Forest fires

under climate, social and economic changes in Europe, the Mediterranean and other fire-affected areas of the world

FUME

Lessons learned and outlook

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Executive Summary

Forest fires result from a number of interacting factors like ignitions, conditions amenable for fire initiation and spread, and landscapes with vegetation (i.e., fuels) that can support the combustion process. In Europe, most fires occur in the southern countries with a Mediterranean climate. But fires dominate also in other parts of the world. Factors driving fire have not been stable during the last decades, mainly due to modifications in the territory caused by socioeconomic changes. Climate has equally not been stable. In looking at the future, changes in climate and socioeconomics are projected to continue. Understanding how such modifications in the fire controlling factors affect fire activity is utmost important for anticipating future fire risks.

In FUME we have come together 33 groups of scientists from 17 countries and 5 continents to investigate the relationships between the various drivers of forest fires. The main focus was the southern countries of Europe, although Northern Europe, Northern and South Africa, Anatolia, California and Chile were also investigated. The project addressed the relationships between socioeconomic, landscape and climate factors and fires across various scales and countries during the last decades. Additionally, future projections of these drivers were used to anticipate future risks. Modeling and experiments assessed impacts of future changes, including extreme episodes like droughts, on the vegetation and fuels. The effects of changes in fire regime on the vegetation were also investigated. Restoration needs under changing conditions and for reducing fire hazard were also explored. Policy needs and procedures used in a number of countries were evaluated in regards coping with fire. Following are some of the main results:

Segesta (Sicily, Italy). Photo: J.M. Moreno

- Fire activity has been changing in the Euro Mediterranean countries (EUMed). Assessing fire regimes and changes through time require long-term databases that include more complete information about fire characteristics and harmonized data to permit comparisons among countries. Further efforts are still needed to have harmonized definitions, formats and methodologies in fire data acquisition and assemblage across countries.
- Mediterranean landscapes were dynamic in the last decades, and fires responded to the changes that occurred in them, independently of whether they were planned (e.g., afforestation) or unplanned (land abandonment). Fires often burned where hazardous changes occurred. Changes driven by socioeconomics are likely to continue in the future. Because they operate on large time scales, anticipating future risks should be possible.
- Assessing impacts and future risks requires spatially explicit information on burned areas, at least for the fires above a certain size (a few hectares). Reconstructing the near past and setting procedures to gather this information for the future is a requisite for a sound management of fire-prone areas.
- Fires do not burn equally all areas in a landscape, and preferentially burn certain surfaces over others. Furthermore, positive feedbacks driven by fire have been documented across Southern Europe. This is, fires favour burning again in a short time. Understanding these positive feedbacks to prevent certain areas entering into fire-driven degradation loops is a necessity.
- The rural-urban interface (RUI) is a particular area of risk. Methods have been developed to map the RUI and model fire risk in relation to RUI characteristics. Furthermore, RUI development can be modeled and taken into consideration in urban development to reduce risk.
- Socioeconomic factors were important for explaining fire occurrence in EUMed countries, and their knowledge should have an increasing role in operational fire risk systems that focus on prevention activities.
- Fires are driven by weather, and dry spells and other weather anomalies (heat waves, strong winds) play a major role in determining fires. Extreme episodes, like long dry spells, can be most relevant in determining fire season severity. Improvements in weather forecasting (seasonal, yearly) may allow developments in fire danger and risk prediction.
- Attributing fires to climate change requires differentiating the role of climate from other confounding factors. Using the appropriate mathematical procedures to relate climate and fires, while controlling for the possible interference of other factors in this relationship, a significant and positive relationship was revealed between climate and fires during the last three decades for the various EUMed regions. This occurred despite the fact that, in recent years, fires (numbers, area burned) were decreasing while fire weather danger was increasing.
- Anticipating future fire hazard and risk requires that concurrent changes in climate and socioeconomy are jointly analyzed to assess future allocations to land use and land cover types, including RUI development. Modelling at EUMed showed that land use and land cover (LULC) will continue changing, but changes can be affected by a priori decisions.
- Wildfire simulators can be used with different planning strategies, from tactical and strategic planning of wildfire management, to firefighter training, to even real-time firefighting. In a perspective of climate and global changes, these tools can assist policy makers and management agencies to evaluate risks and needs to mitigate them.
- With global warming, great increases are projected in mean fire-weather indices, length of the fire season and extreme values over large extensions of Europe, including areas in which fires were not prevalent until now. Procedures are now available to make projections in the near future, in the time when adaptation to changes in climate will be needed.
- Climate projections when used in fire models under the assumptions of persisting current fire-climate relationships and disregarding other limiting factors project an important (up to 3 times) increase in burned area in case-study areas like the Iberian Peninsula.
- Plant species differ in their seasonal variability in live fuel moisture content and in their capacity to produce necromass during drought periods. Live fuel moisture content can be modeled using drought indices, but improvements are possible using adjustments based on actual vegetation and soil.
- Despite increased meteorological fire danger with climate change, vegetation-fire models show that under scenarios of high climate change low productivity in parts of Southern Europe could limit burned area.
- Vegetation-fire models applied for contrasting climate change scenarios indicate that fire would enormously increase in Eastern Europe. This region is identified as the main potential new fire-prone area. Therefore, if climate change goes un-abated, this region would require specific new developments in fire research, management and protection.
- Regeneration by germination of Mediterranean species will suffer from changes in climate. However, species and populations showed idiosyncratic germination responses, which indicates that generalization of impacts will be difficult to make.
- Post-fire regeneration in field experiments simulating future drought can lead to altered vegetation due to the differential sensitivity of seeders (more sensitive) than resprouters (less sensitive). Alterations in ecosystem functioning are likely due to downstream effects on the plant community and nutrient cycling.
- Changes in fire regime due to increased fire frequency caused by climate change or other factors can compromise vegetation stability to fire in low fire-frequency areas but also in high-frequency areas with resilient vegetation.
- Pine woodlands burn frequently nowadays. The post-fire vegetation in these systems is affected by the interplay of previous management and geophysical variables. Changes in vegetation can occur due to fires, yet anticipating post-fire vegetation characteristics is difficult. Site-specific, local information is needed to identify possible vulnerable areas subject to change due to fire.
- Mediterranean pine forests require active management to increase resilience. Pine thinning and introduction of hardwood resprouting species are recommended. Management actions have to be adapted to each stage of the pine-stand dynamics and site conditions, especially considering soil moisture availability vs. light availability for selecting drought-tolerant vs. shade-tolerant resprouter species.
- Post-fire restoration should consider fire-resilient, drought-tolerant species in the perspective of climate change. A structured approach has been produced for post-fire impact assessment and restoration under climate change, including technical options for improving restoration success: seedling acclimation to drought, soil preparation to increase water supply, and microhabitat conditioners to reduce water losses.
- Increased fire load and costs are anticipated under future scenarios of climate and other global changes. This requires increased efficiency in investments in wildfire management operations, and resolving the disconnect problem between science, policy and management.

Quercus suber resprouting. Photo: V.R. Vallejo

Introduction

Every year, over 60.000 forest fires are recorded in Europe, mainly in the southern countries with a Mediterranean climate, burning more than 0.6 million hectares of forest and shrublands. Although forest fires are not recent phenomena, half a century ago there were fewer fires, and these were not considered as an important problem as they are today. Most forest fires in these countries are human caused and burn virtually everywhere across their geography, through any type of vegetation, causing important damages to human and environmental assets. Some areas, like the rural-urban interface (RUI), are of particular concern. In general, forest fires are considered to be controlled by weather, fuels (i.e., vegetation in the landscape), and the availability of ignitions. Fire-prevention and -fighting capacity, amongst others, can also play a role (Fig. I.1). What exerts the ultimate control on fires is subject of scientific debate. On one hand, some authors have argued that differences in fire regime across the geography may be controlled by fuel accumulation (amount, distribution, etc.) over time. If that is correct, then the landscape, and the changes that occur in it through time, would play a major role in fires because having more or less patches with more or less flammable fuel could be critical for these. On the other hand, others sustain that weather is a much more important factor in determining fires. This being so because, when weather conditions are severe, fires will spread uninterrupted over virtually any piece of land with a minimum of vegetation capable of sustaining combustion.

Southern Europe, the Mediterranean region in particular, is a good area to test these contrasting views. Unlike in other fire-prone areas of the world, where landscapes have been more stable, here humans have played a much greater role in crafting the landscapes for centuries. The socioeconomic changes caused by industrialization and rural exodus starting in the second half of the 20th century brought subsequent alterations to the landscapes, thus offering a good opportunity to verify the impact that such changes had on fire. Furthermore, the contrasting socioeconomic conditions among the various countries offer an additional opportunity to verify this. Hence, in this region, the effects of changes in the landscape on fires should be discernible. This has been a main working hypothesis in FUME.

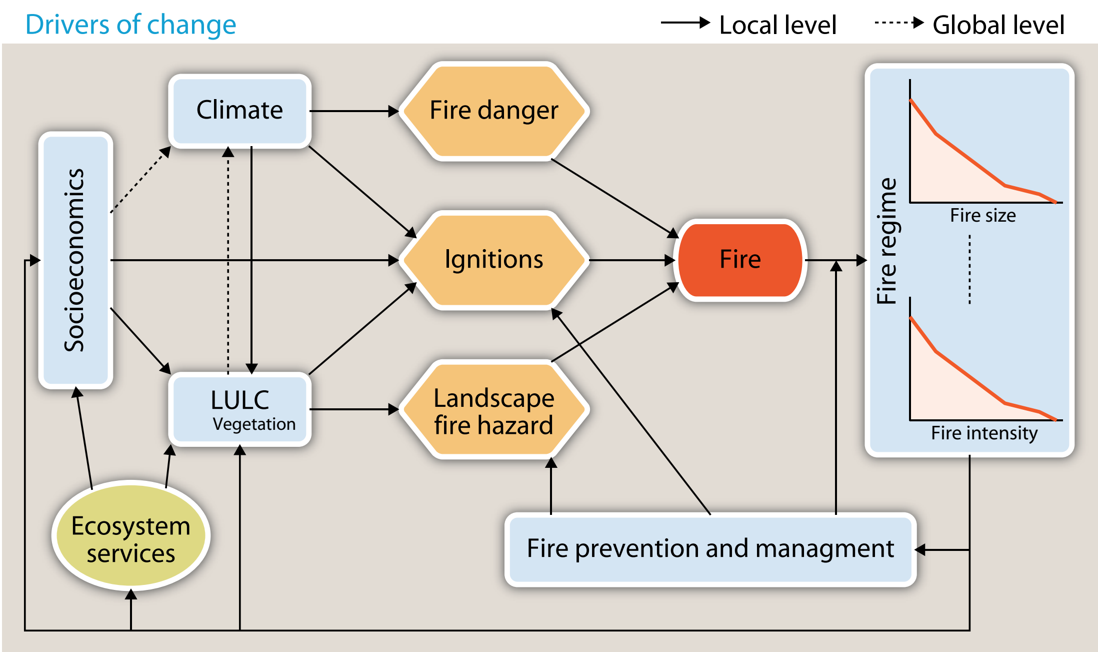

Fig. I.1: Diagram showing the complex interactions among the various factors that govern fire. Socioeconomic drivers affect the global economy and, through it, the global and local climate and land use and land cover (LULC). These determine fire danger, ignition sources and fire hazard. Fire spread will depend on fire fighting and other management measures. Fire regime is the result of these interacting factors. Fires can modify the landscape and affect future fires as well as ecosystem services. Changes in drivers will affect fire regime

Top: Montes de Toledo (Toledo, Spain). Photo: I.R. Urbieta

Bottom: Mazarete (Guadalajara, Spain). Photo: J.M. Moreno

This region has a contrasting climate, with very hot and dry summers, often subject to extreme episodes of high temperature and droughts, both of which could affect fires. Additionally, the region has warmed during the last decades, at the time when such changes in the landscapes were occurring. Furthermore, significant climate changes are also projected to occur as global warming continues due to the alteration of the climate system caused by humans. Looking into the future, neither climate nor the socioeconomic conditions in the region are projected to remain stable. Thus, fire activity may continue changing. The capacity of our ecosystems to cope with anticipated changes in climate and fire needs to be evaluated. Our vulnerability to these future changes depends on a proper evaluation of anticipated impacts and on the capacity of our ecosystems and the society at large to cope with them.

