douglas fir, 9 – other conifers)

tree growth and would also increase the risk of forest fires (Kellomäki et al. 2000; McCarthy et al. 2001; Pausas 1999).

The following sections describe how the impact of climate change on fire regime and on tree growth were modelled in this study. In Section 2.7.1, the relationship between climate variables and burnt forest in the French Mediterranean area is analysed. On the basis of that relationship, a regression model that estimates the future burnt area based on climate variables is established and implemented in EFISCEN (Section 2.7.2). Section 2.7.3 describes how the average increment was adapted in order to take into account the effect of a changing climate on forest growth.

2.7.1. Relationship between climate variables and burnt forest area

In the Mediterranean part of France, most fires occur in the summer months. There is a second peak in spring (March-April), but summer fires are more devastating. It is assumed that the majority of the annual area burnt is caused by summer fires and that hence annual burnt area



(a) Languedoc-Roussillon

(b) Provence-Alpes-Côtes d'Azur

Figure 2.8.: Burnt area in Languedoc-Roussillon (a) and Provence-Alpes-Côte d'Azur (b) between 1973 and 2000 as a function of summer precipitation (May to September). The diamonds represent the observed values, the line represents the fitted regression function.

can be related to meteorological variables depicting the summer weather condition.

The climate data available for this study were described in Section 2.4.3. They include mean monthly air temperature, precipitation, PET and AET values, aggregated for the administrative regions of France. For each of the three Mediterranean regions, annual burnt area was plotted against various regional climatic variables and summer drought indices retrieved from the climate data. The strongest correlation was found between summer precipitation and burnt area, inter-annual variations in temperature did not seem to have a marked impact on fire occurrence.

In Figure 2.8 the values of the burnt area as a function of summer precipitation are plotted for the regions Languedoc-Roussillon and Provence-Alpes-Côte d'Azur. As the relationship seemed to be exponential, the natural logarithm (ln) of the data on burnt forest area was taken and used for the correlation analysis. The correlation coefficients and significance values are shown in Table 2.14.

Correlation between summer precipitation and burnt forest area was significant at the 0.01 level for Languedoc-Roussillon and Provence-Alpes-Côte d'Azur. The correlation was higher in the latter region ($r = -0.78$ compared with $r = -0.51$ in Languedoc-Roussillon). For Corsica, this analysis did not yield satisfying results: the correlation was small ($r = -0.29$) and not significant ($p = 0.132$). Therefore, Corsica was neglected in the subsequent analysis and in the climate change model runs. In Languedoc-Roussillon there were a few relatively dry years with nonetheless little fire occurrences, mainly in the 1990s. This can probably be attributed to efficient fire prevention and control measures, following a government plan which became effective in 1989 and which was aimed to accelerate the rehabilitation of burnt forests and to

Table 2.14.: Correlation between the ln values of the forest area burnt and summer precipitation (May–September, $Prec_{5\text{-}9}$) in the French Mediterranean regions (1973–2000).

ln (burnt area)		$Prec_{5\text{-}9}$
Languedoc-Roussillon	Pearson Correlation	-0.51
	Sig. (2-tailed)	0.006
	Number of cases	28
Provence-Alpes-Côte d'Azur	Pearson Correlation	-0.78
	Sig. (2-tailed)	<0.001
	Number of cases	28
Corsica	Pearson Correlation	-0.29
	Sig. (2-tailed)	0.132
	Number of cases	28

improve fire prevention, e.g. by means of mandatory fuel reduction campaigns and new forest fire brigades (van Effenterre 1990).

No attempt was made to remove outliers, because the data set included only 30 years of observations and it was impossible to say if any of the values were unrealistic.

2.7.2. Regression models

An exponential regression function of the format

$$burnt\,area = a \times e^{b \times summer\,precipitation} \tag{2.8}$$

can be used to describe the nature of the relationship found between the burnt area and summer precipitation. Parameters a and b are constants, $summer\,precipitation$ denotes the sum of precipitation for the months May to September. Because linear regression is easier to analyse, equation 2.8 was linearised by calculating the natural logarithm (ln) on both sides of the equation:

$$ln(burnt\,area) = c + b \times summer\,precipitation \tag{2.9}$$

where $c = ln(a)$. The parameter values of c and b, together with their standard errors and 95% confidence intervals for both regions are given in Table 2.15. The standard errors are smaller and the confidence interval is narrower for Provence-Alpes-Côte d'Azur, as the relationship between precipitation and burnt area is closer in that region, compared to Languedoc-Roussillon.

Table 2.16 shows the statistics of the analysis of variance (ANOVA) of the linear regression

Table 2.15.: Parameter values, standard errors and 95% confidence intervals for the linear regression function for Languedoc-Roussillon and Provence-Alpes-Côte d'Azur.

Model	Coefficients	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Languedoc-Roussillon				
c	9.641	0.773	8.052	11.229
b	-0.007	0.002	-0.012	-0.002
Provence-Alpes-Côte d'Azur				
c	10.717	0.532	9.624	11.810
b	-0.0096	0.002	-0.013	-0.006

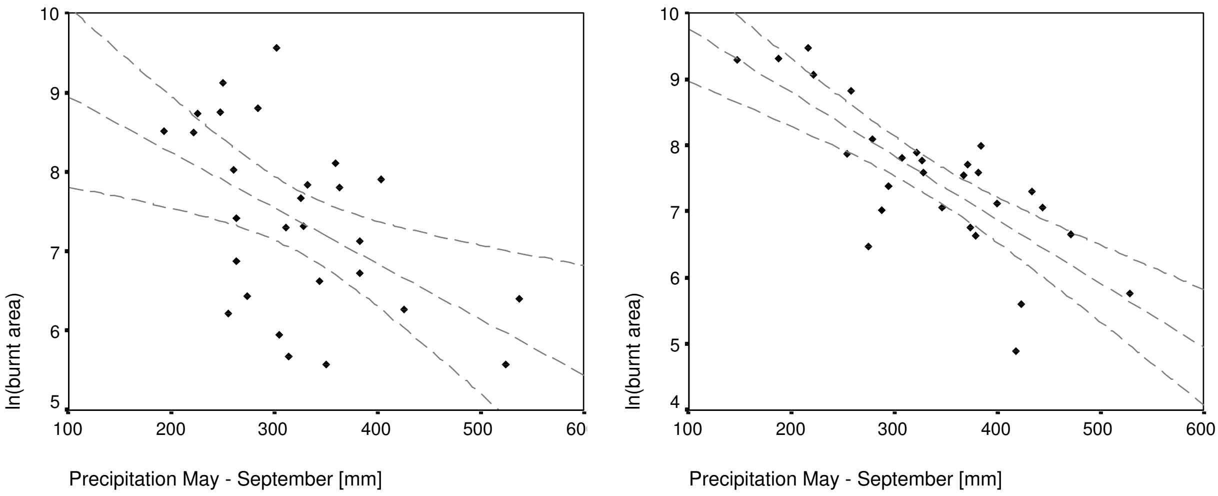
Table 2.16.: ANOVA statistics for the linear regression functions.

Model	Sum of Squares	DF	Mean Square	F	Sig. F
Languedoc-Roussillon					
Regression	9.022	1	9.022	9.052	0.006
Residual	25.913	26	0.997		
Total	34.935	27			
Provence-Alpes-Côte d'Azur					
Regression	19.855	1	19.855	39.471	0.000
Residual	13.079	26	0.503		
Total	32.933	27			

functions for both regions. The residual sum of squares is greater than the regression sum of squares in Languedoc-Roussillon, indicating that the model accounts for less than half of the variation in the dependent variable, i.e. burnt area. Nonetheless, the significance value of the F statistic (Sig. F) is small ($p = 0.006$), therefore summer precipitation has a significant influence on the variability in the burnt area in Languedoc-Roussillon. In Provence-Alpes-Côte d'Azur, the residual sum of square is smaller than the regression sum of square, hence the model accounts for the majority of the variation of burnt area. The significance value of the F statistic is very small ($p < 0.001$), indicating that summer precipitation has a significant influence on the variability in the burnt area in Provence-Alpes-Côte d'Azur as well.

In Figure 2.9 the natural logarithms of the burnt forest area are presented as a function of summer precipitation, together with the fitted linear regression line and the 95% mean prediction interval. In Provence-Alpes-Côte d'Azur more than 60% of the variance in the observed data is explained by the equation ($R^2 = 0.61$), in Languedoc-Roussillon only 26% ($R^2 = 0.26$).

To implement the effect of climate change on fire occurrences in the disturbance module, the way of deriving the fire hazard ratio (compare equation 2.2 on page 12) was modified. Using equation 2.8, the future burnt area in Languedoc-Roussillon and Provence-Alpes-Côte d'Azur



(a) Languedoc-Roussillon

(b) Provence-Alpes-Côte d'Azur

Figure 2.9.: Scatterplots of summer precipitation (May-September) versus the ln value of the forest area burnt for the Mediterranean regions Languedoc-Roussillon (a) and Provence-Alpes-Côte d'Azur (b), 1973–2000, linear regression with 95% mean prediction interval.

was estimated for both climate scenarios (PCM-A2 and HadCM3-A2). The actual fire hazard was then calculated by comparing the estimated burnt area per region and climate scenario with the theoretical burnt area without climate change (equation 2.10):

$$A_{m,n,t} = \frac{C_{m,n}}{D_{m,n}} \tag{2.10}$$

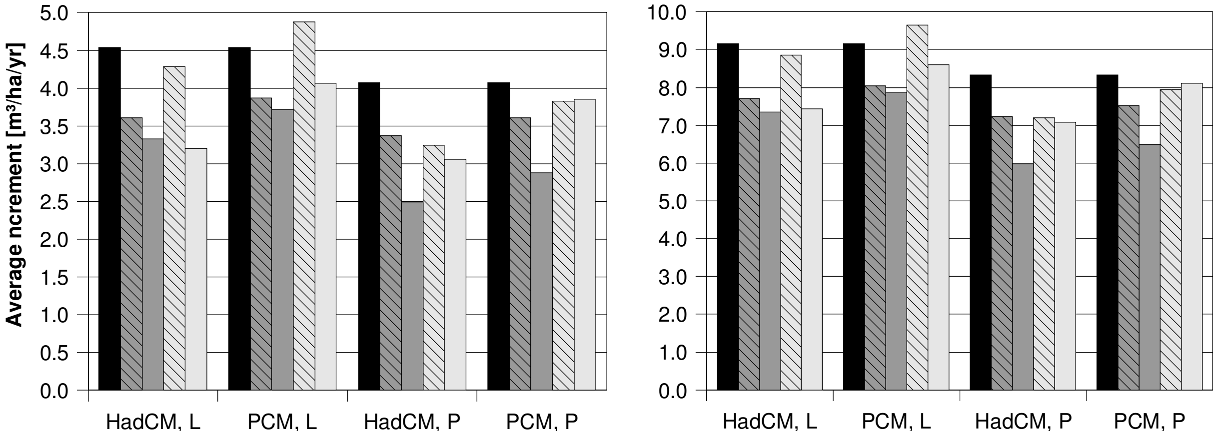
where A is the fire hazard ratio under climate change conditions at time step t in region m for climate scenario n, C is the burnt area for climate change conditions, D is the burnt area without climate change. If $A > 1$, more area is burnt under climate change conditions than under current climate conditions, if $A < 1$, the area burnt is less.

2.7.3. Impact of climate change on forest growth

Lapveteläinen et al. (unpublished) studied the relationship between selected climate variables and forest growth by utilising measured national forest inventory data and observed climate data, on a European scale. They fitted a multiple linear regression function to the data in order to describe the impact of temperature and drought on forest growth:

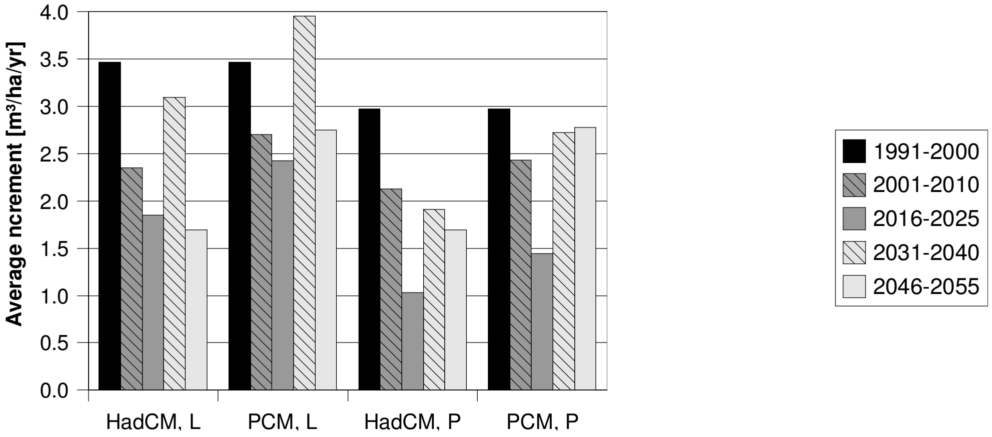
$$Increment = a + b \times \log(degree\,days) + c \times summer\,drought \tag{2.11}$$

Parameter a is a constant, b defines the impact of heatsum and c the impact of summer drought



(a) Pine

(b) Spruce



(c) Deciduous species

Figure 2.10.: Average annual increment for pine (a), spruce (b) and deciduous species (c), as projected by regression function 2.11 for the observed period of 1991–2000 and for the climate change scenarios HadCM3-A2 and PCM-A2. L = Languedoc-Roussillon, P = Provence-Alpes-Côte d'Azur.

on increment. Degree days are calculated on an annual basis with the threshold value of 0°C; summer drought is the difference between total summer precipitation ($P_{5\text{-}9}$) and the potential evapotranspiration ($PET_{5\text{-}9}$), both for the months May to September. When the difference between $P_{5\text{-}9}$ and $PET_{5\text{-}9}$ was positive (i.e. precipitation exceeded potential evaporation), the drought value was set to zero, assuming that drought would not limit forest growth. The function explained 39% of the variation in the increment data for pine, 54% for spruce and 38% for deciduous species. No other tree species were studied. The parameter values of *a*, *b* and *c* are listed in the Appendix.

To use this function for changing the increment in EFISCEN in the climate change scenarios, summer drought and degree days were calculated for the period 2001–2060 for the two climate

Table 2.17.: Relative increment change for pine, spruce and deciduous species under two climate scenarios (HadCM3-A2 and PCM-A2) in Languedoc-Roussillon (L-R) and Provence-Alpes-Côte d'Azur (PACA).

	Pine				Spruce				Deciduous			
	HadCM3-A2		PCM-A2		HadCM3-A2		PCM-A2		HadCM3-A2		PCM-A2	
	L-R	PACA	L-R	PACA	L-R	PACA	L-R	PACA	L-R	PACA	L-R	PACA
2006	0.80	0.83	0.85	0.88	0.84	0.87	0.88	0.90	0.68	0.72	0.78	0.82
2021	0.73	0.61	0.82	0.71	0.80	0.72	0.86	0.78	0.53	0.35	0.70	0.49
2036	0.95	0.79	1.08	0.94	0.97	0.86	1.05	0.95	0.89	0.64	1.14	0.92
2051	0.71	0.75	0.90	0.95	0.81	0.85	0.94	0.97	0.49	0.57	0.79	0.93

scenarios applied in this study (HadCM3-A2 and PCM-A2), as well as for the observed climate data for the years 1991–2000. For these periods, the function was applied and 10-year increment averages calculated. Figure 2.10 presents the resulting increment averages for pine, spruce and deciduous species for both climate scenarios. The change in increment is strongly influenced by summer drought, water availability being the most important factor limiting forest growth in the Mediterranean area. The expected increment was generally lower for the HadCM3-A2 scenario than for the PCM-A2 scenarios, as the HadCM3-A2 scenario projects a stronger increase in summer drought than the PCM-A2 scenario. Apart from the 2031–2040 period under the PCM-A2 scenario, the application of linear regression function resulted in lower future increment rates compared to the situation in the 1990s, for pine, spruce as well as deciduous species. The relatively high increment in the period 2031–2040 was caused by the comparatively high summer precipitation in this period, which limited the growth-inhibiting effects of summer drought.

To implement this in EFISCEN, the ratios between the increment averages for the climate scenarios and the observed period of 1981–2000 were calculated (Table 2.17). These ratios determine the relative change in increment that is taking place starting at a predetermined simulation step. A value of 1.0 means no change, a value of e.g. 1.4 means an increase in increment by 40% compared to the original increment. The same ratio was used for all age classes. Increment was changed four times during the simulation, in 2006, 2021, 2036 and 2051.

Some of the EFISCEN tree species groups were not directly covered by these increment change estimations, as these were only available for pine, spruce and deciduous species. In such cases, species with similar growth characteristics were assigned the same ratio. The pine ratios were used for Maritime pine, Scots pine and other conifers, the spruce ratios for fir & spruce and Douglas fir, and the ratios for the deciduous species were applied to all the remaining, deciduous species (oak, beech, chestnut and other deciduous).

2.8. Applied scenarios

The EFISCEN model was run for the current climate scenario and two climate change scenarios (PCM-A2 and HadCM3-A2), both with and without the fire module, amounting to a total of six model runs. Table 2.18 summarises which scenarios were analysed in this study.

In the current climate model simulations, the observed distribution of burnt area was used to extrapolate fire damages into the future, as described in Section 2.3. Because of the stochastic character of this approach, Monte-Carlo simulation was used. The average as well as the standard deviation of 300 runs were calculated. In the climate change scenarios, burnt area was defined by summer precipitation, with the help of a regression function.

EFISCEN was run over 65 years, starting in 1996. The average of the years 1973–2002 was used as input for the model runs with the fire module. Only the three Mediterranean regions were modelled, both in the current climate and in the climate change scenarios. For the years 1996 to 2002, fire data were available, so the observed values of burnt area were used for these years in both approaches, instead of modelling them. To make the results consistent and comparable, in the climate change runs the three regions – Languedoc-Roussillon, Provence-Alpes-Côte d'Azur and Corsica – were modelled. The increment was changed for the three regions as described in Section 2.7.3. In Corsica, a fire hazard of 1.0 was applied, i.e. the average area of the current climate approach was burnt in that region.

Table 2.18.: Analysed scenarios.

	Current climate		HadCM3-A2		PCM-A2	
Region	without fire	with fire	without fire	with fire	without fire	with fire
Languedoc-Roussillon	x	x	x	x	x	x
Pr.-Alpes-Côte d'Azur	x	x	x	x	x	x
Corsica	x	x				

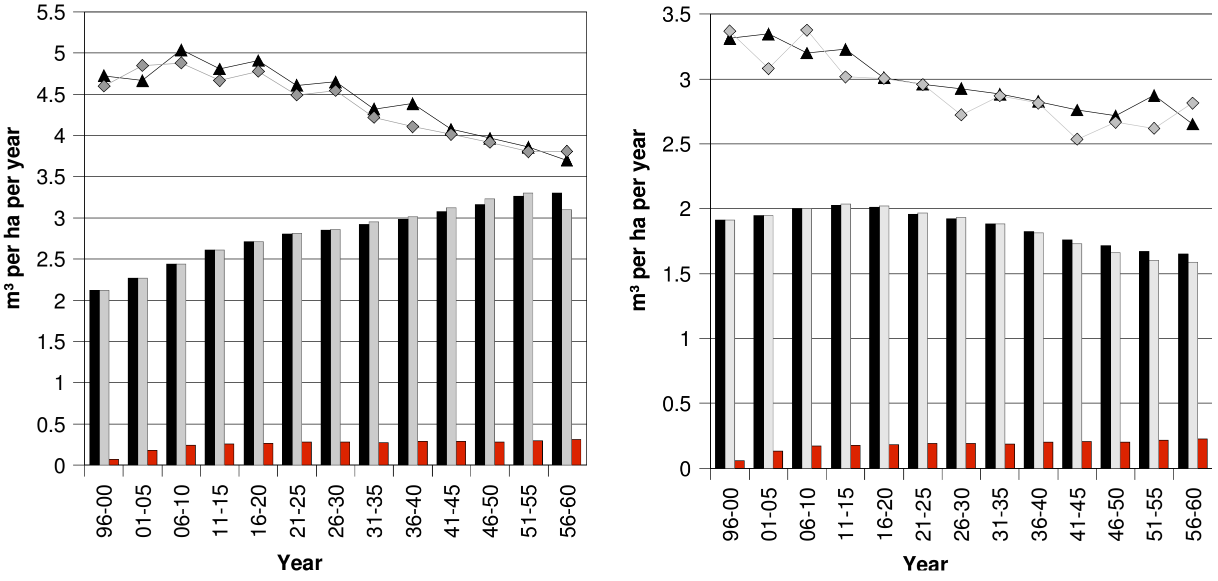
3. Results

3.1. Current climate runs

In Figure 3.1 increment and fellings (sum of thinnings and final fellings) are compared for the current climate run with and without the fire module. For the run with fire the burnt volume is also included in the graph. The development of the growing stock, with and without fire, is presented in Figure 3.2. In both Figure 3.1 and 3.2, subfigures (a), (b) and (c) present the results for Languedoc-Roussillon, Provence-Alpes-Côte d'Azur and Corsica, respectively, while subfigure (d) presents the weighted average of these three regions.

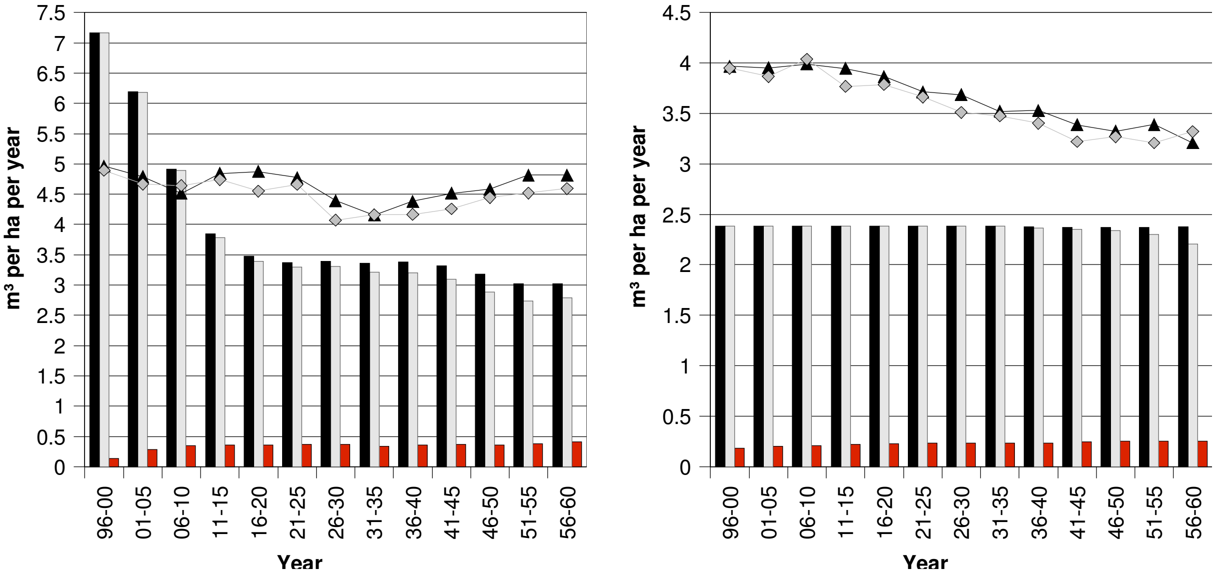
The effects of fire disturbances on increment were minor, increment in the runs with and without fire differed very little. After a slight increase until 2010, annual increment per hectare decreased in Languedoc-Roussillon (Figure 3.1(a)), without fire from 4.7 m^3 ha^{-1} per year in 1996–2000 to 3.7 m^3 ha^{-1} per year in 2056–60 , and with fire from 4.6 to 3.8 m^3 ha^{-1} per year. In Provence-Alpes-Côte d'Azur (Figure 3.1(b)), increment generally declined over time, too. Without fire, increment decreased from 3.3 m^3 ha^{-1} yr^{-1} to 2.7 m^3 ha^{-1} yr^{-1}, and with fire from 3.4 m^3 ha^{-1} yr^{-1} to 2.8 m^3 ha^{-1} yr^{-1}. Maturing of the forests was the main cause for the decrease in increment in both Languedoc-Roussillon and Provence-Alpes-Côte d'Azur. In Corsica (Figure 3.1(c)), increment decreased until 2010, then increased slightly until 2015, followed by another decrease. From the 2030s onwards, increment increased steadily again, both with and without fire. Felling levels were very high in Corsica in the first 15 years of the modelling period, because on average Corsican forests are older than forests in the other two Mediterranean regions, and were therefore first subjected to final fellings. This also explains the decrease in increment in the first 15 years in Corsica, as the cells that undergo a final felling are transferred to the bare forest land class and do not enter the matrix again before the next modelling period (compare Section 2.2). Due to the relatively high felling levels, the proportion of forests older than 60 years decreased from 81% in 1995, to 43% in 2060 without fire, and to 34% with fire. Due to the shift in the age class distribution towards younger forests, increment still increased in Corsica towards the end of the simulation period.