In FUME, 33 groups from 17 countries and 5 continents gathered to investigate the role of the various drivers affecting forest fires. The focus was on the countries of Southern Europe. However, Northern Europe, Northern and South Africa, Anatolia and other areas with Mediterranean climate (California, Chile) were also investigated. The work comprehended empirical analysis, field experiments, including field manipulations simulating conditions of extreme drought projected to occur with continued global warming, and modeling. The FUME research strategy was the following:

1. Determining factors controlling past fire activity

We assessed how landscapes changed in the past, what factors drove such changes and how these, in turn, interacting with climate, affected forest fires, including focussing on some main areas of impact, like the RUI. Of particular interest was the study of the relationship between climate and fires.

2. Assessing future changes and impacts

Scenarios of change (socioeconomics, land use and land cover, climate) were developed and/or used to produce future changes in fire potential and risk. The implications of these future changes were evaluated by various modeling approaches. Additionally, experiments were implemented in the field to test vulnerabilities of vegetation and ecosystem functioning, including fuels, to climate changes, with a particular focus on droughts. The sensitivity of the vegetation to changes in fire regime was also addressed.

3. Options to cope with change

The capacity to cope with forest fires in the future was evaluated by addressing how future risks can be reduced through preventive or reactive measures. The main focus was on restoration under changing conditions, and increases in extreme episodes like droughts. The potential damages and economic costs and policy implications of the expected changes were also analyzed.

Next we present a summary of the many research activities conducted in FUME. These activities are organized around 22 research topics, which cover the most relevant aspects of all activities undertaken. Each research topic addresses the problem investigated and why it was important; a brief description of what was done and results obtained. We then identified the lessons we learned, and their management and policy implications. Messages for management and policies are highlighted up front, in an attempt to give prominence to the practical implications of the project findings. Finally, for each topic, we looked into the immediate future to identify what are some of the outstanding research questions that still remain open.

Topic 1 Recent trends in forest fires in Mediterranean areas and associated changes in fire regimes

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Understanding fire regimes is very important to assess the ecological effects of forest fires and project them under future scenarios. FUME project characterised fire regimes at different spatial scales and analysed trends and shifts in fire occurrence during the recent history. Overall, the results highlighted an inter-annual variability of fire activity, a general slight decreasing trend in burned area (with the exception of Portugal), and a shift in number of fires in several countries. Such trends are likely due to a combined effect of extreme fire weather events, changes in policies and management practices, law enforcements and reporting systems.

Implications for policy and management

- *Need to further strengthen efforts towards harmonized definitions, formats and methodologies in fire data acquisition and assemblage across countries.*
- *Need for additional fire characteristics to be measured and recorded in the fire databases to accomplish a more comprehensive picture of fire regimes in Europe.*
- *The collection and recording of a consistent and comprehensive European fire database is a paramount knowledge base instrument to support fire management and related policies.*

The problem: Fire regimes are commonly described from the main characteristics of fires occurring in a region (i.e., fire intensities, seasonality, frequency, type and pattern), and are mainly driven by climate, vegetation and human factors. The thorough knowledge of these characteristics and their trends is essential for (1) understanding the effects of fire on ecosystems and the interactions between fires and their driving factors, (2) anticipating and limiting the potential negative impacts of fires (especially in areas experiencing rapid changes or newly exposed to fire), (3) supporting fire management (prevention and fighting) and land planning, and (4) projecting future fire potential under changing environmental and social conditions.

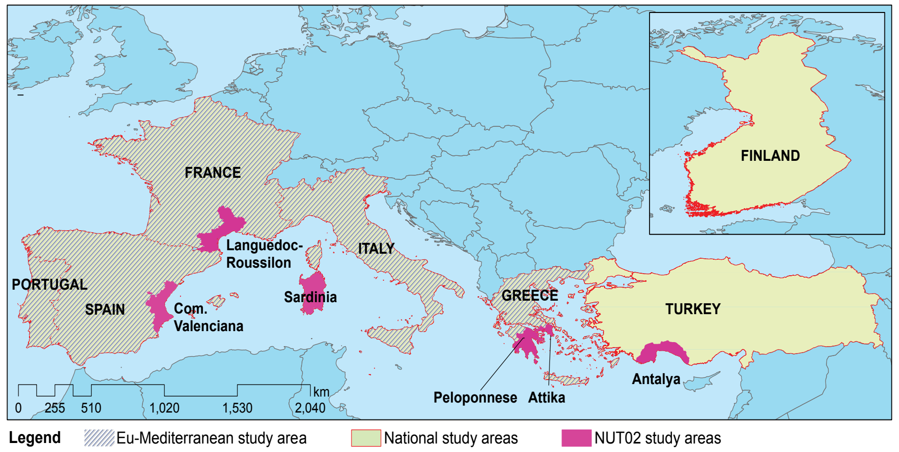

Fig. 1.1: Fire Statistic study area, composed of 7 countries (Portugal, Spain, France, Italy, Greece, Turkey, and Finland) and 6 NUT02 regions (Comunidad Valenciana, Languedoc-Roussillon, Sardinia, Peloponnese, Attica, Antalya).

The approach: Contemporary (1985-2005) fire regimes, in terms of frequency, seasonality, and inter-annual variability, were characterized in the Euro-Mediterranean area at different spatial scales (from EUMed to National level down to NUTS2[1] scale, Fig. 1.1) using fire statistics (monthly fire number and burned area) derived from different sources. The existence of significant trends and shifts in fire occurrence was also investigated. Because during the last decades their number was considered significantly affected by the variation in data recording and reporting systems, fires smaller than 0.01 ha were deleted from the analysis (Fig. 1.2).

Achievements:

Fire regime characterization: Throughout the analysed period (1985-2005), the majority (about 85%) of fires burned less than 10 hectares, although, as a whole, they accounted for a small portion (about 11%) of the total burned area (Fig. 1.2). At EUMed level, fire incidence (i.e., the burned area over the land area) was higher in Portugal, followed by Spain and Italy (Table 1.1). Summer (JJAS) was the main burning period, although several countries presented a secondary peak in early spring. Fires tended to start earlier in South-Western regions, while in the South-Eastern regions a number of ignitions were recorded in October. Countries were characterized by a certain degree of inter-annual variability; higher variability was found in NUTS2 with medium-low fire activity (Table 1.1).

Recent trends and changes: The whole study area exhibited a general increase in the number of fires. Portugal (1989 and 1994) and Greece (2000) show an upward trend, while Italy (1994) exhibits a downward trend (Fig. 1.3). The burned area had an opposite trend, with a generalized slight decrease throughout the period considered, significantly in Italy, Greece, and Turkey. At NUTS2 level, a significant increase in the number of fires was observed only in Attica and Peloponnese, while burned area followed a general decrease in all the study areas.

Lessons learned and implications: One of the main limitations for the analysis of fire regimes is the lack of long-term comparable and harmonized historical records. Differences in datasets across countries and throughout the years need to be considered when comparing past and recent years or when analysing trends and shifts. In this respect the European Fire Database of EFFIS (San Miguel-Ayanz et al., 2012) is an important tool that needs to be maintained and further enhanced.

Law enforcements in State and European legislation, as well as the improvement of fire management services and monitoring systems have certainly contributed to contain fire activity and incidence (e.g. Salis et al., 2013). However, apparently they have not been sufficient to balance the increased severity of extreme events under severe weather conditions observed in recent years.

[1] Nomenclature of territorial units for statistics (NUTS): is a geographical nomenclature subdividing the EU territory into regions at three different levels. It is based on the administrative divisions applied in the EU Member States. NUTS level 2 in most EU countries corresponds to the administrative level of Regions.

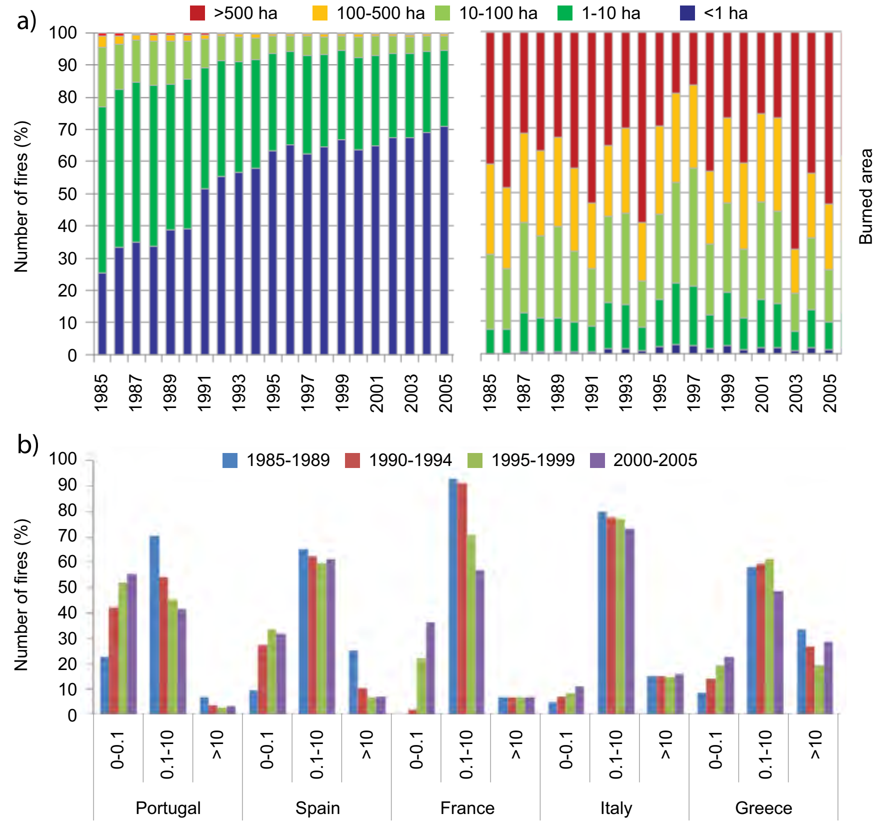

Fig. 1.2a: Temporal evolution of annual number of fires and burned area in EUMed by share (in %) of fire size categories (data elaborated from the European Fire Database of EFFIS, San Miguel-Ayanz et al., 2012). Note the increasing trend in the number of small fires, likely due to the variation of recording and reporting systems throughout the period considered.

Fig. 1.2b: Evolution of number of fires in FUME EUMed study areas by share (in %) of fire size categories and by time steps (1985-1989, 1990-1994, 1995-1999, 2000-2005). Note the increasing trend in the number of small fires, likely due to the variation of recording and reporting systems throughout the period considered.

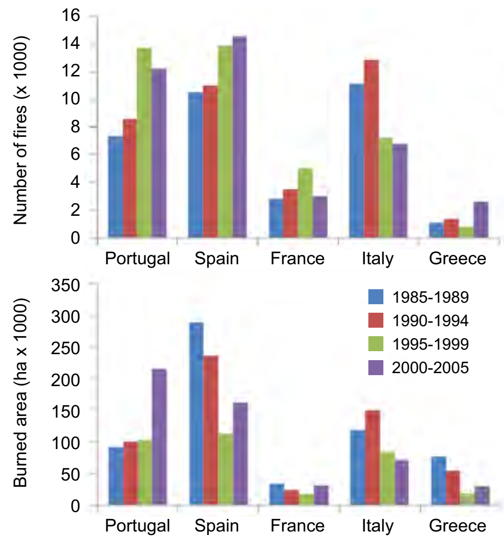

Fig. 1.3: Evolution of average fire number and area burned by time steps (1985-1989, 1990-1994, 1995-1999, 2000-2005) in FUME EUMed study areas.

Table 1.1: Number of fire (FN) and burned area (BA) statistics at EUMed, national, and NUTS2 scales, for the period 1985-2005. The table is based on monthly values from FUME partners.

	Total FN (x 1000)	Total BA (ha x 1000)	Total FN/country land area	Total BA/country land area (%)	Average fire size (ha)	Coefficient of variation FN	Coefficient of variation BA
EUMed	1076.67	10509.65	0.69	6.73	9.76	0.91	0.98
Portugal	429.42	2772.82	4.69	30.30	6.46	0.47	0.72
Spain	366.67	4170.85	0.73	8.36	11.37	0.30	0.62
France	28.60	454.59	0.05	0.83	15.89	0.31	0.87
Italy	213.04	2184.01	0.72	7.43	10.25	0.36	0.50
Greece	38.94	927.38	0.30	7.19	23.82	0.67	0.97
Turkey[a]	31.82	185.66	0.04	0.24	5.84	0.26	0.78
Finland	19.16	10.28	0.06	0.03	0.54	0.62	0.58
Com. Valenciana	4.82	213.40	0.21	0.92	44.31	0.34	1.97
Languedoc[b]	9.51	3.95	0.35	0.01	0.42	0.39	3.30
Sardinia	65.27	619.61	2.71	25.72	9.49	0.38	0.69
Peloponnese	7.22	170.71	0.34	7.98	32.36	0.62	1.77
Attica	1.57	50.87	0.41	13.36	23.64	0.65	1.05
Antalya[b]	3.71	26.93	0.18	1.30	7.27	0.33	0.81

[a] Data from 1990-2005
[b] Only data related to fire in forests and shrublands were available.