Felling levels did not differ much between the model runs with and without fire. After a slight increase in the first 20 years, felling levels decreased in Provence-Alpes-Côte d'Azur. In Cor-



(a) Languedoc-Roussillon

(b) Provence-Alpes-Côte d'Azur



(c) Corsica

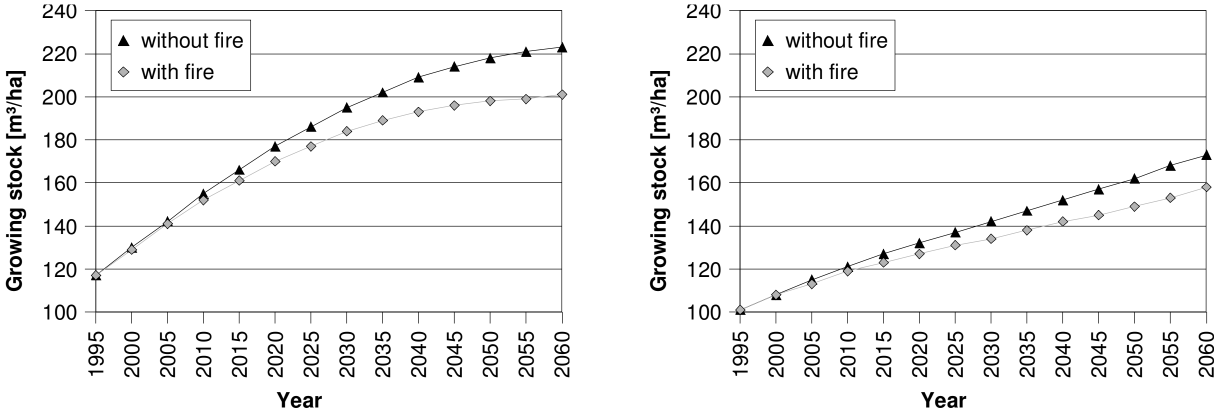
(d) Weighted average of (a) – (c)

Figure 3.1.: Increment and fellings projected under current climate conditions, with and without fire. For the scenario incorporating fire disturbances, burnt volume is also included.

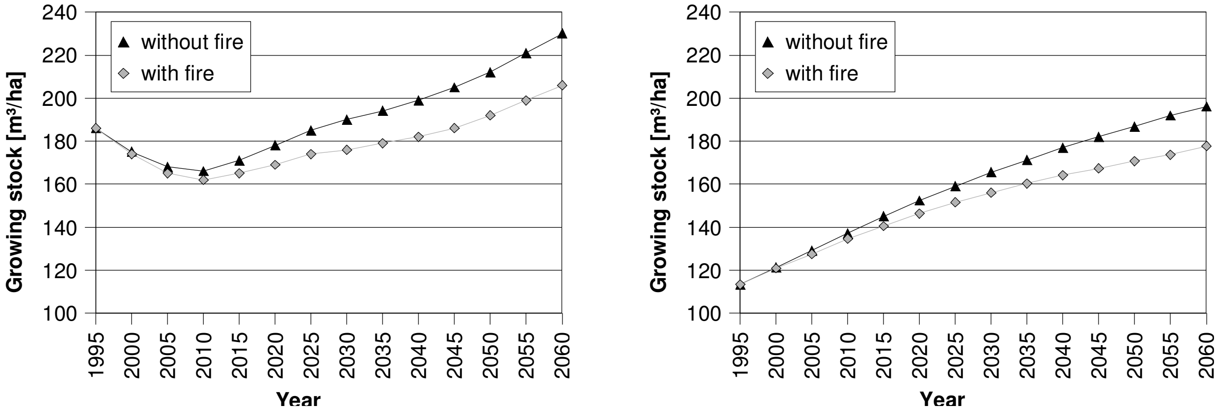
sica, felling levels also decreased over time, especially in the beginning. To compensate these decreases, felling levels in Languedoc-Roussillon increased over the years, so in total fellings in the model run without fire remained constant for the three regions. When fire was included, however, the required felling level could not be complied with in the last four time steps (2041–2060) (Figure 3.1(d)).

In the fire scenario, growing stock remained lower than in the model simulation without fire in all regions (Figure 3.2). The difference between the two scenarios was increasing over the years. In 2060, the growing stock of model simulations with fire was 9–10% lower than the corresponding results of the simulations without fire. The standard deviation of the growing stock from the 300 Monte-Carlo simulations was relatively small, in 2060 it lay between 2.0 m^3 ha^{-1} and 3.0 m^3 ha^{-1} in the three regions, on average it was 2.25 m^3 ha^{-1} (in 2060).

In Languedoc-Roussillon, growing stock increased from 117 m^3 ha^{-1} in 1995 to 223 m^3 ha^{-1} in 2060 without, and to 201 m^3 ha^{-1} with fire (Figure 3.2(a)). The relative increase in growing stock declined over the years, as a result of the rising felling levels in Languedoc-Roussillon (see Figure 3.1(a)), and because of the decline in increment. Growing stock also increased in Provence-Alpes-Côte d'Azur (Figure 3.2(b)), from 101 m^3 ha^{-1} in 1995 to 173 m^3 ha^{-1} in 2060 without fire, and to 158 m^3 ha^{-1} with fire. There was a clear difference between the initial growing stock in Corsica (186 m^3 ha^{-1}) and the other two Mediterranean regions (117 m^3 ha^{-1} Languedoc-Roussillon and 101 m^3 ha^{-1} in Provence-Alpes-Côte d'Azur), because forests in Corsica were generally much older than in the other two Mediterranean regions. Growing stock decreased in Corsica from 186 m^3 ha^{-1} in 1995 to 166 m^3 ha^{-1} without, and to 162 m^3 ha^{-1} with fire in 2010 (Figure 3.2(c)), because fellings clearly exceeded the increment in that period (see Figure 3.1). From 2010 onwards, growing stock increased and reached 230 m^3 ha^{-1} in 2060 without fire and 206 m^3 ha^{-1} with fire.



(a) Languedoc-Roussillon (b) Provence-Alpes-Côte d'Azur



(c) Corsica (d) Weighted average of (a) – (c)

Figure 3.2.: Development of growing stock with and without fire as projected under current climate conditions.

Table 3.1 presents the annual average increment and burnt volume together with the percentage of the increment that is burnt per year. The burnt volume was relatively low in the first two modelling periods, because the observed data for burnt area were used for the years 1996 to 2002. In these years, the forest area affected by forest fires was below average. From 2006 on, the annual area burnt remained quite constant, because the averages of 300 Monte-Carlo simulation were used. The percentage of the forest area burnt was on average 0.31% in Languedoc-Roussillon, 0.25% in Provence-Alpes-Côte d'Azur and 0.39% in Corsica. Due to the increase in growing stock (compare Figure 3.2), the burnt volume increased over time in the three regions (Table 3.1). The greatest relative proportion of forest burnt in Corsica, both in terms of area and volume, followed by Languedoc-Roussillon and Provence-Alpes-Côte d'Azur. The relative increase in burnt volume was smallest in Corsica, because there the growing stock increased only by 11% between 1995 and 2060 in the fire scenario, compared to 72% in Languedoc-Roussillon and 56% in Provence-Alpes-Côte d'Azur. Due to the declining increment and the increase in

Table 3.1.: Proportion of the average annual increment burnt in Languedoc-Roussillon (L-R), Provence-Alpes-Côte d'Azur (PACA) and Corsica.

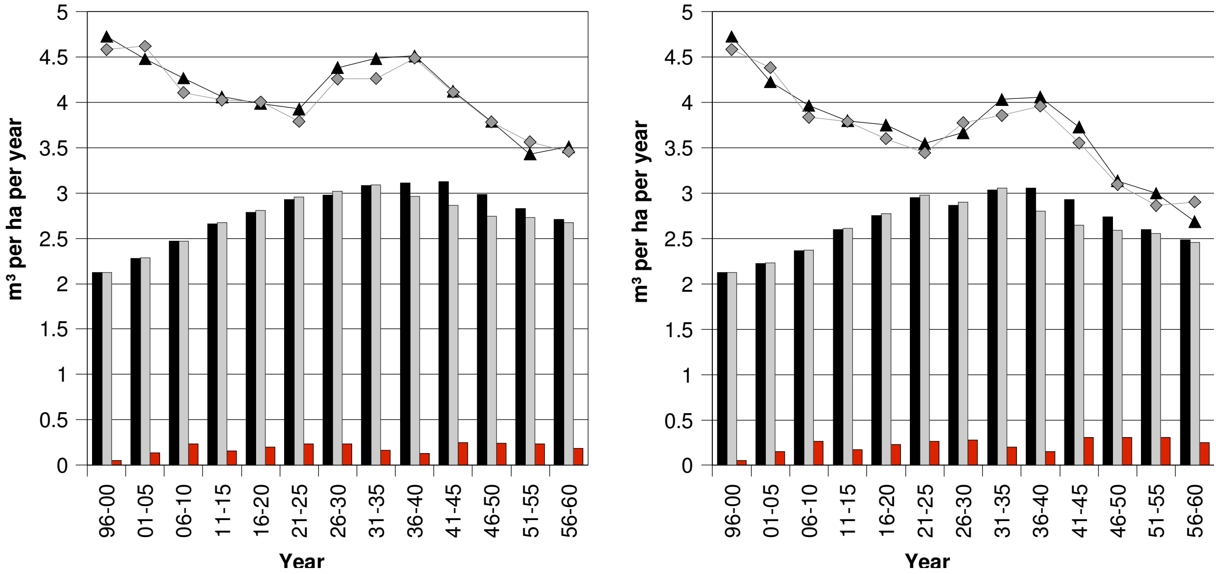
	Average increment [m^3 ha^{-1} yr^{-1}]			Average volume burnt [m^3 ha^{-1} yr^{-1}]			Percent of the annual increment burnt [%]		
Period	L-R	PACA	Corsica	L-R	PACA	Corsica	L-R	PACA	Corsica
1996–2000	4.60	3.37	4.89	0.08	0.06	0.13	1.6	1.7	2.7
2001–2005	4.85	3.08	4.67	0.18	0.13	0.29	3.8	4.3	6.1
2006–2010	4.88	3.38	4.64	0.24	0.17	0.35	5.0	5.1	7.5
2011–2015	4.67	3.02	4.74	0.26	0.18	0.36	5.5	5.9	7.5
2016–2020	4.78	3.00	4.55	0.27	0.18	0.36	5.6	6.1	7.9
2021–2025	4.49	2.96	4.66	0.28	0.19	0.37	6.2	6.5	7.9
2026–2030	4.54	2.72	4.07	0.28	0.19	0.36	6.2	7.1	8.9
2031–2035	4.22	2.87	4.16	0.27	0.19	0.34	6.4	6.5	8.2
2036–2040	4.11	2.81	4.16	0.29	0.20	0.36	7.1	7.2	8.7
2041–2045	4.01	2.54	4.26	0.29	0.21	0.37	7.3	8.2	8.6
2046–2050	3.92	2.67	4.44	0.28	0.20	0.36	7.2	7.6	8.0
2051–2055	3.80	2.62	4.52	0.30	0.22	0.38	7.9	8.3	8.5
2056–2060	3.81	2.81	4.59	0.31	0.23	0.41	8.2	8.0	8.8

growing stock, the proportion of the annual average increment burnt increased over the years and reached 8.0–8.8% in the last time step (2056–2060).

3.2. Climate change runs

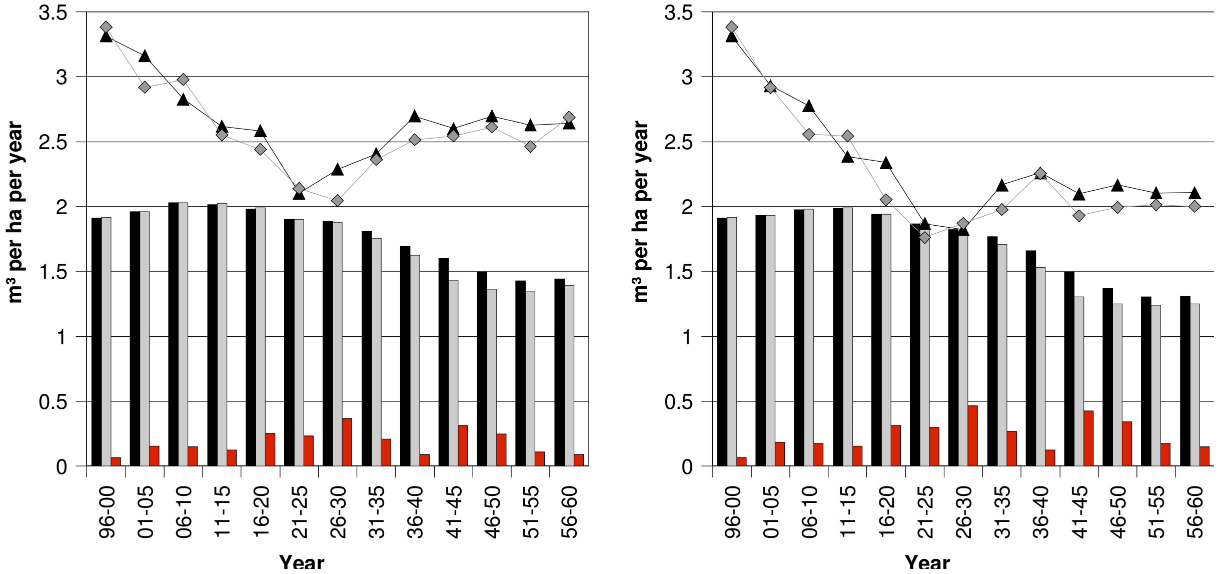
Increment, fellings and burnt volume for the PCM-A2 and HadCM3-A2 climate scenarios are shown in Figure 3.3. The development of the growing stock is presented in Figure 3.4. In both figures, the results of the model simulations, with and without the fire module and for both climate change scenarios, are compared for the regions Languedoc-Roussillon and Provence-Alpes-Côte d'Azur.