Topic 2 Trends in land use and land cover changes and socioeconomics

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In Southern Europe, socioeconomic changes in the last decades may have altered fire hazard and fire activity. We reconstructed land use and land cover (LULC) history since the 1950's in several areas and at various scales, using old maps, aerial photographs and/or satellite information. LULC changes were modelled in relation to socioeconomic and geophysical factors. Furthermore, we assessed the extent to which burned areas were related to LULC changes. We found a close link between LULC and fires demonstrated when most changes increased landscape fire hazard, and that these were related to physiographic (unproductive soils, erodibility) and socioeconomic factors (farm size, population age), and fire themselves.

Implications for policy and management

- *Fire hazard increased across EUMed rural areas since the 1950's due to interactions between socioeconomic and geophysical factors.*
- *Fires responded to changes in hazard, independently of whether LULC changes were planned (afforestation) or unplanned (abandonment). Because these changes take long to operate, impacts on fire risk could be anticipated or avoided.*
- *Once fires occurred they became drivers of hazard change, by turning most areas into shrublands, which are generally highly flammable, thus perpetuating increased hazard.*
- *LULC changes in the landscape will continue occurring but at different rates in space and time due to the varying factors driving the process (socioeconomics, fires).*

The problem: Since the middle of the 20th century, changes in traditional agrarian activities and afforestation have modified the landscapes of Mediterranean rural areas. A working hypothesis in FUME is that landscape changes have modified fuel quantity, quality and arrangement, and consequently fire hazard and risk. Although several studies have documented LULC changes leading to increases in hazard, a causal framework to understand this process is still missing. Knowing which factors in LULC changes led to hazardous conditions and their consequences on fires is important to understand how future changes due to continued socioeconomic and climate change may affect fire risk.

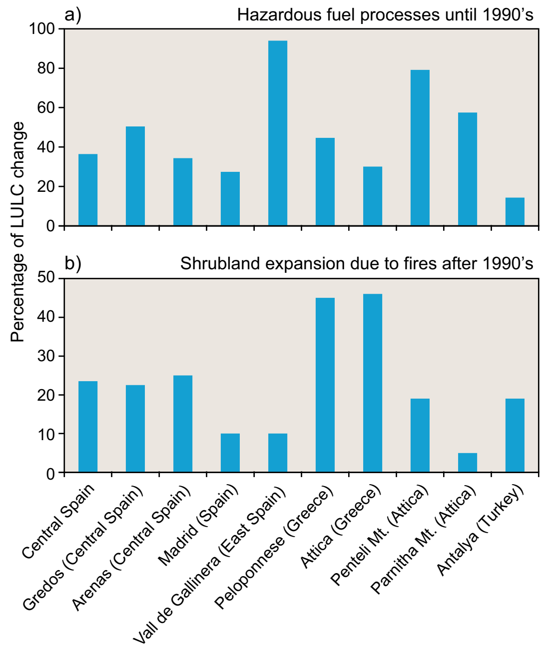
The approach: Trends in LULC changes were investigated at several spatial and temporal scales across EUMed countries: the whole EUMed or countries (Greece), regions (France, Greece, Italy, Spain, and Turkey), and particular local areas (Greece and Spain). We focussed on LULC changes that could have increased landscape fire hazard (encroachment, densification of open woodlands, afforestation). The study period varied but started in the 1950's until present (Fig. 2.1). LULC changes were reconstructed based on national LULC maps, aerial photos, satellite images and/or CORINE maps. Trends in socioeconomic factors were also investigated, using data from population and agrarian censuses from 1960's onwards, with a decadal resolution. Geophysical data (soils, relief, and climate) were obtained from available European or national sources. LULC changes were modelled as a function of socioeconomic and geophysical data. We used fire maps to assess the relationship between LULC changes and fires.

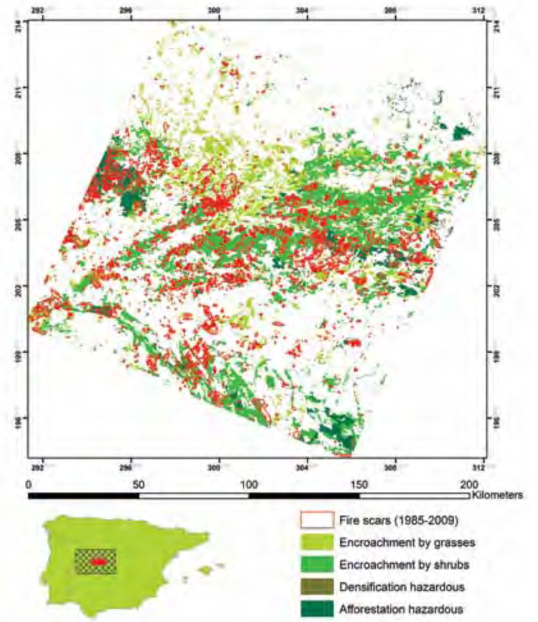
Fig. 2.1: Study sites in Euro-Mediterranean region where changes in LULC and socioeconomic factors since the 1950's were investigated.

Achievements: Until the middle of the 1980's, LULC changes considerably increased landscape fire hazard in all study areas. The main LULC processes were: land abandonment (farms turned into pastures or shrublands), densification of shrublands and transitional (i.e., open woodlands), and afforestation. On average, these LULC changes together accounted for more than 45% of all changes occurred in the areas studied (Fig. 2.2). Moreover, depopulation of some areas was matched by concentration in others, mainly large cities. After the 1990's, the dominant LULC change was the land conversion of forests to shrublands (about 25% of all changes) caused mainly by fires (Fig. 2.3). Densification of shrublands and transitional woodlands, and encroachment by pastures and shrubs of abandoned lands continued in rural areas during this period, further increasing fire hazard. A period of population stability in most areas followed this decade, though in some areas like Central Spain and the Peloponnese in Greece the depopulation/concentration process still continued. In addition, in most areas farm and livestock density decreased from 1960's until now. However, in some municipalities an increase in farms and livestock was observed. The rate of land abandonment was high in low productive soils, with large erodibility, under unfavourable topographic and climatic conditions, and far away from population centres. Land abandonment was high in villages with low population and low farm density, and a high proportion of land-holders older than 55 years, with small farms and low mechanization level.

Carrascalejo (Cáceres, Spain). Photo: O. Viedma

Lessons learned and implications: In many rural areas across Southern Europe, socioeconomic and geophysical factors interacted to increase landscape fire hazard since the middle of the 20th century. In a first phase, these processes dominated the dynamics of the landscape. Thereafter, fires occurrence increased and dominated much of the LULC change process, becoming in itself an additional factor of change. Because the factors that initially led to abandonment and land transformation (soil quality, distance to villages, local climate, and socioeconomic conditions) may differ from those favouring ignitions and fires, this indicates that landscapes will continue changing but at different rates and for different drivers.





Left Fig. 2.2: Percentage of LULC change at the various sites by processes related to: a) land abandonment (encroachment by grasses and shrubs), densification of transitional [i.e., open] woodlands, and afforestation before 1990's, and b) shrubland invasions caused by forest fires after 1990's.

Right Fig. 2.3: Map of LULC changes linked to increases in hazardous fuels from the 1950´s to 2006 (grasses and shrubs expansions, densification and afforestation in green colours); and forest fire scars (in red) during 1985-2009 derived from Landsat images, in Central Spain. Fire occurrence was highest in areas that experienced LULC changes.

Topic 3

Multi-scale burned area mapping in EUMed using historical series of satellite images

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Burned area maps permit knowing the extent and location of fire affected areas at different spatial and temporal scales. Remote sensing has shown to be an appropriate tool to detect and map fire-affected areas and monitor the succession and recovery of burned surfaces. This information enables scientists, managers and policy makers to understand how fire is influencing vegetation and other relevant processes at short- or long-term scales. In FUME project, multisource satellite data was used to reconstruct recent fire history and characterize fire regimes at multiple spatial and temporal scales in Mediterranean Europe; producing time series of burned area maps relevant for fire-impact assessments, environmental planning and management.

Implications for policy and management

- *Spatially explicit information on burned surfaces facilitates understanding spatial and temporal patterns of fire occurrence providing information on driving factors at different temporal and spatial scales.*
- *Burned area maps provide key information for validation of fire risk and fire behaviour models.*
- *Remote sensing data allows a rapid assessment of the actual magnitude of fire impacts: surfaces affected, biomass consumed, fire-driven emissions, species burned, fire severity, among other.*
- *Knowing the extent and location of fire affected areas at different spatial and temporal scales, provides the necessary information on the fire regime of an area/ecosystem, permitting comparison of recent fires characteristics to the expected natural fire regime; therefore, management measures can be adopted accordingly.*

The problem: Spatially explicit information on the extent and location of fire affected areas is critical in environmental planning and management. Local to global inventories of the location and extent of burned areas are required to assess fire damages on ecosystems and human resources, or quantify the impact of fires on emissions, among other. However, burned area maps allowing for the detailed description of fire incidence and the reconstruction of fire history are often missing; thus, restricting fire scientists and managers ability to understand the reasons of fire ignition and spread, analyse changes in fire regimes, estimate fire emissions or to investigate post-fire vegetation regeneration.

The approach: Remote sensing is an essential technology for gathering information on burned areas in a timely, cost-effective and methodologically consistent manner. The availability of satellite images allowed us in FUME to reconstruct the fire history (last decades, but mainly since the 1970's) through fire scars mapping at local, regional and Euro-Mediterranean scales by processing satellite image (mainly Landsat MSS, TM, ETM and NOAA-AVHRR) temporal series. Simple and accurate methods based on visual and digital analysis of satellite images (preferably using free or low cost data) have been proposed that allow producing burned area maps at low cost and in a consistent basis for historical fire occurrence analysis. At local/regional scales, time series of burned area maps were produced in different study sites in Portugal, Spain, France and Greece (Fig. 3.1). Additionally, maps of large fire events (> 500 ha) were obtained for Euro-Mediterranean countries from 1981 to 1999 by processing low resolution NOAA-AVHRR satellite data (Fig. 3.2).

Achievements: The different techniques applied and the results achieved have demonstrated that operational mapping of burned surfaces and the reconstruction of recent fire history at EUMed, regional and local scales is possible using low cost remotely sensed data. Operational semi-automatic methodologies were used in FUME that could be applied by non-specialists but trained personnel at the different management institutions equipped with basic hardware and software systems and using low or no cost satellite images. The main limitation of these techniques is the short temporal series available (only from 1970's) and the existence of some data gaps which can hinder the reconstruction of fire history in a long-term basis. In this case, other techniques such as dendrochronology and complementary data sources such as official fire statistics can be used in combination with remote sensing data to ensure an appropriate and fully operative historical fire inventory and assessment system. Spatially explicit information derived from remote sensing data on fire characteristics such as frequency, return interval, or interval since last fire has provided consistent information to assist in further investigations necessary for environmental planning and management. Within FUME, this information was used to analyse fire regimes and also the interactions between fire and landscape components at different spatial scales both from an historical perspective and also in the context of future land use and land cover scenarios. Accurate fire perimeters derived from satellite data allowed performing innovative fire selectivity analysis, which incorporates the fire shape in the modeling process. Additionally, this satellite-derived information was used to explore the relationship between fire occurrence and environmental and socioeconomic driving factors.

Lessons learned: FUME has produced for the first time a complete historical series of burned area maps for the EUMed using consistent low resolution satellite data. Results show a trend to underestimate number of fires and area burned when compared to fire statistics. However, this fact does not preclude the usefulness of the results, especially because they have shown to be consistent in time and, therefore, could be considered, at least, a reliable sampling of historical trends on large fire events in Mediterranean Europe. FUME also produced historical series of burned area maps in specific study sites that permitted analyzing fire impacts and can help analyze fire patterns contributing to fire risk assessment and prevention planning.