Like in the current climate scenarios, there were only slight differences in increment between the model simulations with or without fire. In both regions, increment declined until 2025, then increased due to a period of more humid summers during the 2030s, projected by both climate scenarios. From 2041 onwards, increment decreased again in Languedoc-Roussillon, but remained rather constant in Provence-Alpes-Côte d'Azur. Although increment changes followed the same pattern for both climate scenarios, increment was generally higher under PCM-A2 climate conditions. In Languedoc-Roussillon, without fire, increment decreased from 4.7 m^3 ha^{-1} yr^{-1} in 1996–2000, to 3.5 m^3 ha^{-1} yr^{-1} in 2056–2060 under the PCM-A2 sce-



(a) Languedoc-Roussillon, PCM-A2

(b) Languedoc-Roussillon, HadCM3-A2



(c) Pr.-Alpes-Côte d'Azur, PCM-A2

(d) Pr.-Alpes-Côte d'Azur, HadCM3-A2

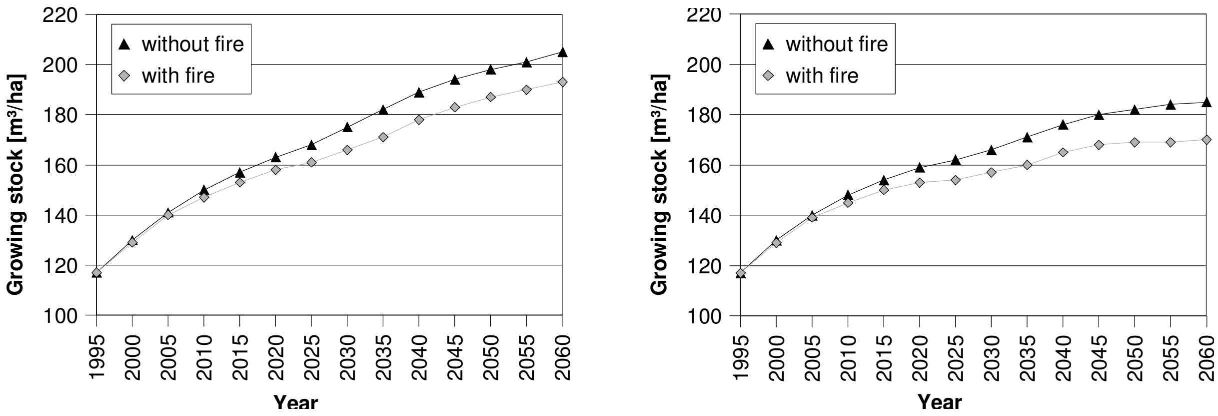
■ Fellings without fire ☐ Fellings with fire 🟥 Burnt volume ▲ Increment without fire ◇ Increment with fire

Figure 3.3.: Increment and fellings projected under the PCM-A2 and HadCM3-A2 climate scenarios, with and without fire. For the scenarios incorporating fire disturbances, burnt volume is also included.

nario, and to 2.7 m^3 ha^{-1} yr^{-1} under the HadCM3-A2 scenario. With fire, increment decreased from 4.6 m^3 ha^{-1} yr^{-1} to 3.5 m^3 ha^{-1} yr^{-1} for PCM-A2, and to 2.9 m^3 ha^{-1} yr^{-1} for HadCM3-A2. In Provence-Alpes-Côte d'Azur, without fire increment decreased from 3.3 m^3 ha^{-1} yr^{-1} to 2.6 m^3 ha^{-1} yr^{-1} under PCM-A2, and to 2.1 m^3 ha^{-1} yr^{-1} under HadCM3-A2 conditions. With fire, increment declined from 3.4 m^3 ha^{-1} yr^{-1} to 2.7 m^3 ha^{-1} yr^{-1} for PCM-A2, and to

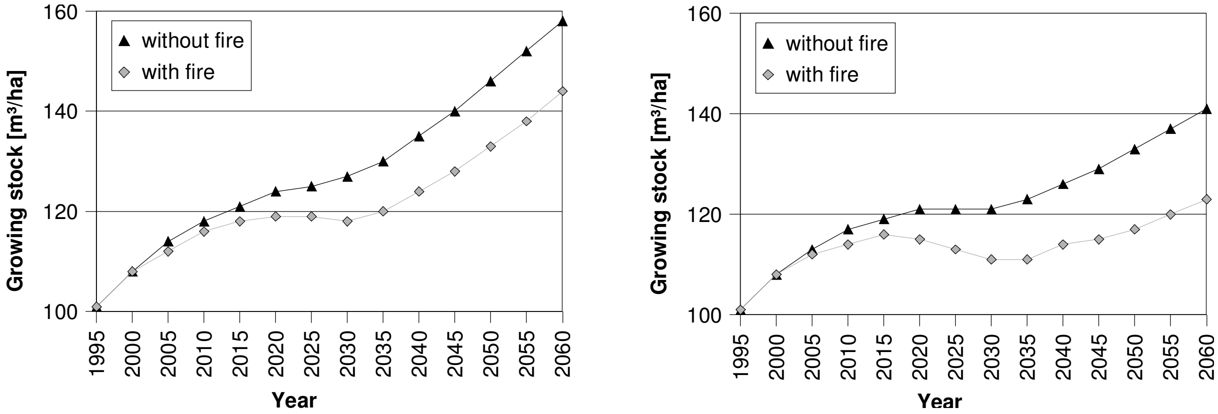
2.0 m^3 ha^{-1} yr^{-1} for HadCM3-A2.

Initially, felling levels were almost identical for the model simulations with and without fire. But in the second half of the modelling period, felling levels of the fire scenario were up to 13% lower compared to those of the model simulation without fire. This trend was more pronounced in the HadCM3-A2 scenario. The variation in felling levels between the scenarios with and without fire decreased again towards the end of the modelling period. Throughout the whole modelling period, felling levels were higher under PCM-A2 conditions than under those of the HadCM3-A2 climate scenario, regardless of whether fire was taken into account or not.



(a) Languedoc-Roussillon, PCM-A2

(b) Languedoc-Roussillon, HadCM3-A2



(c) Pr.-Alpes-Côte d'Azur, PCM-A2

(d) Pr.-Alpes-Côte d'Azur, HadCM3-A2

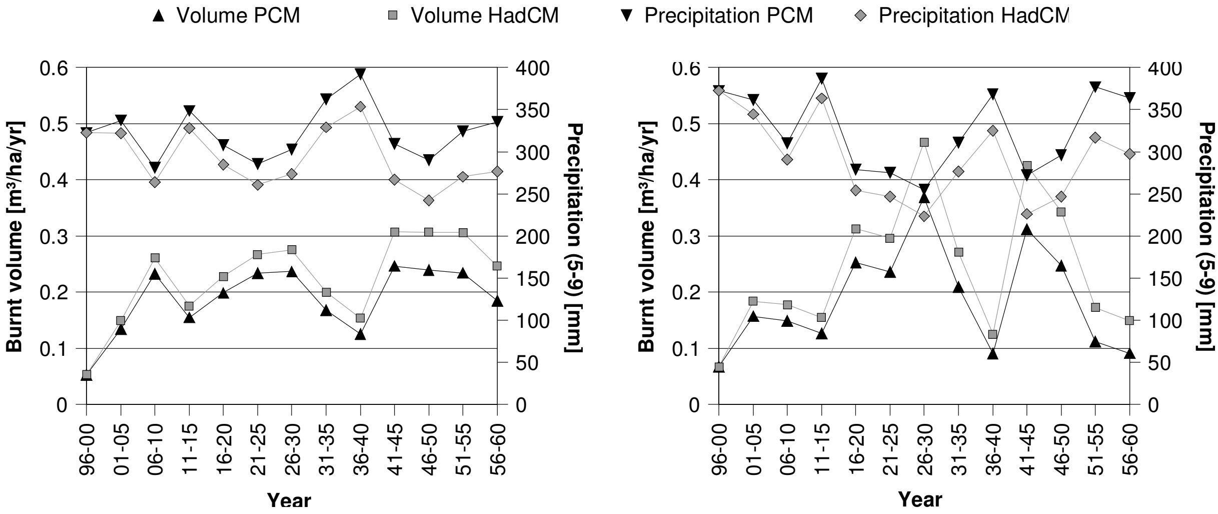
Figure 3.4.: Development of growing stock with and without fire as projected under the PCM-A2 and HadCM3-A2 climate change scenarios.

Growing stock generally increased in both regions and for both climate scenarios (see Figure 3.4), but more slowly for the HadCM3-A2 climate scenario than for the PCM-A2 scenario. When fire was included in the model simulations, growing stock increased more slowly than in the scenarios without fire. The difference in growing stock development between the simulations with and without fire was more pronounced in Provence-Alpes-Côte d'Azur than in

Languedoc-Roussillon, for both climate scenarios. In Languedoc-Roussillon, the growing stock increased under the PCM-A2 scenario from 117 m^3 ha^{-1} in 1995 to 205 m^3 ha^{-1} in 2060 without fire, and to 193 m^3 ha^{-1} with fire (subfigure 3.4(a)). For the HadCM3-A2 scenario, the respective values were 185 m^3 ha^{-1} without, and 170 m^3 ha^{-1} with fire in 2060 (subfigure 3.4(b)). In Provence-Alpes-Côte d'Azur, the growing stock increased in from 101 m^3 ha^{-1} in 1995 to 158 m^3 ha^{-1} without fire and to 144 m^3 ha^{-1} with fire for the PCM-A2 scenario (subfigure 3.4(c)), and to 141 m^3 ha^{-1} without fire and 123 m^3 ha^{-1} with fire for the HadCM3-A2 scenario (subfigure 3.4(d)). In the fire scenario, growing stock decreased temporarily in the 2020s, because the volume that was either felled or burnt in this period clearly exceeded the increment (see Figure 3.3(d)). The decrease was more prolonged for the HadCM3-A2 scenario than for the PCM-A2 scenario.

Figure 3.5 presents the annual burnt volume for the two climate scenarios in Languedoc-Roussillon and Provence-Alpes-Côte d'Azur, together with the corresponding summer rainfall (May to September). Burnt volume mirrors the fluctuations in summer precipitation observable in both the PCM-A2 and HadCM3-A2 climate scenarios – low summer precipitation triggered a relatively high burnt volume, and vice versa. For the first seven years (1996–2002), data on burnt area were available, therefore the observed values were used instead of calculating the burnt area with the help of the regression model. The PCM-A2 climate scenario exceeded the HadCM3-A2 scenario in terms of summer precipitation. Accordingly, burnt area was generally lower for PCM-A2 climate conditions. Because the growing stock increased over the years in both regions (see Figure 3.4), the relative volume burnt per hectare increased steadily when compared to the proportion of the forest area that was subject to fire. The average burnt volume between 1996 and 2060 was almost the same in both regions: 0.19 m^3 ha^{-1} yr^{-1} under the PCM-A2 scenario in both Languedoc-Roussillon and Provence-Alpes-Côte d'Azur. For the HadCM3-A2 scenario, the respective values were 0.23 m^3 ha^{-1} yr^{-1} in Languedoc-Roussillon, and 0.24 m^3 ha^{-1} yr^{-1} in Provence-Alpes-Côte d'Azur. But the range (difference between minimum and maximum value of burnt volume throughout the years) was about 60% higher in Provence-Alpes-Côte d'Azur.

Table 3.2 presents the proportion of the average annual increment that was burnt for the two climate scenarios in Languedoc-Roussillon and Provence-Alpes-Côte d'Azur. Relative to the increment, more volume was burnt in Provence-Alpes-Côte d'Azur than in Languedoc-Roussillon. In both regions, the proportion of the increment burnt was higher for the HadCM3-A2 climate scenario than for the PCM-A2 scenario, as the increase in summer drought projected by the HadCM3-A2 scenario had adverse effects on tree growth and favoured the occurrence of fire.



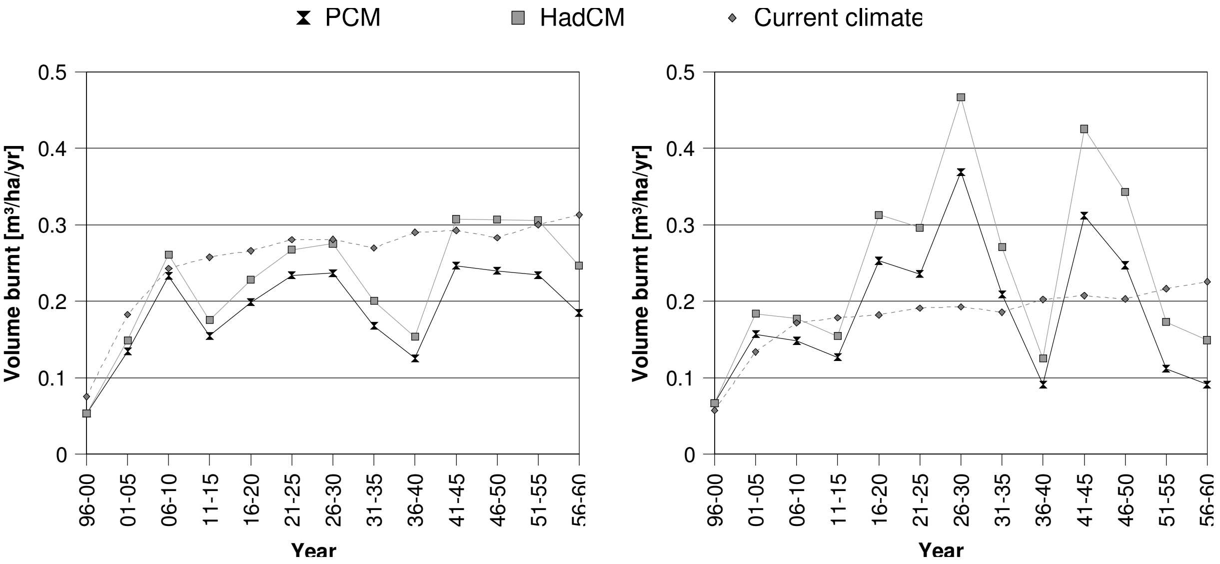
(a) Languedoc-Roussillon

(b) Provence-Alpes-Côte d'Azur

Figure 3.5.: Development of the burnt volume in the climate change scenarios.

Table 3.2.: Proportion of average annual increment burnt (%) in Languedoc-Roussillon and Provence-Alpes-Côte d'Azur for the climate scenarios PCM-A2 and HadCM3-A2.

	Languedoc-Roussillon		Pr.-Alpes-Côte d'Azur	
Period	PCM-A2	HadCM3-A2	PCM-A2	HadCM3-A2
1996–2000	1.2	1.2	2.0	2.0
2001–2005	2.9	3.4	5.4	6.3
2006–2010	5.7	6.8	5.0	6.9
2011–2015	3.9	4.6	5.0	6.1
2016–2020	5.0	6.3	10.4	15.2
2021–2025	6.2	7.8	11.0	16.8
2026–2030	5.6	7.3	18.0	25.0
2031–2035	3.9	5.2	8.9	13.7
2036–2040	2.8	3.9	3.6	5.6
2041–2045	6.0	8.7	12.3	22.1
2046–2050	6.3	9.9	9.5	17.2
2051–2055	6.6	10.7	4.5	8.6
2056–2060	5.3	8.5	3.4	7.5



(a) Languedoc-Roussillon

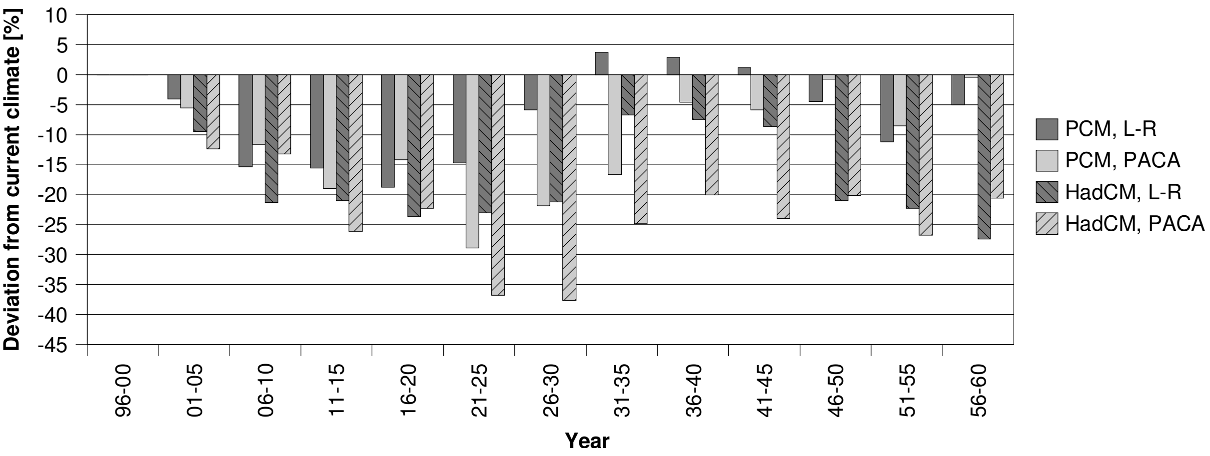
(b) Provence-Alpes-Côte d’Azur

Figure 3.6.: Comparison of the burnt volume between the current climate approach and the two climate scenarios, PCM-A2 and HadCM3-A2, in Languedoc-Roussillon and Provence-Alpes-Côte d’Azur.

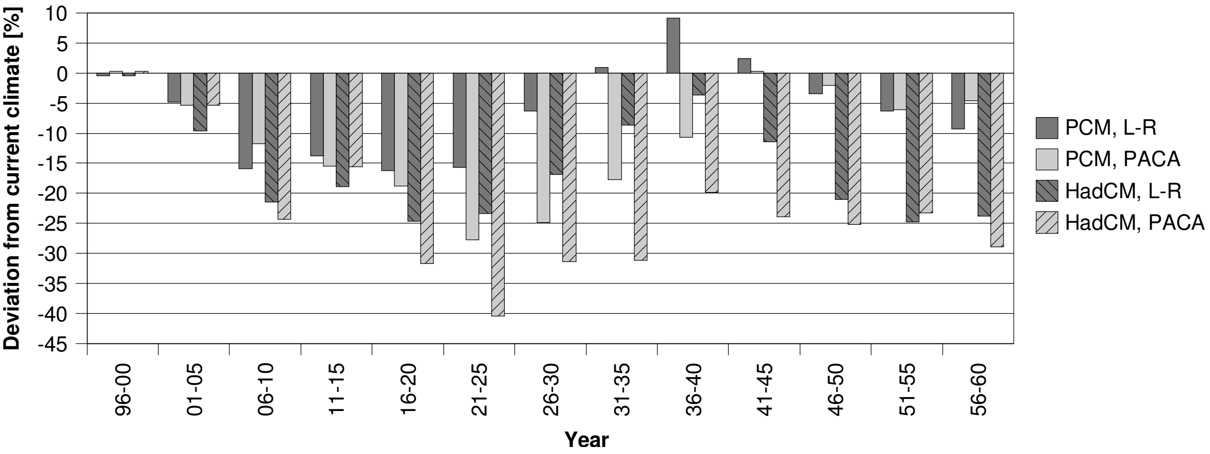
3.3. Comparison of the current climate and the climate change runs

Figure 3.6 compares the burnt volume of the current climate approach with the results of the climate change model simulations, for Languedoc-Roussillon and Provence-Alpes-Côte d’Azur. In the current climate approach, less volume was burnt on average in Provence-Alpes-Côte d’Azur (0.26 m^3 ha^{-1} yr^{-1}) than in Languedoc-Roussillon (0.18 m^3 ha^{-1} yr^{-1}). But for the climate change model runs, the situation was different: almost the same volume was burnt on average in Provence-Alpes-Côte d’Azur (0.19 m^3 ha^{-1} yr^{-1} for PCM-A2 and 0.24 m^3 ha^{-1} yr^{-1} for HadCM3-A2 climate conditions) and in Languedoc-Roussillon (0.19 m^3 ha^{-1} yr^{-1} for the PCM-A2 scenario and 0.23 m^3 ha^{-1} yr^{-1} for HadCM3-A2). Burnt volume for both climate scenarios remained below the current climate modelling results in Languedoc-Roussillon, but not so in Provence-Alpes-Côte d’Azur. This difference is due to the fact that there were several rather dry years in Languedoc-Roussillon with nonetheless little fire occurrence, which exerted a stronger influence on the regression function than in Provence-Alpes-Côte d’Azur, where relatively dry years usually correlated to bad fire years (compare Section 2.7.1).

Figure 3.7 presents the deviation of the increment, Figure 3.8 the deviation of the growing stock, under HadCM3-A2 and PCM-A2 climate conditions, from the results of the current climate model run. The situation without the fire module is shown in subfigures 3.7(a) and 3.8(a), the results of the model run with fire are presented in subfigures 3.7(b) and 3.8(b). The deviation is



(a) Without fire

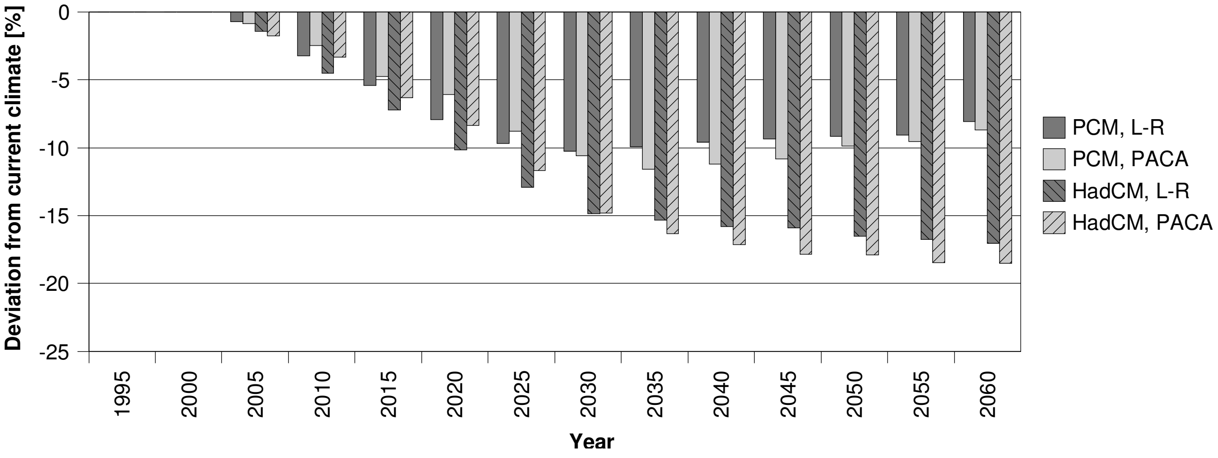


(b) Without fire

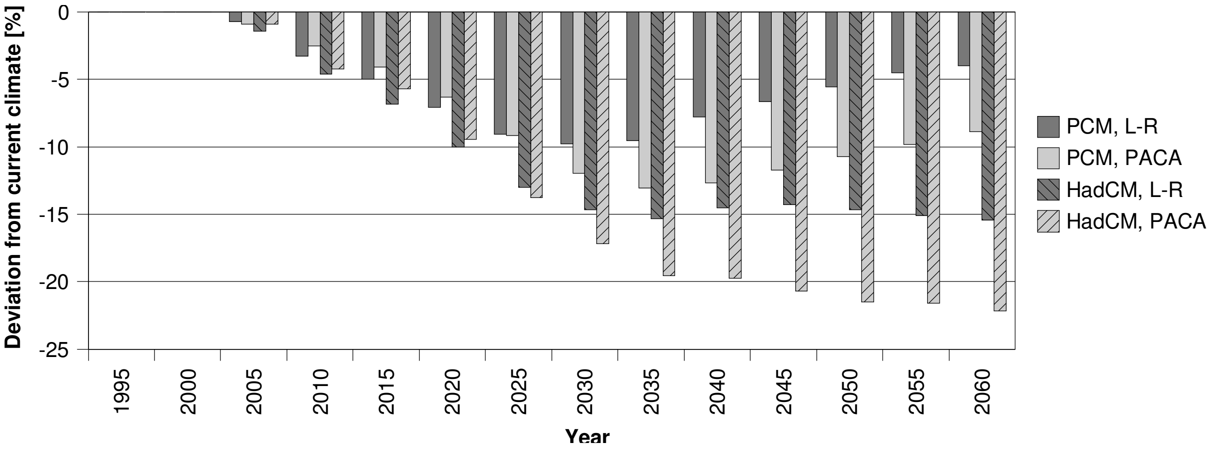
Figure 3.7.: Deviation of the increment under climate scenarios HadCM3-A2 and PCM-A2 from current climate conditions, for Languedoc-Roussillon (L-R) and Provence-Alpes-Côte d'Azur (PACA), without (a) and with (b) the fire module.

given in percent. Negative numbers mean a decrease, positive numbers an increase in increment or growing stock compared to the current climate situation.