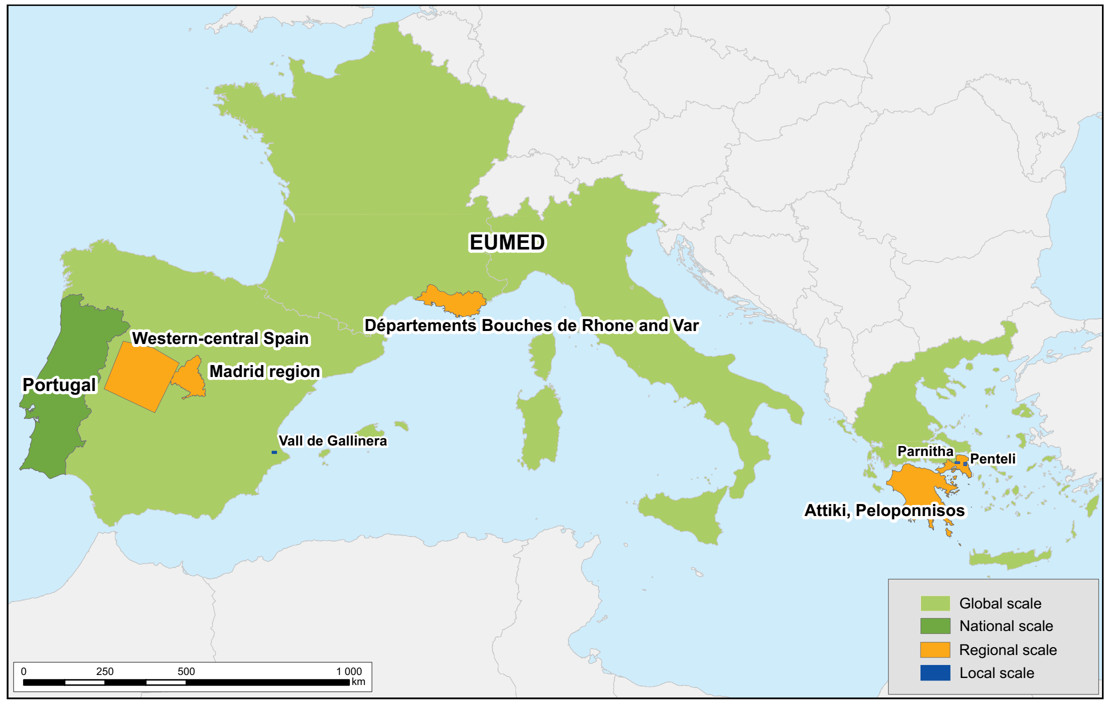

Fig. 3.1: *Study areas where time series of burned area maps have been produced from remote sensing data.*

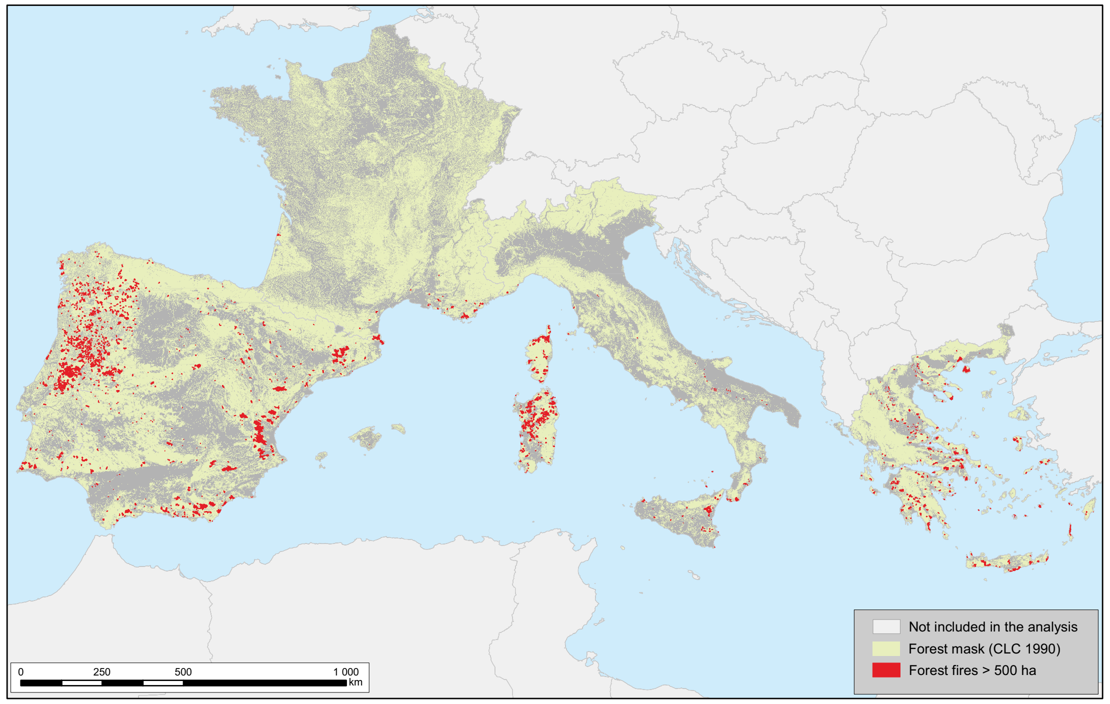

Fig. 3.2: *Forest fires >500 ha in Mediterranean Europe obtained from NOAA-AVHRR images (1981-1999).*

Pinus brutia, Mount Carmel (Israel). Photo: J.M. Moreno

Topic 4 Assessing burned landscape features and their interaction with fire

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In a given area, not all areas are equally prone to burn. Hence, fires may differentially burn a landscape, and exhibit a particular selectivity. Assessing selectivity by fires is important to determine fire impacts. Fire selectivity is usually expressed on the basis of a resource selection index which is compared to the availability of land use and land cover (LULC) classes or other landscape components. In FUME we analyzed fire selectivity against the various LULC classes at multiple spatial scales -from local to the EUMed- taking into consideration the spatio-temporal nature of the fires. Through the study cases here, it has been shown that wildland fires in the Mediterranean Europe show clear evidence of selectivity patterns towards certain LULC types.

Implications for policy and management

- *Wildland fires in Mediterranean Europe show clear evidence of selectivity towards certain LULC types, and particularly for already burned sites. Small and large-size fires show different selectivity patterns. These should be considered in fire-management and planning.*
- *Landscape planning that modifies the spatial arrangement of the fire-prone LULC classes could eventually reduce fire risk.*
- *A planning aiming to reduce the number of fires by LULC management should take into consideration the danger of favouring the occurrence of large, infrequent fires.*
- *Factors like topography, socioeconomy and weather play an important role in fire occurrence. They should be considered for LULC management planning for fire prevention.*

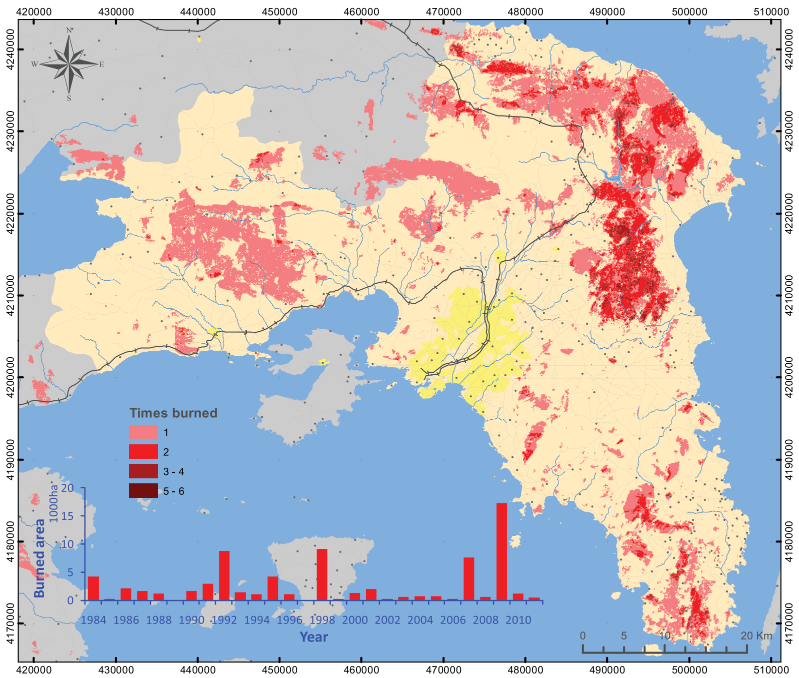
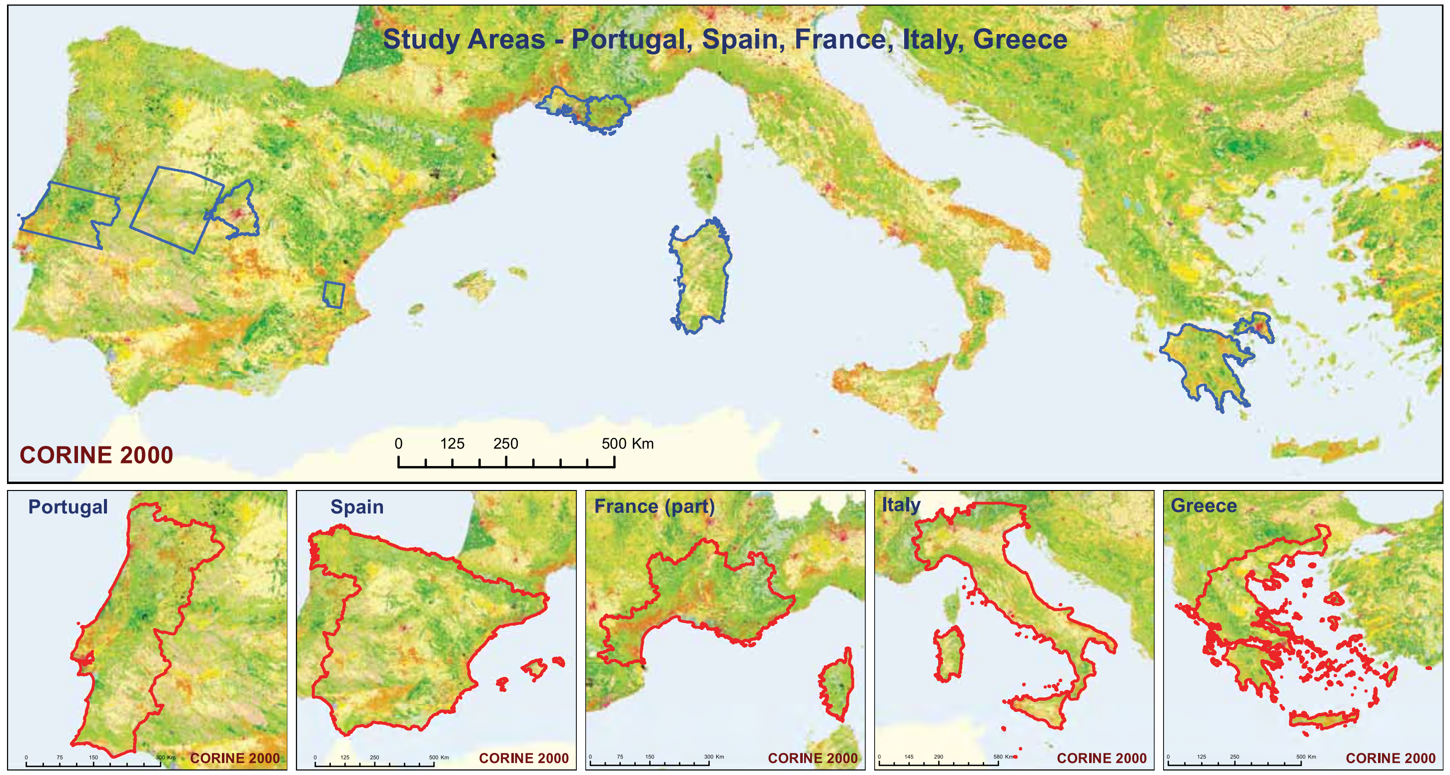


Fig. 4.1: Fire occurrence patterns in Attica, Greece during the period 1984-2011. Specific spatial and temporal patterns of fire occurrence have been created according to the selective preference of fire on landscape components.

The problem: Where, when and why do fires occur are important questions aiming at a better understanding of the fire problem. Specific spatial and temporal patterns of fire occurrence at multiple scales have been determined according to the selective preference of fire on landscape components (Fig. 4.1). The extent to which fires are more selective (e.g., fire occurrence is higher [preferred] or lower [avoided]) than what would be expected by chance, not only as far as LULC but also as other landscape components are concerned, becomes critical in fire management for a better understanding and management of the underlying causal factors.

The approach: Fire areas and annually-resolved fire perimeters at multiple scales, covering local/regional, national and EUMed study cases (Fig. 4.2) were used for the estimation of fire selectivity patterns. We aimed to distinguish and assess the different selectivity patterns that fires exhibit towards the various landscape features and calculate their hazard burning functions. The probability that fires of different sizes exhibit different selectivity towards LULC types was also considered. To achieve the aforementioned, novel methods that consider the spatio-temporal nature of the fires were developed and tested at multiple spatial scales. Resource selection indices were estimated and the outputs at the various spatial scales were used to distinguish cross-spatial selectivity patterns, valid throughout the geographical range of the study.

Achievements: The analysis of fire selectivity at different spatial scales over a wide geographical range provided an opportunity to summarize common patterns and distinguish important differences among the study cases, resulting in valuable information, like the identification of fire-prone and resilient LULC classes, for fire management



and policy. Through the study cases (Fig. 4.2), we found that wildland fires in Mediterranean Europe show clear evidence of selectivity towards certain LULC types. Large fire events rarely burn croplands; whereas they usually prefer forests and shrublands. Additionally, it was shown that, at least at the EUMed scale, fires show a preference for recently burned areas (Fig. 4.3). Moreover, it was shown that fires of different size classes and of different cause may have varying selectivity patterns. Small-size fires are associated with agricultural activity, while large-size fires are associated with natural ecosystems such as shrublands and forests. In addition to the individual case studies, which all produced results showing the selectivity towards similar LULC classes, fire selectivity was assessed through a comparative study including six study cases in the European Mediterranean basin. In years with high fire occurrence, fires were selective in more LULC classes as compared to years of low fire occurrence. Summarizing, the selectivity analysis revealed a pattern relating small fires with human-influenced ecosystems and large, infrequent fires with natural ecosystems. This pattern was consistent, with small variation, throughout the study cases.

Lessons learned and implications: Knowledge of fire selectivity patterns allows for the development of landscape management policies in which fire prevention, pre-suppression and suppression strategies as well as knowledge of local fire history and ecology are fully integrated. Understanding the links between landscape and fire patterns can assist managers in arranging fuel breaks or reduce fuel load and reduce the hazardous characteristics of the landscape. Moreover, such knowledge allows development of LULC management rules and the implementation of policies leading to specific landscape goals adapted to the fire-proneness of the landscape features. Additionally, fire suppression forces are provided with information on priority areas with high fire hazard.

Fig. 4.2: The analysis of fire selectivity at different spatial scales over a wide geographical range provided an opportunity to summarize common patterns and distinguish important differences among the study cases, resulting in valuable information for fire management and policy.

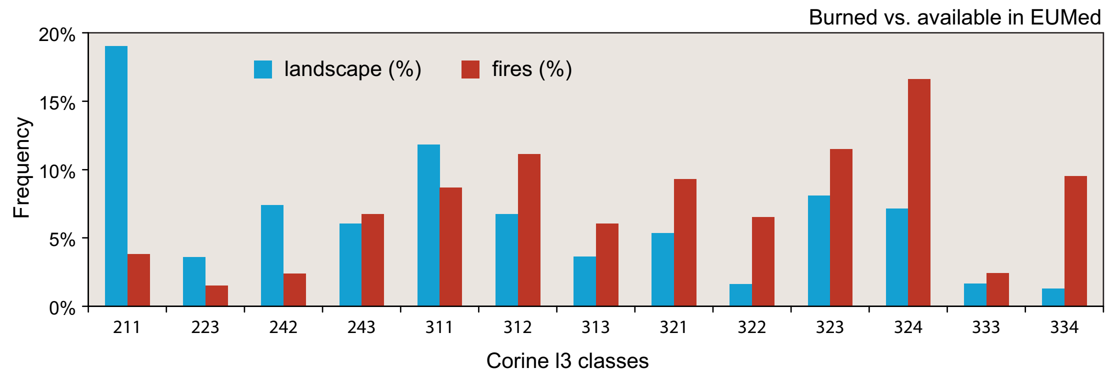


Fig. 4.3: It has been shown that wildland fires in Mediterranean Europe show clear evidence of selectivity towards the various LULC types. Additionally, it was shown that, at least at the EUMed scale, fires show a preference towards recently burned areas. Selectivity is shown when fires burn more (positive selectivity) or less (negative selectivity) (fires %) than what it is available (landscape %) in the territory.

Topic 5 Wild fire risk in the rural-urban interface

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Rural-urban interface (RUI, synonym of WUI, wildland-urban interface) are key areas in land management and planning for wildfire risk mitigation. A tool for RUI mapping was developed to help decision makers cope with risk management. Several methods for fire-risk assessment in RUI were developed, depending on the scale, the geographical context and data availability. Methods and tools were validated based on fire simulations and are now available. In addition, projections of future risk in RUI were obtained using land cover and climate change simulations. In the next four or five decades, mitigation of wildfire risk will depend on land managers capacity to control RUI development.

Implications for policy and management

- *RUIMap is a tool for RUI mapping. It enables land managers to locate critical areas for wildfire ignition and human vulnerability.*
- *Wildfire risk in RUI depends on fuel and building characteristics and their interaction.*
- *RUI are changing areas. If urban sprawl is not controlled, risk in RUI will increase notably in the next forty years.*
- *Future risk in RUI can be mitigated by limiting RUI sprawl and fuel load, by increasing building density and limiting RUI spatial complexity.*

The problem: During the last decades, discontinuous urban sprawl within Mediterranean forest lands and wildlands led to the formation of large RUI problem (Lampin-Maillet et al., 2010). In such areas, burnable vegetation is closely mixed with buildings and infrastructures. As a consequence, RUI are critical areas regarding the risk of wildfires (Salis et al., 2013). In the RUI, ignition probability is high because of human activities; while human vulnerability is maximized because of the high density of people. The knowledge of the spatial distribution of the different kinds of RUI, the associated risk and their past and future changes are key-decision elements for land management and planning.

Fig. 5.1: *The RUImap tool.*

The approach: The RUI research three main objectives were to: i) map the different types of RUI in the Mediterranean territories, ii) assess the wildfire risk associated to each RUI type, and iii) assess past and future change in RUI and the associated risk they induce. To do so, three methodologies for RUI mapping were specified and tested in different Mediterranean contexts: Central Spain, southern France and Sardinia (Italy). When validated, the methods were implemented in a dedicated easy-to-use tool, called "RUImap" (Fig. 5.1). Then, based on past fire studies, different models for risk assessment in RUI were specified. The models aimed at taking into account both hazard and vulnerability in RUI. Finally, past and future changes and risk in RUI were studied in several Mediterranean contexts using diachronic mapping and land cover change simulations.

Achievements: RUIMap is an easy-to-use software designed for RUI mapping at different scale levels (Fig. 5.2). The tool gives the user a choice between three main methods for RUI mapping: two at local or regional scale and one at global scale. The choice between regional scale methods depends on the geographical context and the available data. When using the RUI tool to map the different types of RUI, it is possible to assess risk in RUI by using one of the risk models specified in the FUME project. Again, the choice between methods depends on the user objective, the geographical context and scale, and the data availability. The "Irstea method" is designed to assess the fire ignition probability, the wildfire probability, the burned area ratio and finally, the global risk in relation to RUI types and other geographical variables. The "TRAGSATEC method" is designed to assess the demographic risk linked to population, a propagation risk linked to vegetation fuel, and a statistical risk linked to past fires. A model for human vulnerability assessment was also designed based on experts' analysis. Finally, all the models were validated using fire propagation simulations in RUI. The risk models were used to predict future-risk in RUI, in relation to future land cover change and climate change. An important increase of RUI areas and of risk is to be expected in the next forty years because of discontinuous urban sprawl and more importantly, dryness.

Lessons learnt and implications: During the next decades, forest fire-risk will continue to be a significant problem for land-managers. A clear map of RUI types enables decision-makers to more efficiently locate their operational actions for wildfire risk mitigation. The actions have first to simplify the interface between vegetation fuel and the resources protected. Reducing urban sprawl by concentrating urban development would help mitigate wildfire risk in RUI. However, this would also increase vulnerability. Therefore, fire protection resources and fuel breaks should be located all around the discontinuous and continuous urban areas, to create a buffer between them and the forest.

Left: Patones (Madrid, Spain)

Right: Altinkaya (Antalya, Turkey)

Photos: J.M. Moreno

Rural-urban interface

The rural-urban interface (RUI) represents an area between continuous artificial zones and continuous fuel vegetation (forest, shrubland, grassland). Small patches of agriculture may also be present. Within RUI, buildings and human infrastructures are closely mixed with fuel vegetation creating high wildfire risk. RUI are also changing areas in time: they become wildlands around towns, and disappear with the urban densification. The dynamics can be controlled by land management and planning measures.

Fig. 5.2: *An example of rural-urban interface map at local scale. AI = Aggregation Index (i.e., an assessment of vegetation continuity).*

Topic 6 Socioeconomics and fire relationships

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The importance of the human component on forest fires is difficult to model because it involves quantifying and mapping human activities operating at scales and magnitudes difficult to match with those of other geophysical and biological factors. In FUME we defined and compiled a number of socioeconomic variables with a direct or indirect influence on forest fires, and applied different statistical methods to generate spatial models that could explain the human component in wildfires. Analyses were done at EUMediterranean level but also at national and regional scales in study sites located in Greece, Italy, Spain and France.

Implications for policy and management

- *Socioeconomic factors (e.g., land uses and their interfaces, accessibility, age of agrarian holders) highly determined past forest fire occurrence in EUMed. Therefore, they should play an increasing role in operational fire risk systems.*
- *The role played on fires by a given factor, however, can vary across regions. Hence, region-specific models would be needed.*
- *Factors affecting ignition are different from factors affecting fire spread. Hence, changes in fire risk are the result of particular combinations of changes in socio-economic factors.*
- *Consistent and regularly updated, spatialized socio-economic information is needed to anticipate changes that could affect future fire risk.*

The problem: Socioeconomic changes occurring in the last decades in European Mediterranean countries resulted in an increase of wildfire risk. Rural lands depopulation and abandonment has facilitated invasion by flammable species thus increasing fire hazard. Additionally, a shift of rural areas towards recreational use has led to the rural-urban interface (RUI) problem, increasing ignition risk. Socioeconomic factors have a critical importance in all phases of fire management (prevention, extinction and restoration). In spite of its importance, modeling the role of socioeconomic changes on fire occurrence, both in space and time, and its integration with other natural factors in a comprehensive scheme that helps understanding fire regimes, is poorly developed.

The approach: In FUME, we worked on the evaluation of the historical contribution of observed socioeconomic changes (including land use and land cover changes) on fire activity at different temporal and spatial scales. We first identified socioeconomic factors and related variables associated with fire occurrence in Mediterranean Europe. Afterwards, these variables were compiled in different study sites and used as predictors or independent variables in the development of models to assess the role of socioeconomic factors on fire occurrence. Analyses were done at several scales: EUMediterranean level, national level (Greece and Italy), and regional level (Peloponnese – Greece, Central Spain and Madrid region – Spain, and Languedoc Roussillon – France). Figure 6.1 shows some of the socioeconomic variables compiled at the EUMediterranean level for the period 1983-2000. Figure 6.2 displays the maps of fire occurrence and main socioeconomic driving factors spatially-explicit and aggregated by time (1974-2008) in the study area of Central Spain.

Achievements: FUME activities demonstrated how human factors can be modelled to integrate them into general fire-ignition risk-estimation systems with a spatial–temporal dimension. Results show that socioeconomic factors are relevant to explain fire occurrence in Mediterranean Europe although their characteristics and importance differ between regions. In general, results showed that the probability of fire occurrence was high in areas with:

1) high proportion of interfaces (contact areas between forest and other specific land uses in EUMed, Madrid and Central Spain, and Languedoc – France);
2) high road and railway density (Madrid and Central Spain, Italy);
3) high proportion of labour force in services sector and touristic flows (Madrid – Spain, Italy);
4) high proportion of farm holders older than 55 years (EUMed, Central Spain);
5) high proportion of transitional woodlands, conifer forests (Central Spain) and shrublands (Languedoc – France);
6) high proportion of reforestation (conversion of deciduous forests to conifer forests) and stable hazardous land use and land cover (LULC) types (i.e., shrublands and forests) (Central Spain).

Lessons learned and implications: Explanatory models of fire occurrence across different European areas indicated the significant role of the rural-urban interface (RUI) in affecting fire regimes, confirming the need of adopting prevention measures in those areas where human activity is an important ignition source. Additionally, road and railway networks increased fire occurrence because better accessibility may imply more human pressure on wild lands and, consequently, more ignition sources. A positive relation was also found between fire occurrence and labour force in services sector and touristic flows that could be indirectly related with an increase of recreational activities in the forest, leading to an increase in fire ignition risk. Agricultural and livestock activities have also explained fire occurrence, however, the sign of those activities differed among study areas and scales. For land cover variables, fire occurrence was higher in areas with high occupation of shrubland, transitional woodlands, conifer and mixed forests as well as in areas with high proportion of reforestation.