Variations in increment under the PCM-A2 and HadCM3-A2 climate scenarios followed the pattern of the predefined ratios, which were used to modify the future increment under climate change conditions (see Table 2.17 on page 40). With a few exceptions, increment was lower under the climate conditions of the PCM-A2 and the HadCM3-A2 scenarios than in the current climate approach. Only in Languedoc-Roussillon under the PCM-A2 scenario, increment was slightly higher between 2031 and 2045, compared to current climate. Deviations in increment varied between the simulation results with and without fire, due to changes in the age class distribution caused by fires. Deviations were highest in Provence-Alpes-Côte d'Azur for the



(a) Without fire



(b) With fire

Figure 3.8.: Deviation of the growing stock under climate scenarios HadCM3-A2 and PCM-A2 from current climate conditions, for Languedoc-Roussillon (L-R) and Provence-Alpes-Côte d'Azur (PACA), without (a) and with (b) the fire module.

HadCM3-A2 scenario, reaching slightly more than -40% between 2021 and 2025 in the fire run.

Growing stock was lower under both climate scenarios compared to the current climate results, both with and without fire (Figure 3.8). The slightly higher increment for the PCM-A2 climate scenario in the 2030s, compared to current climate, was not enough to compensate the lower increment in the previous years. In general, the deviation was lower for the PCM-A2 scenario, which was closer to current climate compared to the HadCM3-A2 scenario. In Languedoc-Roussillon, the deviation of the growing stock under both climate scenarios from the growing stock in the current climate simulation was more pronounced in the scenario without fire, but the opposite was true for Provence-Alpes-Côte d'Azur. In the model simulations without fire, deviation of the growing stock from the current climate results differed only slightly between the two regions, both for the PCM-A2 and the HadCM3-A2 scenario. When fire was included, the difference was much more pronounced. This fact can be attributed to the difference in burnt volume between both regions: in Provence-Alpes-Côte d'Azur, more volume was burnt when the regression function was used to model fire occurrences under climate change scenarios, compared to the current climate modelling approach, but the opposite was true for Languedoc-Roussillon (see Figure 3.6).

The age class distribution shifted towards older forests under all scenarios in both Languedoc-Roussillon and Provence-Alpes-Côte d'Azur (see Table 3.3). This development was most pronounced for the current climate scenario when fire was excluded, and smallest under the HadCM3-A2 scenario with fire. In the fire scenarios, the area covered by forests older than 60 years was 4–7% smaller compared to the corresponding runs without fire. In Languedoc-Roussillon, where in the initial situation young forests (< 60 years) dominated (approx. 75% of the forest area), the relative shift towards older forests was stronger than in Provence-Alpes-Côte d'Azur. However, as there were more older forests in Provence-Alpes-Côte d'Azur from the beginning (approx. 40% of the forest area), the proportion of forests older than 60 years was projected to be greater in Provence-Alpes-Côte d'Azur than in Languedoc-Roussillon in all scenarios.

Table 3.3.: Proportion of forests older than 60 years in 1995 (initial situation) and 2060, projections for the current climate and climate change scenarios.

		Languedoc-Roussillon		Pr.-Alpes-Côte d'Azur	
Year	Scenario	Area (1000 ha)	Percent (%)[1]	Area (1000 ha)	Percent (%)[1]
1995	Initial situation	202	25.3	461	39.6
2060	Current climate, without fire	354	44.4	570	49.1
2060	Current climate, with fire	298	37.4	498	42.9
2060	PCM-A2, without fire	330	41.3	548	47.2
2060	PCM-A2, with fire	300	37.6	485	41.8
2060	HadCM3-A2, without fire	329	41.3	552	47.5
2060	HadCM3-A2, with fire	294	36.9	468	40.3

[1] Percent of total forest area

4. Discussion and Conclusions

4.1. Simulations based on current climate

For the current climate model runs, a statistical distribution, which was fitted to observed fire damages, was used to extrapolate the burnt forest area into the future. In doing so, it was assumed that the extent of forest does not change significantly during the modelling period, compared to the characteristics of the past three decades. There was hardly any inter-annual variation in the burnt area projected by EFISCEN, because the average of 300 Monte-Carlo simulations is used. For the same reason, the annual burnt area in each of the 5-year time steps in the model simulation approximated the average burnt area over the period 1973–2002.

The results of the current climate model runs indicate that fire has considerable effects on the development of forest resources in the French Mediterranean area. The average growing stock increases more slowly when fire is included in the model simulations, because of the higher timber losses due to forest fires. Burnt volume increased over time, due to the increase in growing stock. The increase in drain (fellings plus burnt volume) in the fire scenario caused a shift towards younger forests. The impact of fires on annual increment, caused by changes in the age class distribution, was only minor. In both scenarios, with and without fire, the increment declined over time due to the ageing of the forests and the increase in average growing stock. Annual increment was high enough to compensate for additional timber losses due to forest fires, so that harvest demands could be complied with until 2045. But from 2046 onwards, EFISCEN could not locate enough forest stands suitable for thinnings or final fellings in the fire scenario, and harvests were therefore lower than in the scenario without fire. This trend seemed to increase towards the end of the simulation period. However, these findings should be regarded with care. The EFISCEN model is designed to work on a large-scale basis, and the definition of the management regime is not explicitly adapted to the conditions in the Mediterranean area. In Corsica, felling levels are very high during the first three time steps in the current climate model run, because Corsican forests are on average much older than forests in Languedoc-Roussillon and Provence-Alpes-Côte d'Azur. Therefore EFISCEN selected much of the forest in Corsica for final felling in the beginning of the simulation period, which may not be very realistic. This might indicate that the management regime defined for French forests in EFISCEN, i.e.

the constraints determining at what age and volume thinnings or clearcuts may be carried out, does not apply to Corsican forests very well. To prevent this behaviour, it would be necessary to refine the management regime on a regional level, which would require more detailed data regarding forest management practises.

4.2. Simulations based on climate change

4.2.1. Impact of a changing climate on forest growth

In the climate change model runs, the impact of a changing climate on tree growth was modelled with the help of a linear regression function, taking into account the effects of temperature and summer drought on the annual increment. The available projections for the rainfall regime in southern Europe are uncertain, but many of them agree on the accentuation of seasonality in rainfall (de Luís et al. 2001; Loustau et al. 2000; McCarthy et al. 2001). This could increase water deficits during summer and thus cause a decline in tree growth. In general, summer drought was projected to increase according to both climate scenarios used in this study, PCM-A2 and HadCM3-A2, due to higher temperatures and/or a decline in summer precipitation. Therefore, annual increment was considerably lower under climate change conditions than the projected increment in the current climate model runs, especially under the HadCM3-A2 scenario. The increase in growing stock was consequently slower under both climate scenarios than under current climate conditions. This development caused a decline in felling levels, especially when fire was included. These findings go along with statements in the Third Assessment Report of the Intergovernmental Panel on Climate Change (McCarthy et al. 2001), which notes that an increased frequency of hot, dry summers is likely to reduce tree growth and affect timber yield and quality, as well as increasing the risk for wildfires. Forestry activities in the Mediterranean area may hence become even less profitable than they are nowadays if summer drought increases.

It should be noted that the regression function used in this study neglects the influence of other factors besides temperature and drought. Although the impact of precipitation change is possibly crucial in determining tree growth in Southern France and the Mediterranean area in general, factors like stand age, soil properties, forest management, changing nitrogen and carbon dioxide levels, and past land use play an important role as well (Karjalainen et al. 1999; Loustau et al. 2000; Rathgeber et al. 2003; Sabaté et al. 2002). For example, the reduction or abandonment of former forest practises like grazing, litter raking, burning and resin tapping are, among others, believed to have caused an acceleration of height growth of Aleppo pine forests in south-eastern France (Vennetier and Herve 1999). The effects of CO_2 increase may interact with precipitation changes. It has been demonstrated that water use efficiency and drought resistance of

Quercus ilex are enhanced in naturally CO_2 enriched areas, compared to neighbouring control plots (Loustau et al. 2000).

Sabaté et al. (2002) applied a process-based forest growth model (Growth Of Trees Is Limited by WAter in the Mediterranean, GOTILWA+) to simulate the effects of climate change on growth of various tree species in the Mediterranean region. The climate scenario they used projected an increase in temperature and rainfall, in addition to the increase of atmospheric CO_2 concentration. Intra-annual rainfall distribution did not change significantly according to the climate scenarios. Sabaté et al. (2002) found that increasing CO_2 concentration and rainfall promoted higher production. On the other hand, the results indicated that temperature and rainfall possibly restrict growth during certain periods. A seasonal change in rainfall distribution may have adverse effects on growth, and even higher annual rainfall amounts do not necessarily result in better water availability during summer.

Rathgeber et al. (2003) used a mechanistic bio-geochemistry model (BIOME3) to simulate forests productivity responses to climatic change and CO_2 increase for *Pinus halepensis* in Provence. They found a moderate increase (20%) in productivity when only climate change effects were considered, a large increase (85%) when only the atmospheric CO_2 increase was considered and a very large increase (125%) when both factors were combined. But in contrast to the current study, the climate scenario used by Rathgeber et al. (2003) projected an increase in summer, autumn and winter precipitation, while precipitation in spring remained unchanged. Comparing their results with other studies, Rathgeber et al. concluded that the projected growth enhancement for *Pinus halepensis* might be overestimated. Higher productivity due to an increase in CO_2 may be constrained by other limiting factors, such as nitrogen.

According to the climate scenarios used in the current study, summer drought is expected to be more pronounced than suggested by the climate scenarios used by Sabaté et al. (2002) and Rathgeber et al. (2003). Therefore the application of the regression function, taking into account the impact of temperature and summer drought on tree growth, in general resulted in a decrease in the expected increment. However, the approach used in the current study seems to be more sensitive to drought compared to model results of other studies (Lapveteläinen et al., unpublished). The decreases in increment in the climate change runs might therefore be overestimated in the current study. Furthermore, the climate data and scenarios are regional averages, presenting a combination of various sub-climates, e.g. of coastal, hilly and mountainous areas. The tree species distribution within the administrative regions is – among other factors like elevation or soil characteristics – determined by spatial variations in climate. Therefore, the effects of heatsum and summer drought on tree growth may be over- or underestimated for some species. At a local scale, climate changes and their impact on growth show high heterogeneity (de Luís et al. 2001). Keller et al. (2000), in Rathgeber et al. (2003), found a response of forest productivity to climate change ranging between -50 and +50% for 24 stands in south-east France, depending on species and the location of the site. Additionally, temperature and precipitation change patterns may differ between coastal and mountainous areas, which cannot be expressed by regional averages.

4.2.2. Relationship between climate and fire

Climate and local weather conditions determine the fire regime at two levels: i) by controlling primary productivity and thus the amount of combustible fuel, and ii) by controlling variables like the moisture content of the fuel, relative humidity and wind speed, which in turn determine fire spread. Weather as ignition source (lightning) is not very important in the Mediterranean area where most fires are human-induced (Alexandrian et al. 1999). In the current study it was assumed that climate will remain a driving force in determining the extent fire occurrence, and that the relationship between summer precipitation and burnt area can be used to estimate the fire damage under climate change scenarios. A significant relationship could be established between the amount of summer precipitation and the burnt area in Languedoc-Roussillon and Provence-Alpes-Côte d'Azur. These findings are in line with those of Viegas and Viegas (1994), who found a similar relationship for Portugal. The relationship between burnt area and other climate variables like temperature, actual and potential evaporation, and combinations of these, was also analysed in the current study, but the highest correlation was found between summer precipitation and burnt area. The impact of climate on primary productivity was neglected as no relationship could be found with the available data.

In the climate change model runs, burnt area and burnt volume vary considerably over time, due to inter-annual variations in summer precipitation, projected by both climate scenarios. Relative to the burnt area, burnt volume is increasing over the years, due to the increase in growing stock.