Bozyaka (Antalya, Turkey). Photo: J.M. Moreno

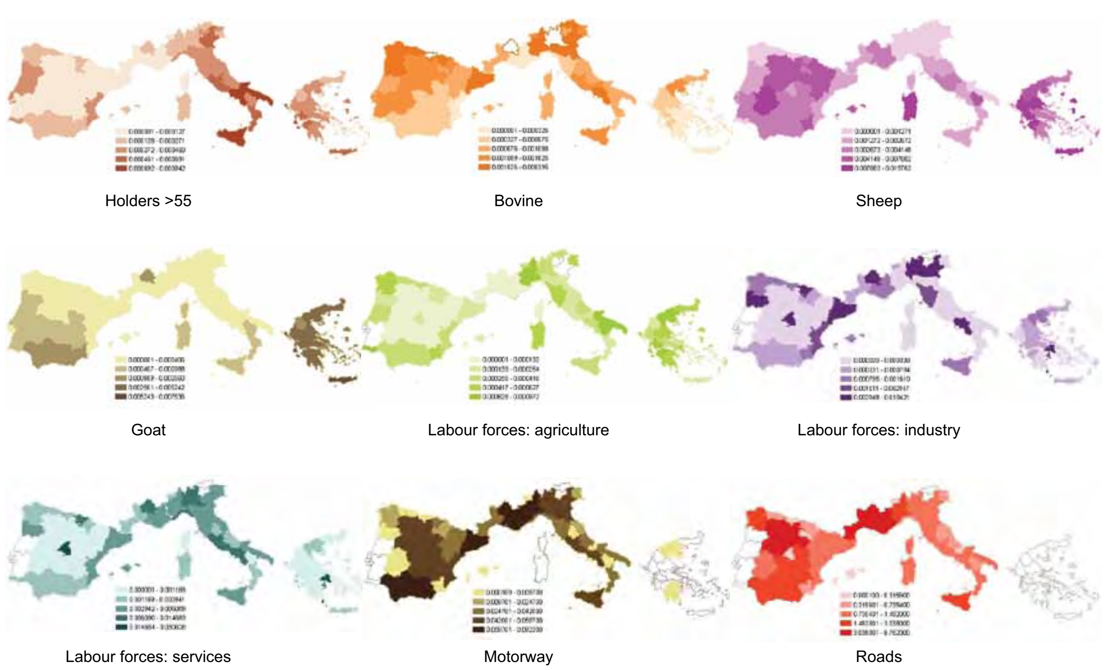

Fig. 6.1: Maps of socioeconomic driving factors of fire occurrence at EUMediterranean level (2000's time period). Source: EUROSTAT. ***Holders >55:*** *Agrarian holders older than 55 years. Structure of agricultural holdings by eurofarm region, main indicators: number of Holder's being a natural person by NUTS2 [number/km²]* ***Bovine, Goat, Sheep:*** *Number of heads of livestock. Number of farms and heads by livestock units of farm and region: number of heads bovine, goats, sheep by NUTS2 [number/km²]* ***Labour forces – Agriculture, industry, services:*** *Density of labour force in different economic sectors (agriculture, industry, services). Employment by economic activity (agriculture, industry, services), by NUTS2 regions [number/km²]* ***Motorway, Roads:*** *Road/motorway and navigable inland waterways networks at regional level (NUTS2) [total lines/ km²].*

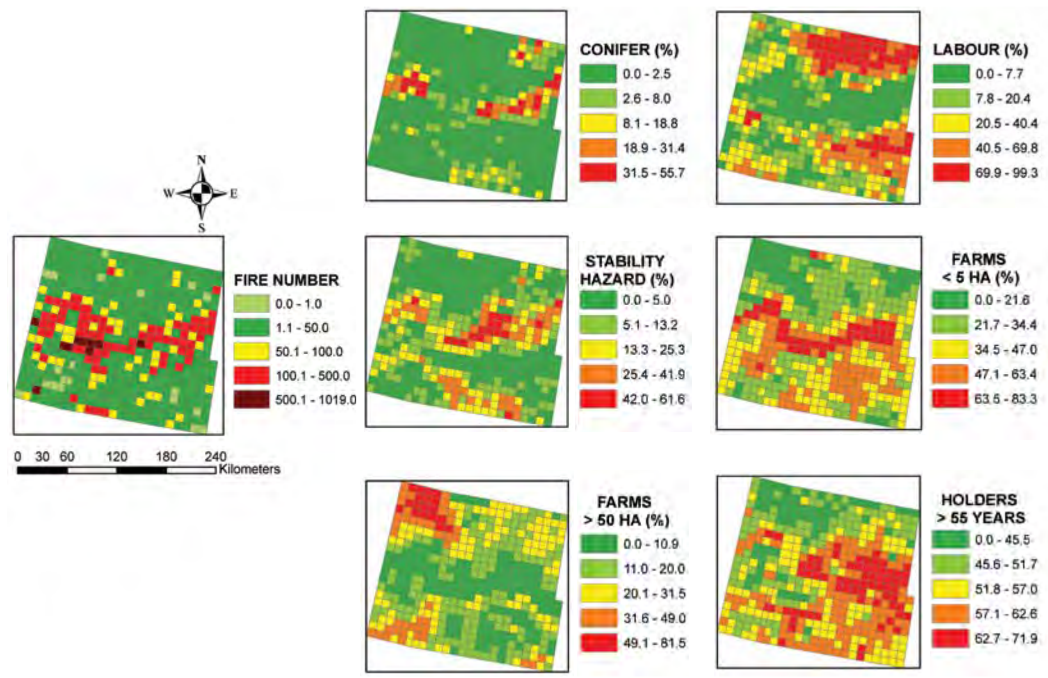

Fig. 6.2: Maps of fire occurrence and of main driving factors spatially-explicit and aggregated by time (1974-2008) in the study area of Central Spain (by UCLM); cell scale 10 x 10 km. ***Fire number:*** *Sum of daily number of fires from 1974 to 2008. Source: Spanish Fire Statistics from the Ministry of Agriculture and Environment.* ***Conifers (%):*** *Mean percentage of occupation of conifer forests, based on LULC maps from 1978-1986-2000-2006.* ***Labour (%):*** *Mean percentage of occupation in agriculture areas, based on LULC maps from 1978-1986-2000-2006.* ***Stability Hazard (%):*** *Mean percentage of occupation of stable areas (no change areas) between pairs of LULC maps (1978-1986, 1986-2000 and 2000-2006).* ***Farms <5 ha:*** *Mean density of small farms (<5 ha), based on Agrarian Censuses from 1972-1982-1989-1999-2009.* ***Farms >50 ha:*** *Mean density of large farms (>50 ha), based on Agrarian Censuses from 1972-1982-1989-1999-2009.* ***Holders >55 years:*** *Mean percentage of land-holders older than 55 years, based on Agrarian Censuses from 1972-1982-1989-1999-2009.*

Topic 7

Fire and weather relationships: present climate

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The relationships between weather/climate conditions and fire through the analysis of historical meteorological data and fire records were investigated using different algorithms and methodologies at several scales, from the Euro-Mediterranean level, through national, NUT02, and local scale. In spite of the use of such a wide range of methodologies and spatial scales, the importance of similar concurrent (and precedent) fire season climatic factors was observed. In particular, seasonal droughts in the months prior to the fire season peak, occurrence of heat waves, and strong winds during the fire season have a strong influence on fire occurrence and seasonal severity across scales.

Implications for policy and management

- *Dry spells and other weather anomalies (heat waves, strong winds) play a driving role in fire outbreaks.*
- *Progress in weather forecasting may allow improvements in fire danger and risk prediction.*
- *Climate anomalies (e.g. long drought periods) are causal factors of severe fire season. Long-range predictions can be thus used to anticipate fire season dynamics, helping in planning activities such as resource allocations and strategic fuel management.*
- *Trends of meteorological variables at larger scales do not necessarily reflect what happens at smaller scales. Improvements of local knowledge would enhance all fire management phases, from prevention to firefighting activities.*

The problem: Fire occurrence in the Mediterranean region varies considerably from year to year, suggesting a strong dependence on meteorological conditions. In fact, climate and weather are two key fire drivers acting directly and indirectly on fuel biomass and moisture, which are among the main factors of fire ignition and behaviour. However, these relationships must consider the anthropogenic component, particularly in areas where most ignitions are human caused. Specific analysis of the driving forces of fire regime across countries and scales are still required in order to better anticipate fire occurrence and also to advance our knowledge of future fire regimes.

The approach: FUME project attempted to unravel the relationships between fire and weather using several statistical approaches and data for at least the last two decades (1985-2005). The analyses were performed at several scales (Fig. 7.1) in different Mediterranean climate areas of the world, ranging from the Euro-Mediterranean level, through national (Portugal, Spain, Italy, Greece, Finland) and NUT02 scales (North Morocco, Comunidad Valenciana, Languedoc-Roussilon, Sardinia, Tuscany, Peloponnese, Attika, Antalya, S. Central Chile, Western S. African Cape), to very local level (Mt. Parnitha and Mt. Penteli, Greece).The main variables collected were: fire number (FN) and burned area in hectares (BA), precipitation, temperature, relative humidity, and wind, mainly at daily/monthly time resolution. A series of common analyses were firstly done across areas to investigate the relationship between the series of data, followed by more sophisticated non-linear algorithms. In few study areas, synoptic conditions forcing fire occurrence were also investigated.

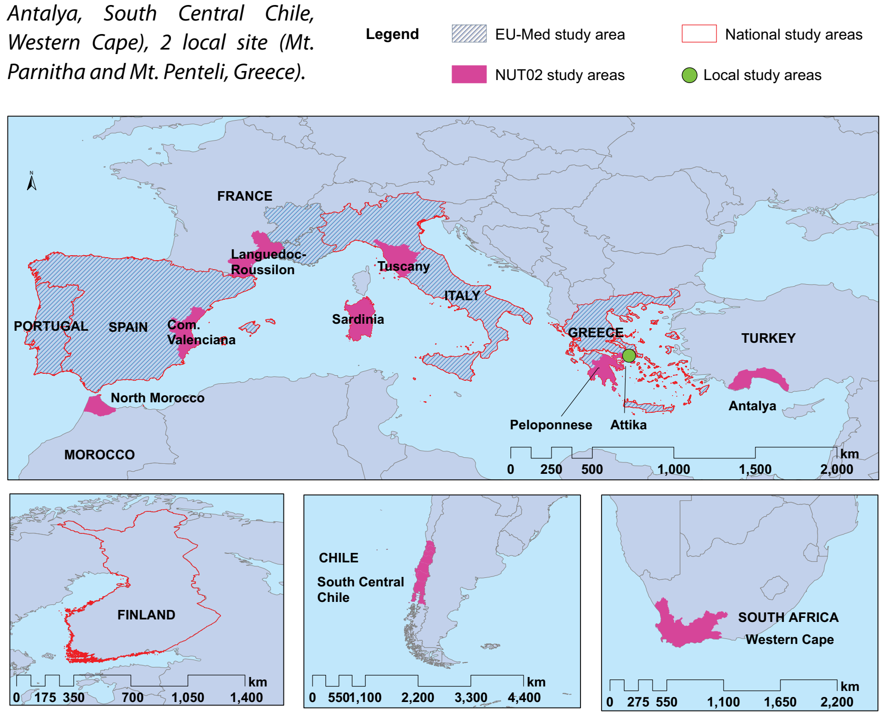
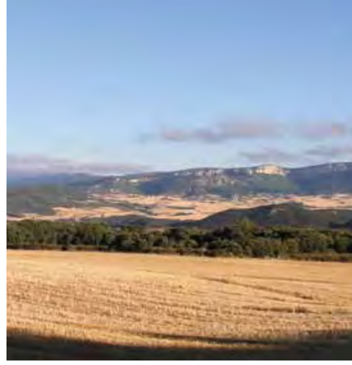


Fig. 7.1: FUME project study areas: EUMed (Portugal, Spain, South France, Italy, Greece), 5 countries (Portugal, Spain, Italy, Greece, Finland), 10 NUT02 regions (North Morocco, Comunidad Valenciana, Languedoc-Roussilon, Sardinia, Tuscany, Peloponnese, Attika, Antalya, South Central Chile, Western Cape), 2 local site (Mt. Parnitha and Mt. Penteli, Greece).

Achievements: EUMed scale: Precipitation was the variable that more influenced the multiple linear regression models at this scale. National scale: In general, severe years in terms of burned areas were related to anomalies in precipitation, both before and during the fire season, and anomalies of temperature (Fig. 7.2 and Fig. 7.3). Northern Italian areas showed a significant negative correlation also with minimum temperature. In Finland, annual precipitation and relative humidity correlated more strongly with annual BA. On the Iberian Peninsula, warm and dry fluxes associated with anticyclonic regimes were found to be the typical synoptic configurations favouring large burned areas. Regional scale (NUT02): both antecedent and concurrent fire season weather conditions appeared to be well correlated with the number of fire outbreaks and BA. In general, the total area affected by fires during wet summers tends to be small, while during dry summers it could be either small or large. On the other hand, in Antalya (Turkey), highest correlations were found with mean and minimum temperature. In Valencia (Spain), dry situations associated with Atlantic frontal and continental backward advections are responsible for a greater extent of BA per day. In South Central Chile, strong relationships between fires and large-scale climatic oscillation patterns (e.g., ENSO) were found. In South Africa, the focus on event-driven fires (e.g. foehn wind conditions) provided more insight than exploring mean annual fire risk conditions. Local scale: significant relationships between BA and summer precipitation were found in Mt. Parnitha and Mt. Penteli (Attica, Greece); however, accounting only for a small part of the BA variability.

Lessons learned and implications: Meteorological conditions, both antecedent (such as droughts) and during the fire season (such as strong wind, heat waves), seemed to have a strong influence on seasonal severity (i.e., area burned). Several results suggested the dual role of precipitation in fuel build-up and dryness. The simple statistical models developed in FUME and the identified synoptic conditions can reproduce a great part of the inter-annual fire variability and the circumstances triggering large or extreme fires. They could be easily incorporated in short-term predictive models of fire risk, long-term planning strategies, as well as inputs for the construction of future fire scenarios (see topic 12).



Los Arcos (Navarra, Spain). Photo: B. Pérez

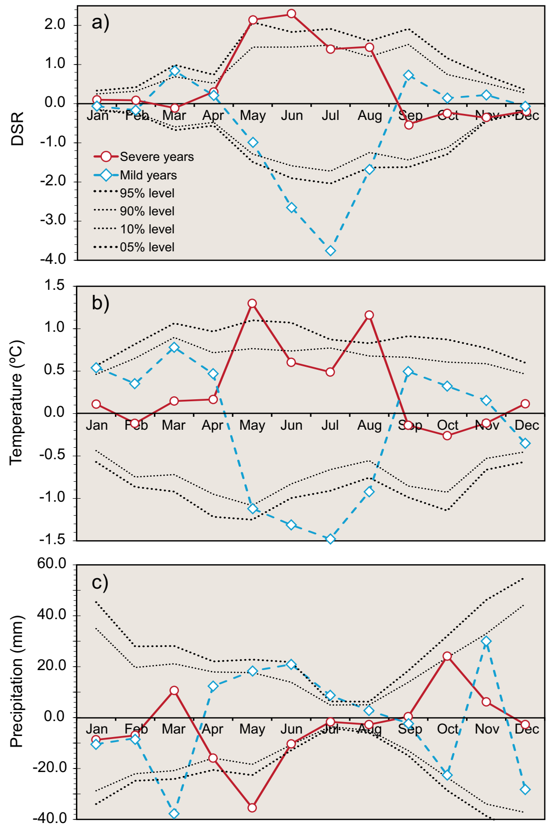


Fig. 7.2: Monthly anomalies of a) the daily severity rating (DSR), b) temperature, and c) cumulated precipitation for composite of severe (Severe years) and mild (Mild years) fire season within the 1980-2011 period in Portugal. Dotted lines: 95, 90, 10, and 5% statistical significant level (from Pereira et al., 2013).

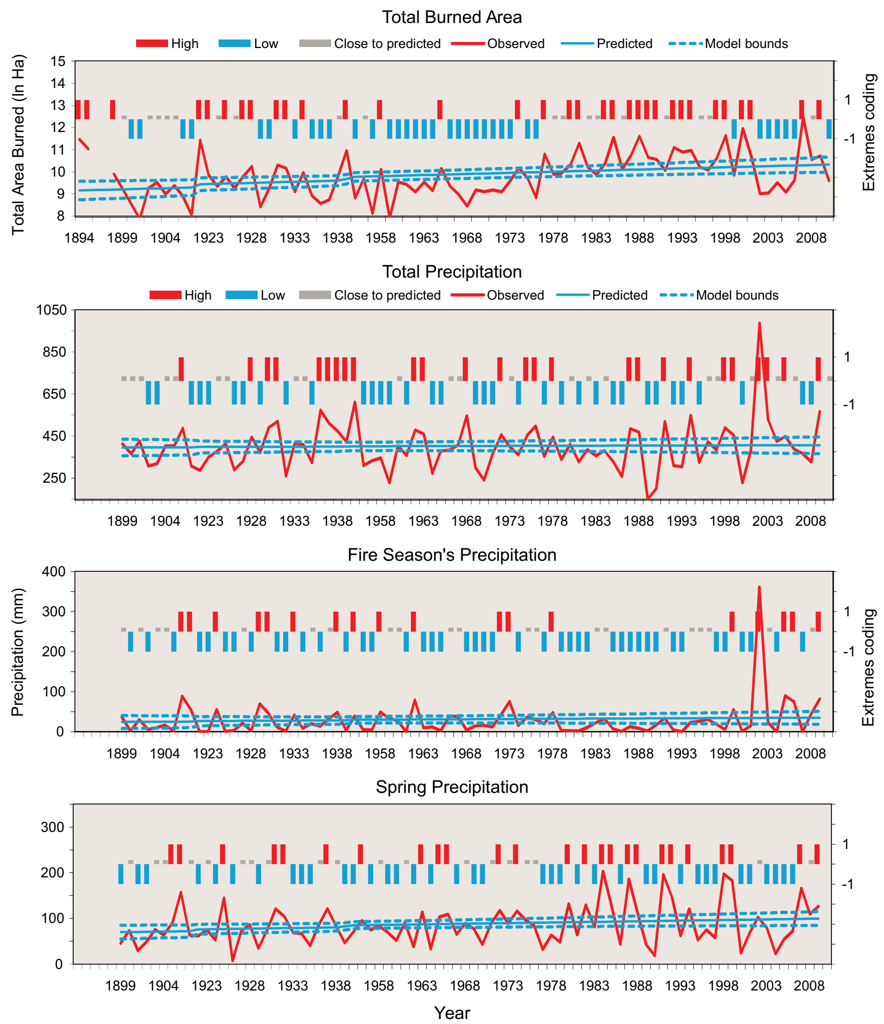


Fig. 7.3: Trend lines and 95% confidence intervals of the trend line of fire occurrence statistics (burned area) and the trend line of precipitation related meteorological parameters (total, spring and fire season precipitation). These are used as bounds to define strongly positive (red columns), strongly negative (blue columns), and close-to-predicted (grey columns) values of fire occurrence (modified from Xystrakis et al., 2013).

Topic 8 Disentangling confounding factors in the fire-climate relationships

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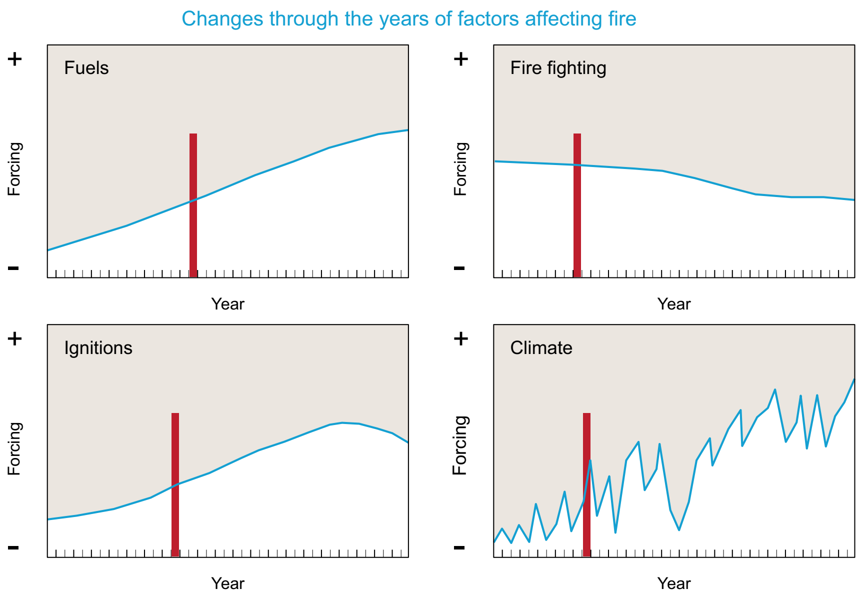
Fires result from a number of interacting factors that change through time. Climate-fire relationships through the years can be confounded if the change in each factor is not properly considered. Climate is the main variable that can significantly change from year to year. We investigated climate-fire relationships in EUMed and California using the first year derivative of fires and climate. We used the Canadian Fire Weather Index (FWI) as proxy of climate variability. We found that, in general, the relationship between the two is significant for either yearly number of fires or, less robust, area burned. This relationship is independent of any other changing factor, allowing attributing change in fires to climate. The relationships were stronger in EUMed than in California.

Implications for policy and management

- *Forest fires (number of fires, area burned) were positively correlated with climate (via FWI) and independently of other factors during the last 30 years, clearly in EUMed, despite the fact that number of fires and area burned have been recently decreasing.*
- *In areas where strong changes in other drivers have occurred, observed fire-climate relationships need to be revisited and appropriate methods used to attribute change in fires to climate.*
- *The large range of variability observed in FWI indicates that extrapolations to a changing climate in the near future are likely.*
- *The robustness of the relationships at higher levels of aggregation (countries, whole EUMed) indicates that seasonal forecast can be used to anticipate fire activity at large scales.*

Fig. 8.1: Fires result from multiple interacting factors, some positively contributing to increase fire risk, others negatively, which can vary through time independently from one another and at various rates of change. Relating fires to climate using long study periods needs to take into account the other possible "confounding" factors. From year to year (red bars), climate is assumed to be the only relevant changing factor.



The problem: Forest fires are the result of a number of interacting factors (climate, fuels, landscape structure, ignitions, firefighting capacity, etc.). The study of climate-fire relationships requires long series of data. However, changes through time in factors other than climate can also affect fire activity (i.e., yearly number of fires, area burned). Relating changes in fire through time to just climate, even if it is the most relevant one, ignoring the other, can be misleading (Fig. 8.1). Therefore, procedures are needed that account for changes in all relevant factors to attribute changes in fire to climate. This is important in a context of climate change where attribution to climate and climate change is a desired objective of research.

The approach: The procedure used was based on the assumption that factors affecting fire differ in their temporal frame for enacting a significant impact. Climate was assumed to be the only factor that could significantly change from one year to the next. All other factors were assumed to need time exceeding one year to produce a significant impact on fires. Based on this, the changes in fires (number of fires or area burned) that occur from one year to the next can be assumed to be caused mostly by the changes that occurred during the same time period of the relevant climate variables. Regressing the year-to-year changes in both variables (% change in fires vs. change in climate) through time (up to 30 years of data were available) permitted determining the relationship between climate and fires discarding the influence of other slow-changing factors. Therefore, an indirect attribution of fires to climate was possible. Because the climate of the year can be characterized by a number of variables, we used as a surrogate of climate the Canadian FWI index, which is calculated based on a few climatic variables.



From left to right:

Anchuras (Ciudad Real, Spain). Photo: I. Torres

Santa María del Espino (Guadalajara, Spain). Photo: A. Velasco

Arbutus unedo resprouting (Cabañeros National Park, Spain). Photo: I.R. Urbieta

Achievements: We tested climate-fire (number of fires and area burned) relationships in two contrasted areas: EUMed and California. At EUMed, calculations were made for provinces (Peninsular Spain) [1979-2008], regions (proxy of NUTS2) [1985-2010] and whole EUMed [1985-2010]. In California, calculations comprised national forests [1979-2008], and NOAA climatic regions [1985-2010]. The analysis was performed for the main fire season (summer) and fires occurred during that season (Spain, EUMed) or during the whole year (California, owing to the fire season being longer, up to and including autumn). We found that, for most Spanish provinces, there was a significant relationship between the year-to-year change in number of fires (78% of the provinces) or area burned (64%) and year-to-year change in FWI. Number of fires was usually better correlated than area burned to yearly-change in FWI. As the level of aggregation increased, from provinces to regions within EUMed, these relationships were maintained or increased, and virtually held up in all regions tested (95%, 83% for number of fires and area burned, respectively) (Fig. 8.2). Furthermore, when the whole EUMed countries were considered as a single unit, the relationship was rather strong, with R^2 values of 0.6 and 0.7 for number of fires and area burned, respectively. The analysis for California rendered similar, although more variable and usually less robust, results. Significant relationships were found in 35% and 50% of the national forests for number of fires and area burned, respectively. At the regional level, 40% of the regions showed a significant relationship for number of fires and area burned.