In Languedoc-Roussillon, the fitted regression between summer rainfall and burnt area seems to underestimate fire damages. Burnt area and volume under both climate scenarios are lower than the corresponding results for the current climate scenario, although one of the climate scenarios (HadCM3-A2) suggests a decrease in summer precipitation. This can be attributed to the fact that only small burnt areas were reported in several years with nevertheless relative little summer precipitation. Though significant, the correlation between burnt area and summer precipitation was not very high ($r = -0.51$). Only 26% ($R^2 = 0.26$) of the variation in the data on burnt area could be explained by the regression model, indicating that other factors besides summer precipitation amount have a vital role in determining the extent of fire damages in Languedoc-Roussillon. These findings demonstrate that the applied approach, i.e. using a regression function to estimate future fire damages, should only be applied if a close correlation between past burnt area and climate variables can be established, a correlation that accounts for the majority of the variation in the observed fire data. The regression function for Provence-Alpes-Côte d'Azur seemed to describe the observed trend in the data on burnt area much better, as the correlation between summer rainfall and burnt area was also higher than in Languedoc-Roussillon. In Provence-Alpes-Côte d'Azur, 61% of the variation in the observed data on burnt area could be explained by the regression function. Burnt area and burnt volume were higher under the PCM-A2 and the HadCM3-A2 scenarios compared to the current climate situation. These findings suggest that a decrease in summer precipitation could cause higher fire damages. This conclusion is supported by several other studies that addressed the relationship between a changing climate and forest fire occurrences. McCarthy et al. (2001) state that elevated summer temperatures and a decrease in summer precipitation may result in an increase in fire risk in the Mediterranean region. Piñol et al. (1998) found a significant relationship between both the number of wildfires and area burnt, and two fire hazard indices for a climatic series from 1941 to 1994 in coastal eastern Spain. During this period, mean daily maximum temperature increased and minimum daily relative humidity decreased, while the number of wildfires and the burnt area increased from 1968 to 1994 in that region. Flannigan et al. (2000) indicated that climate changes could result in "dramatic changes in the fire regime" in the United States of America.

Vázquez and Moreno (1995) supposed that the relationship between meteorological variables and fire size inequalities should be stronger in cooler and wetter areas than in warmer and drier areas where the probability of extreme events may be larger and mean weather values may be less meaningful. Hence for areas with extremely hot and/or dry weather conditions, fire patterns may be more difficult to predict than for milder areas. This might be one of the reasons why no significant correlation between any meteorological variables and burnt forest area could be found for Corsica, as it is the hottest and driest of the three French Mediterranean regions.

Using a regression function to estimate future fire damages depending on the amount of summer rainfall is quite simplistic. Besides precipitation amounts, other weather related variables are also important in determining whether a fire spreads or not. Dry and hot winds, water content in litter and soil, relative humidity and other factors also play an important role. Furthermore, it is not only crucial how much rainfall there is in the fire season, but also how it is distributed over that period. Most of the wildfire impact occurs during extreme dry periods, rather than from effectively drier average climate (Piñol et al. 1998). However, the use of a more detailed meteorological fire risk index was not feasible within the scope of this study, due to the large scale and broad temporal resolution of the applied approach.

Fire incidence depends not only on weather conditions, but also on ignition sources. Especially in the Mediterranean, where almost all fires are human induced, fire incidence may be strongly influenced by changes in the patterns of human activities, both in preventing or causing fire. Rising temperatures and altered precipitation patterns might not only change the duration of the fire season and fire hazard, but may also result in modified land and recreational use. Badia et al. (2002) argue that other causes besides climate change have an important impact on fire incidence. These are i) the decline in agricultural activities, resulting in the growth of forest on abandoned agricultural land, ii) the use of fossil fuels instead of biomass for domestic and certain industrial activities, and iii) the increasing recreational use of forest and conservation policies that constrain traditional management activities. The possible interactions of these changes are almost impossible to predict. Extrapolation from present fire patterns to future scenarios may hence not be very realistic if only weather as the main driver of fire occurrence is taken into account (Vázquez and Moreno 1995).

From 1991 to 2002, the annual area burnt by forest fires was relatively low, as most of the fires were extinguished before they could cause much damage. More effective fire protection measures and thus reduced fire occurrences led to a steady increase in combustible plant biomass in the French Mediterranean forests, thereby increasing the fire risk (Ministry of Agriculture and Fisheries - Countryside and Forestry Department and Inventaire Forestier National 2000). Although the applied policy of rapid initial attack is very effective, it does not seem to be adapted to large fires (Turlan 1991, in Teusan 1995). The fire events of 2003 showed that catastrophic fire years are still very much within the realm of possibility. Fire management policies and effectiveness will continue to change in the future. Other human activities such as the conversion of formerly agricultural land to forest, or the conversion of forest lands to urban areas, along with the fragmentation of the landscape will influence the fire regime (Flannigan et al. 2000). In order to minimise the risk for large fires, much emphasis should be on fire prevention methods. Practically all species burn under the conditions imposed on them in the hot and dry Mediterranean summer (Vélez 2002). Therefore, in addition to replacing easily inflammable species with less inflammable ones, another important aspect is to create discontinuities in forest cover (fuel breaks, patchwork of different inflammability levels etc.). Prescribed burning is gaining more importance, too. It was introduced in 1989 (Teusan 1995) in the Mediterranean part of France, and is well established now (Botelho et al. 2000).

4.2.3. Effects of climate change on natural disturbances in EFISCEN

The natural disturbances module of EFISCEN has already been applied for Switzerland (Schelhaas et al. 2002) and Germany (Dolstra 2002). In both studies, wind, insect and fire disturbances were modelled. But the emphasis was on wind and insects, as fire only plays a minor role in both countries. In contrast to fire, the sensitivity of forest stands to wind and insect disturbances increases with age, due to e.g. a higher risk of diseases, higher wind pressure because of increased heights, and the decreasing elasticity of trees.

In the Switzerland study, the effects of climate change on disturbances were simulated differently than in this study: The distributions of the fire and wind regime were derived from periods with higher disturbance damage. The effects of elevated $CO_2$and temperature on tree growth, together with an projected increase in annual precipitation by 5–15%, were simulated with a process-based forest simulation model, TREEDYN3 (Bossel 1996), which projected a gradual increase in volume increment for a stand of Norway spruce in Switzerland and a beech stand in Austria.

In the study for Germany (Dolstra 2002), storm disturbances in the climate change scenarios were handled in a similar way as in the Switzerland study, by selecting a period of high damages as the basis for a new frequency distribution. Fire regime in the climate change scenario is adjusted based on a scenario study by Gerstengarbe et al. (1999). This study projects an 18% increase in the number of fires in the federal state of Brandenburg, Germany, by 2050, with an assumed temperature increase of 1.5°C and a connected decrease in annual precipitation sum by 50–100 mm. Dolstra (2002) assumed that the annually burnt area will also increase by 18%. The randomly drawn number was increased by 2% in each simulation period, so that in the last period the total increase summed up to 18%.

For both, the studies for Switzerland and Germany, the results indicated a lower increase in growing stock than projected without the natural disturbances module. The simulation results also showed an increase in damage volumes in the future, caused by an increase in growing stock and a higher share of older and thus more vulnerable stands. Under climate change conditions, these effects were reported to be even greater because of the higher growth rates and a higher disturbance frequency. In the present study, an increase in fire damage volume, caused by an increase in growing stock, has also been found. But the growth rates in the climate change scenarios in both the Switzerland and Germany study were predicted to increase, due to the positive effects of elevated CO_2 levels in the atmosphere and an extended growing season. In contrast to this, increment is projected to decrease in southern France, due to the increasingly growth-inhibiting impact of summer drought. The advantage of using a regression function between burnt area and climate variables to model future fire damages lies in the explicit link between fire damages and climate established by this approach. However, this method can only be applied if consistent and long-term time series regarding fire occurrences and climate are available, and if a close relationship between burnt area and climate variables can be established.

4.3. Assumptions and uncertainties

It is inherent to scenario modelling, especially for long-term projections, that the models used are based on assumptions. Models represent complex processes in a simplified, abstract way, which introduces varying degrees of uncertainties into the results. Therefore the results of this study should not be considered as predictions of what is going to happen, but only as an indication of what might happen under the given assumptions. Kangas (1997, 1998) identified four main sources of errors in long-term projections. These are i) uncertainties due to the stochastic character of the estimated model coefficients, ii) bias caused by measurement and sampling errors in the data used for model construction, iii) lack of goodness-of-fit of the utilised model, and iv) assumptions in the model. Some uncertainties regarding the applied approach of modelling the impact of climate change on forest fires and on forest growth have already been discussed in the previous sections. Other assumptions and limitations are outlined in the following paragraphs.

In both the current climate and the climate change runs, forest management was kept constant throughout the modelling period. However, in reality, forest management may change. It is uncertain how felling levels will develop in the future. Continuously rising labour costs and rural depopulation could cause a further decrease in management activities. Parts of the forest area might be set aside for nature reserves. Rotation length, fertilisation, thinning regimes and other forest practises may be affected by the potential large changes in forest growth (Loustau et al. 2000).

It was assumed that the state of the forest did not change over the time from which the frequency distribution was derived. But in reality the forest area in France is increasing, like in most European countries (Ministry of Agriculture and Fisheries - Countryside and Forestry Department and Inventaire Forestier National 2000). Mediterranean forests have expanded at a rate of 1.2% per year from 1989 to 1999. Standing volume is reported to be increasing as well. Neglecting this development probably does not bias the results very much, as forest fires are not so much dependent on the absolute standing volume, but more on the horizontal and vertical distribution of that volume. Furthermore, the burnt forest area had to be estimated from the area burnt on forest and other wooded land, based on the ratio of only two years. The bias introduced by neglecting the expansion of the forests in the past is probably minor compared to the relatively rough estimates from which the frequency distribution had to be derived.

Some fire regime information (e.g. forest types burnt, fire intensity and severity) was necessary for building the susceptibility matrix and to define the ratio between stand-replacing and non-stand-replacing fires. The available data on forest fires in the French Mediterranean area did neither include information on which forest types burnt, nor on the intensity of the fire. Detailed information on fire damages, in terms of burnt volume, was also missing. Therefore, the translation of the fire regime into the susceptibility matrix had to be done based on literature review and estimates, involving many assumptions and uncertainties. This methodological aspect deserves more attention in future studies. In particular, it might be worthwhile to conduct a sensitivity analysis to assess the impact of a changed susceptibility matrix and/or a changed ratio between stand-replacing and non-stand-replacing fires on the simulation results.

In the fire data, errors may be caused by incorrect or incoherent sampling, and by the disaggregation of the data in fires on forests and fires on other wooded land. Furthermore, the fire statistics are probably more accurate now than they were in the 1970s. In the inventory data used as input for the EFISCEN model, bias can be caused by the way the national inventory is carried out in France: the data originate from a period of about 10 years in which the whole country is surveyed.

Spatial neighbourhood relations of forest stands to other forest stands or other fire-prone ecosystems determine the propagation of forest fires and cannot be modelled with the statistical approach used in this study. Human behaviour is another important factor that cannot be modelled directly. Humans are the main fire ignition source in the Mediterranean area (Alexandrian et al. (1999)). The awareness of humans, either tourists or people living in fire-prone areas, may change over the years.

4.4. Conclusions and outlook

This study has demonstrated an effective method to include fire disturbances in large-scale model projections of forest resources, rendered by EFISCEN. Fire is a major agent of natural disturbances, especially in the Mediterranean countries, and in other regions where climate and vegetation favour fire ignition and spread. The simulation results suggest that forest fires have a significant impact on the development of forest resources in the Mediterranean region of France. For the given assumptions, under current climate conditions the burnt volume can be expected to increase substantially due to an increase in average growing stock. The burnt volume may increase even further if summer rainfall decreases in the future. Drier summers would probably also have adverse effects on tree growth, causing a decline in increment. Thus, average standing volume and potential harvest levels would remain clearly below those projected under current climate conditions.

A significant relationship has been found in this study between the amount of summer precipitation and burnt area. By implementing this relationship into the natural disturbances module, the effects of climate change on the fire regime could be explicitly taken into account. The results indicate that this method should only be applied if a close relationship between climate variables and burnt area can be established.

Although there is considerable uncertainty about how climate change will effect tree growth, the method for adapting the increment applied in this study possibly overestimates the adverse impact of summer drought. An alternative for future studies would be to use the outcome of process-based tree growth models.

It can be concluded that fire disturbances can be handled satisfactorily within EFISCEN. But the results should be regarded with care, as they are based on many assumptions and could not be validated in this study, as no independent fire data sets were available. The set-up of the susceptibility matrix deserves more attention in the future. In particular, the impact of changes in the susceptibility matrix on the model results should be analysed in detail. A clear distinction between forest and other wooded land in the fire data, as well as more detailed information on the forest types that actually burn, would help to make future simulation more credible.

This study may be used as a reference for further analysis that involve EFISCEN and the natural disturbances module with regard to forest fires. Drought may become a limiting factor for forest growth and trigger more fires in other regions of France, too. Using the fire data of the 1990s, it would be possible to model the whole of France in more detail in a future study. For the Mediterranean countries, detailed fire data are often available. Information on fire and other disturbances have already been compiled for many European countries in the database on natural disturbances (Schelhaas et al. 2001). The Global Fire Monitoring Center also provides information on regional and national forest fire databases (Global Fire Monitoring Center 2003).

5. Zusammenfassung

In der vorliegenden Arbeit wurden die Auswirkungen von Feuer auf die Entwicklung von Forstressourcen unter heutigen und veränderten Klimabedingungen mit Hilfe eines großräumigen Waldwachstumsmodell (European Forest Scenario Model, EFISCEN) untersucht. Dabei sollte einerseits die Implementierung von Feuer in EFISCEN getestet, sowie der Einfluss von Feuer auf die Entwicklung der Forstressourcen im Untersuchungsgebiet, dem mediterranen Raum von Frankreich, abgeschätzt werden. Außerdem wurde untersucht, wie man den Einfluss von Klimaänderungen auf das Feuerregime in die Simulationen einbeziehen kann.

EFISCEN ist ein statistisches, räumlich nicht explizites Matrixmodell, welches für die Waldwachstumsmodellierung auf nationaler und regionaler Ebene angewendet wird und in Zeitschritten von fünf Jahren operiert. Die Waldfläche pro Waldtyp ist in EFISCEN auf Volumen-Alters-Matrizen verteilt. Holzzuwachs pro Altersklasse und Baumart beruht auf empirischen Wachstumsfunktionen, die aus nationalen Forstinventuren abgeleitet wurden. Um natürliche Störungen in die Simulationen einzubeziehen, wurde in einer früheren Studie ein Modul für EFISCEN entwickelt, welches sich mit natürlichen Störungen befasst. In der vorliegenden Arbeit wurde dieses Modul angepasst und parametrisiert, um Feuerstörungen in die Projektionen der Waldentwicklung im mediterranen Raum Frankreichs einbeziehen zu können.

Das Feuermodul besteht aus zwei Komponenten: i) einer statistischen Verteilung, die auf beobachteten Daten bezüglich der verbrannten Waldfläche in den letzten drei Jahrzehnten beruht, und ii) einer Empfindlichkeitsmatrix, welche definiert wie feueranfällig die einzelnen Baumarten und Altersklassen sind. Die Parametrisierung der Empfindlichkeitsmatrix beruht auf Angaben in der Literatur, da hierfür keine detaillierten Daten verfügbar waren.

Es wurden zwei Arten von Feuer unterschieden: intensive (Kronen-)Feuer, die in der Regel den ganzen Bestand zerstören, und weniger intensive (Boden-)Feuer, die nur einzelne Bäume schädigen. Nadelbäume wurden generell als feueranfälliger eingestuft als Laubbäume. Außerdem wurde eine mit dem Alter abnehmende Feuerempfindlichkeit definiert.

Es wurden zwei verschiedene Methoden für die Modellierung von Feuer innerhalb von EFISCEN getestet – eine für Szenarien, die auf gegenwärtigem Klima basieren und eine für Klimaänderungs-Szenarien. Für die Modellläufe mit gegenwärtigem Klima wurde die verbrannte Waldfläche mit Hilfe der statistischen Verteilung in die Zukunft extrapoliert. Für jeden Zeitschritt (fünf Jahre) wurde das Feuerrisiko bestimmt, indem fünf Zahlen aus der Verteilung gezogen und durch den Erwartungswert der Verteilung dividiert wurden. Die resultierende zu verbrennende Fläche wurde dann mit Hilfe der Empfindlichkeitsmatrix über die gesamte Waldfläche verteilt.

Um den Einfluss eines sich ändernden Klimas auf das Feuergeschehen explizit modellieren zu können, wurde der Zusammenhang zwischen Klimavariablen und der jährlich verbrannten Waldfläche untersucht. Es wurde ein signifikanter Zusammenhang zwischen der Sommerniederschlagsmenge und der Größe der verbrannten Waldfläche gefunden, der durch eine exponenzielle Funktion beschrieben werden konnte. Daraus wurde ein Regressionsmodell abgeleitet, mit dem auf der Grundlage der von zwei Klimaszenarien projizierten zukünftigen Niederschlagsverteilung die verbrannte Waldfläche geschätzt wurde. Die Auswirkungen eines veränderten Klimas auf das Baumwachstum wurden mit einer linearen Regressionsgleichung umgesetzt, die den Einfluss sommerlicher Dürreperioden und der Temperatur berücksichtigt.

Die Entwicklung der Forstressourcen in der französischen Mittelmeergegend wurde unter einem Szenario mit heutigem Klima und zwei Klimaänderungsszenarien bis 2060 projiziert, jeweils mit und ohne das Feuermodul. In den Modellläufen mit dem Feuermodul steigt das Bestandesvolumen langsamer an und der potenzielle Holzeinschlag fällt geringer aus als in den Modellläufen ohne Feuer, während es kaum Unterschiede im Zuwachs gibt. Das verbrannte Volumen nimmt im Laufe der Zeit aufgrund des zunehmenden Bestandesvolumens zu. Die Ergebnisse der Klimaänderungsszenarien lassen vermuten, dass verstärkt auftretende Sommerdürren wachsende Feuerschäden nach sich ziehen würden.

Es kann abschließend festgestellt werden, dass die Implementierung von Feuer in EFISCEN zufriedenstellend gewährleistet werden konnte. Die Ergebnisse sollten jedoch mit Vorsicht interpretiert werden, da sie auf vielen Annahmen beruhen und in dieser Arbeit aufgrund des Fehlens von vergleichbaren Studien nicht validiert werden konnten.

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A. Appendices

Simplified, hypothetical example of the fire module

EFISCEN matrix (ha)

Volume

200	400	500
300	150	50

Age

Susceptibility matrix

Volume

5	4	3
5	4	3

Age

Total area in the matrix:

$X_{total} = 300\,ha + 150\,ha + 50\,ha + 200\,ha + 200\,ha + 500\,ha = 1400\,ha$

Expected value:

$E = 0.01$ (1% of the forest area burns annually, $14\,ha$)

Weighted average of the susceptibilities:

$$W = \frac{0.01 \times (300\,ha + 150\,ha + 50\,ha + 200\,ha + 200\,ha + 500\,ha)}{300\,ha \times 5 + 150\,ha \times 4 + 50\,ha \times 3 + 200\,ha \times 5 + 400 \times 4 + 500 \times 3} = \frac{14}{6350}$$

Area burnt per cell in one year for $A_t = 1$ ($F_{volume,age} = X_{volume,age} \times W \times S_{volume,age}$):

$200\,ha \times \frac{14}{6350} \times 5 = 2.20\,ha$ $\quad$ $400\,ha \times \frac{14}{6350} \times 4 = 3.53\,ha$ $\quad$ $500\,ha \times \frac{14}{6350} \times 3 = 3.31\,ha$

$300\,ha \times \frac{14}{6350} \times 5 = 3.31\,ha$ $\quad$ $150\,ha \times \frac{14}{6350} \times 4 = 1.32\,ha$ $\quad$ $50\,ha \times \frac{14}{6350} \times 3 = 0.33\,ha$

Total area burnt in one year: $\quad$ **In five years:**

$F_{total} = 14\,ha$ $\quad$ $F_{total} = 70\,ha$

Table A.1.: Aggregated Prométhée data for the Mediterranean regions.

Year	Fire on FOWL (ha)			Fire on forest only (ha)		
	L-R	PACA	Corsica	L-R	PACA	Corsica
1973	13418	8245	13980	6281	2952	976
1974	7094	7418	12678	3321	2656	885
1975	5791	4184	5218	2711	1498	364
1976	30228	2190	2799	14150	784	195
1977	1291	892	14055	604	319	982
1978	19580	7375	7671	9166	2641	536
1979	10518	30181	9671	4924	10807	675
1980	3193	5470	6385	1495	1959	446
1981	5406	6171	10289	2531	2210	719
1982	4575	19111	23548	2142	6843	1645
1983	6508	6901	34105	3046	2471	2382
1984	5221	3447	3728	2444	1234	260
1985	14216	9236	22219	6655	3307	1552
1986	13167	24228	8440	6164	8676	589
1987	823	5302	4151	385	1899	290
1988	625	1797	2686	293	643	188
1989	10715	30810	14203	5016	11032	992
1990	3569	36219	12122	1671	12969	847
1991	1063	4482	692	498	1605	48
1992	565	374	11517	264	134	804
1993	1134	2425	7841	531	868	548
1994	2642	2136	17341	1237	765	1211
1995	3148	3281	2577	1474	1175	180
1996	560	759	1462	262	272	102
1997	1605	6664	3467	751	2386	242
1998	2077	3577	4927	970	1155	429
1999	1784	5011	5403	837	1970	284
2000	1343	3108	13120	629	1113	916
2001	3706	6963	6748	1735	2493	471
2002	1266	3083	1483	593	1104	104

Table A.2.: Burnt forest area (ha) in all French regions, 1991–2001.

	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001
Alsace	16.1	14.7	25.1	5.3	5.1	143.6	111.6	18.4	ND	2.5	ND
Aquitaine	491.8	565.3	445.7	326.2	2159.2	513.6	1919.7	674.5	688.1	496.3	490.5
Auvergne	ND	63.3	48.5	1.5	8.8	31.8	110.3	184.9	16.5	27.5	7.8
Basse-Normandie	1.8	3.1	0.5	0	2.6	5.5	13.7	19.9	ND	0	0
Bourgogne	42.2	55.6	6.6	4.3	11.2	255.2	117	13.4	15.7	3.2	0
Bretagne	57.2	46	38.5	28.4	65.8	160.7	116.9	16.4	7.1	22.5	0
Centre	ND	72.6	109.9	10.8	138.3	273.6	232.4	205.8	60.8	35.8	19.8
Champagne-Ardenne	34	41.2	66.4	3.3	3.9	155.8	7.6	39.9	1.4	35.8	0.1
Corsica	ND	ND	ND	ND	ND	ND	ND	428.1	270.9	ND	ND
Franche-Comte	22.5	9.8	24.5	0.2	8.2	44.5	32.3	8.9	7.2	0	0
Haute-Normandie	0.2	0	0.3	1.1	1.1	24	155.9	0.3	794.3	0	1.5
Ile de France	32.8	35.8	6.4	4.4	14	138.9	41	15.8	7.2	0.1	3.8
Languedoc-Roussillon	199.6	ND	ND	ND	ND	ND	ND	853	794.3	ND	ND
Limousin	90.8	96.4	5.6	7	135.9	11.6	120	21.5	4	45.5	15.4
Lorraine	18.3	74.7	37	3.4	8.5	14.7	39.1	10.9	1.2	19.9	ND
Midi-Pyrenees	233	490.9	367.8	430.4	460.6	114.4	656.8	546.7	85.8	137	
Nord-Pas-de-Calais	2.5	6.8	0.8	0	3	20.7	3.5	1	ND	0	0
Pays-de-la-Loire	173.4	293.8	62.9	20.8	27.9	148.8	165.7	45.1	ND	29.3	12.4
Picardie	5.5	11.5	2.3	11.1	12	28.1	14.1	3	ND	0	0
Poitou-Charentes	192.7	43.4	63.2	28.8	268.2	159.1	210.3	40.1	18.3	114	22.1
Provence-Alpes-Cote d'Azur	1739.6	ND	ND	ND	ND	ND	ND	1142.3	1959.2	ND	ND
Rhône-Alpes	132.6	4.1	31.4	11.3	15.8	13.5	105.3	201	95.2	747.1	2

Data sources: Agreste (1993, 1994, 1995, 1996, 1997, 1998, 1999, 2000, 2003); European Commission (2001a)

EFISCEN scenario file

The following scenario file was used for the model runs of the Mediterranean regions. Further explanations and detailed information on its meaning can be found in Pussinen et al. (2001).

```
        ANTAL PERIODER 13
        KATL,KATH 01 03
        BONL,BONH 01 01
Specify species group for every species (1=conif.2=decid.3=copp.)
2 2 2 2 1 1 1 1 1 2
UNGK * AND * AVV1 AVV2 AVV3 BR1 BR2 * GAL1 GAL2 GAL3 BRYT1 BRYT2 *
GAREA
9.834 9.834 9.834 9.834 9.834 9.834 9.834 9.834 9.834 9.834 9.834
9.834 9.834
2.950 2.950 2.950 2.950 2.950 2.950 2.950 2.950 2.950 2.950 2.950
2.950 2.950
15.359 15.359 15.359 15.359 15.359 15.359 15.359 15.359 15.359 15.359
15.359 15.359 15.359
4.608 4.608 4.608 4.608 4.608 4.608 4.608 4.608 4.608 4.608 4.608
4.608 4.608
0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
0.000 0.000
0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
0.000 0.000
The fraction of stem TAKEN OUT FROM the forest by tree species group
(and clear/thinn)
.848 .847 .847 clearcut
.848 .847 .847 thinning
0.50 0.50 0.50 0.50 0.80 0.80 0.80 0.80 0.80 0.90 0.90 0.90
0.75 0.75 0.75 0.75 0.75 0.40
ENTER NEW AREAS AFFORESTATED BY PERIOD AND SPECIES
1   0.0 00.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0 0.0
....
```

Table A.3.: Parameter values of equation 2.11.

Parameter	Pine	Spruce	Deciduous species
a	-29.3947	-59.161	-28.586
b	10.0835	19.898	9.839
c	0.0141	0.021	0.019

Source: Lapveteläinen et al., unpublished