Lessons learned and implications: Results for EUMed and California show that climate (by way of the FWI) and fires have been positively correlated for the last decades, and that this relationship can be ascertained independently of changes in other drivers that occurred in the areas analysed during this time. This has occurred despite the fact that in EUMed the number of fires and area burned has been decreasing during the last years (San Miguel-Ayanz et al., 2013). Thus, we can detect a climate signal in fires. Because during this time FWI showed a significant upward trend, consistent with regional climate change, given the relationships we found, it can be argued that part of the observed change was due to climate change.

Attribution to climate change

Attribution is "…the process of evaluating the relative contribution of multiple causal factors to a change or event with an assignment of statistical confidence…" (Hegerl et al., 2010). Detecting changes in impacts on ecosystems through time and attributing them to climate change is an important subject of investigation. When the measured impacting variables (fires in our case) respond to a number of interacting factors (Fig. 8.1) this must be fully considered when trying to determine cause (climate, climate change) and effect (fires) in order to not attribute an effect to the wrong cause. Actually, effects may be masked or not even be detectable when various drivers affect in opposite direction a given variable. Hence, trends in the measured response variable can be positive, negative or absent. Yet, climate might be affecting the studied response variable.

Fig. 8.2: EUMed regions with positive and significant relationships between the year-to-year change in number of fires or area burned as a function of year-to-year change in climate as reflected by the mean FWI index of the fire season. Positive relationships indicate that climate and fires were related during the studied period, under the assumption that on a year-to-year basis all other factors did not significantly change as to affect fires. Red: Number of fires and area burned significant; Blue: only one relationship significant (number of fires or area burned).

Topic 9 Land use and land cover change modeling

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An ensemble of multi-scale (regional to local) simulations of potential land use and land cover change (LULCC) for the EUMed region was conducted using future projections of climate and socioeconomy. The aim was providing robust estimates of expected changes of land cover in the short- to long-term future. The combination of land cover and climate changes leads to an increase of fire hazard and eventual fire risk. Simulations allow anticipating future change in land cover patterns at regional level as well as discontinuous urban areas and rural-urban interface (RUI) at local scale. Change in land cover, urban sprawl and modifications in spatial structures must be monitored and foreseen to facilitate fire risk prevention and mitigation.

Implications for policy and management

- *If not controlled, Mediterranean future land cover change will continuously increase fire hazard and eventual fire risk in the near- to long-term future.*
- *Fire hazard and risk increase is due to both future changes in land cover and discontinuous urban sprawl within forest land.*
- *Forest spreading on abandoned agricultural or pastoral land will increase fuel loads, while climate change might increase vegetation dryness.*
- *Discontinuous urban sprawl within forest leads to more complex RUI spatial structures which will increase ignition probability and anthropogenic vulnerabilities.*
- *Besides prevention equipment setup, future risk management will have to focus on land planning and forest management.*

Calatafimi (Sicilia, Italy). Photo: J.M. Moreno

The problem: In recent years, land abandonment and reforestation policies increased fires. Moreover, the interaction between forest and urban sprawl resulted in the development of rural-urban interface (RUI). To make land planning and ecosystem management decisions more successful for fire risk mitigation, land cover changes must be projected, taking into account climate change as well, using simulations based on spatially explicit models. Such simulations need considering complex dynamics: while climate change is already influencing the natural suitability of territories to be used for specific purposes or to host natural vegetation, the requirements of surfaces for human activities force LULC allocation and redistribution.

The approach: Using the economic model ICES@CMCC (Michetti and Parrado, 2012), we developed future LULC demands for two years and three EUMed sub-regions. Such demands were interpolated every ten years up to the year 2100 and spatially allocated through the LULCC model LUC@CMCC (Santini and Valentini, 2011). An ensemble of potential LULCC scenarios based on multiple climate change and socioeconomic projections allowed considering a representative range of potential developments. For selected case studies (2 in Spain, 1 in France, 1 in Italy, and 1 in Greece) the LULC model was adapted for local evaluations on land cover change and fire hazard at finer spatial detail (Fig. 9.1). Additionally, future structural changes in RUI were simulated at regional scale using the GIS-based Macropolis model to reproduce changes in RUI types while, at local scale, the multi-agents based model Micropolis simulated fuel mass and building density for a number of local sites (Maillé and Espinasse, 2011).

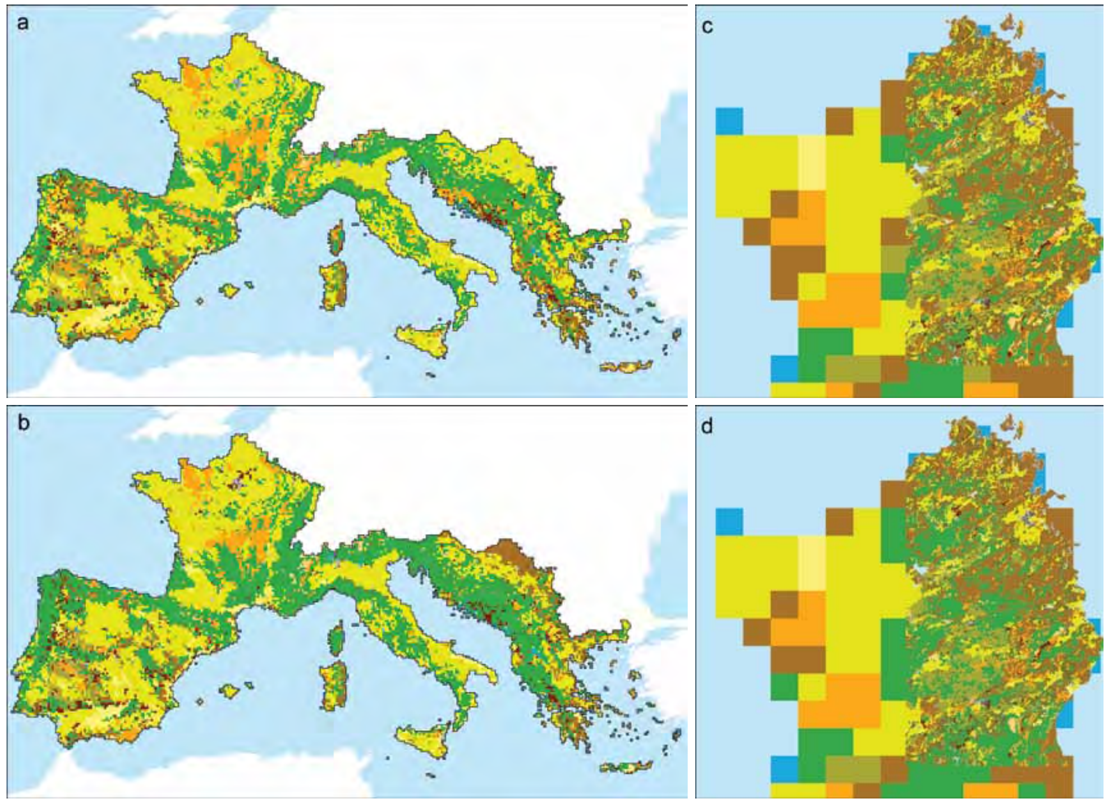
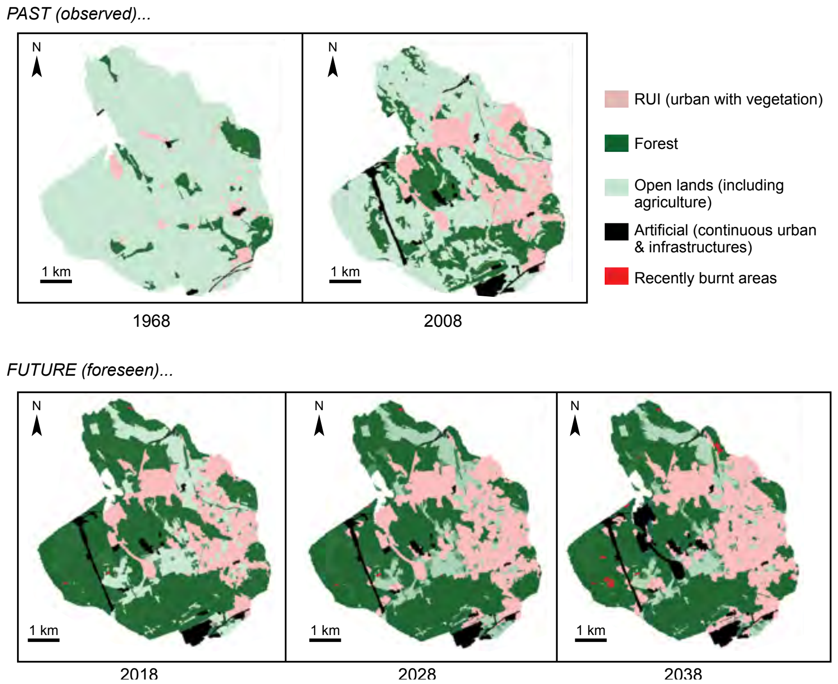


Fig. 9.1: Upper panel: EUMed scale maps show simulated changes in LULC distribution from year 2000 (a) to 2100 (b). Lower panel: local scale land use reconstruction for North-East Sardinia from 2000 (c) to 2100 (d) under the same legend used for the EUMed scale.

Achievements: Based on projections of changes for the two main drivers (i.e., climate and socioeconomy), LULC change scenarios suggest that from 2000 to 2100, more than 10% of the territory (almost 20 Mha) could undergo changes (Fig. 9.1). When assuming protected area as territories preserved from changes, land modifications were reduced to 9% of the region, with about 2 Mha saved from any LULC change. This confirms how land protection and regulation can favour more balanced demands and allocation of lands, avoiding overpressure and loss of natural suitability for specific uses, functions or services. Fuel spatial distribution is a key factor of these future changes: ensemble results show a future increase of areas with medium to high fire hazard (Fig. 9.1). Simulations of changes in spatial structures showed a future increase in spatial complexity of RUI during the next three to four decades, depending on the regional context (Fig. 9.2). Then, urban areas might become denser and fill the remaining fuel areas within RUI. The effect of local scale land planning on regional change in spatial structures might be low if the consistency of the different local plans is not insured.

Lessons learned and implications: Despite gaps in data availability, consistency and heterogeneity across the EUMed region, future LULC change could be modelled. Since a significant portion of the land could change in how it is used, conditioning future fire hazard and risk, indicates that LULC modeling tools could be valuable for fire prevention. Planned decisions, like reserving part of the land for conservation, can affect future landscapes, hence providing tools to assess options for the various needs, including reduced fire hazard. Decisions for land planning to mitigate fire risk must build on accurate and reliable analyses about changes in land cover, urban sprawl and even modifications in spatial structures at RUI.

Fig. 9.2: An example of observed past (top) and simulated future (bottom) land cover change and RUI spread on a local municipality (Cabriès, France), from 1968 to 2038 (Model Micropolis, IRSTEA).



Topic 10 Assessing changes in fire hazard in Mediterranean landscapes by fire modeling

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The prediction of fire spread by wildfire simulators is a convenient way to incorporate spatial and temporal variations of key factors affecting wildland fires. Wildfire simulators based on Rothermel's model were used in different configurations, with the aim to calibrate wildfire models along the Mediterranean basin, and then to analyze the effects through time of the main key factors affecting wildfire likelihood and intensity. An increasing trend of wildfire intensity was observed in several study areas for the past, while future scenarios of climate and land uses highlighted a combined increase of wildfire size and intensity.

Implications for policy and management

- *Wildfire management agencies can increase the use of wildfire simulators for landscape pre operational and operational applications.*
- *Policy makers and management agencies can use wildfire simulators at landscape scale to monitor and evaluate the responses to their prevention plans.*
- *The accuracy and reliability of operational tools and predictions can be enhanced by cooperation between wildfire management agencies and researchers.*
- *The use of wildfire simulators can be the better way to address at landscape scale the complex questions regarding the future changes of wildfire key factors.*

The problem: Policy makers and management agencies require information on wildfire probability and severity to manage fire-prone landscapes and to evaluate the efficacy of prevention plans. The incorporation of the key factors that affect wildfire propagation requires the use of a modeling approach able to provide reliable and accurate estimations of wildfire spread and behaviour. With this aim, wildfire simulators based on semi physical approach are increasingly applied and tested, often in a probabilistic configuration. The use of wildfire simulators for landscape pre operational and operational applications requires landscape scale calibration and validation phases, and evaluation of sensitivity to landscape input data.

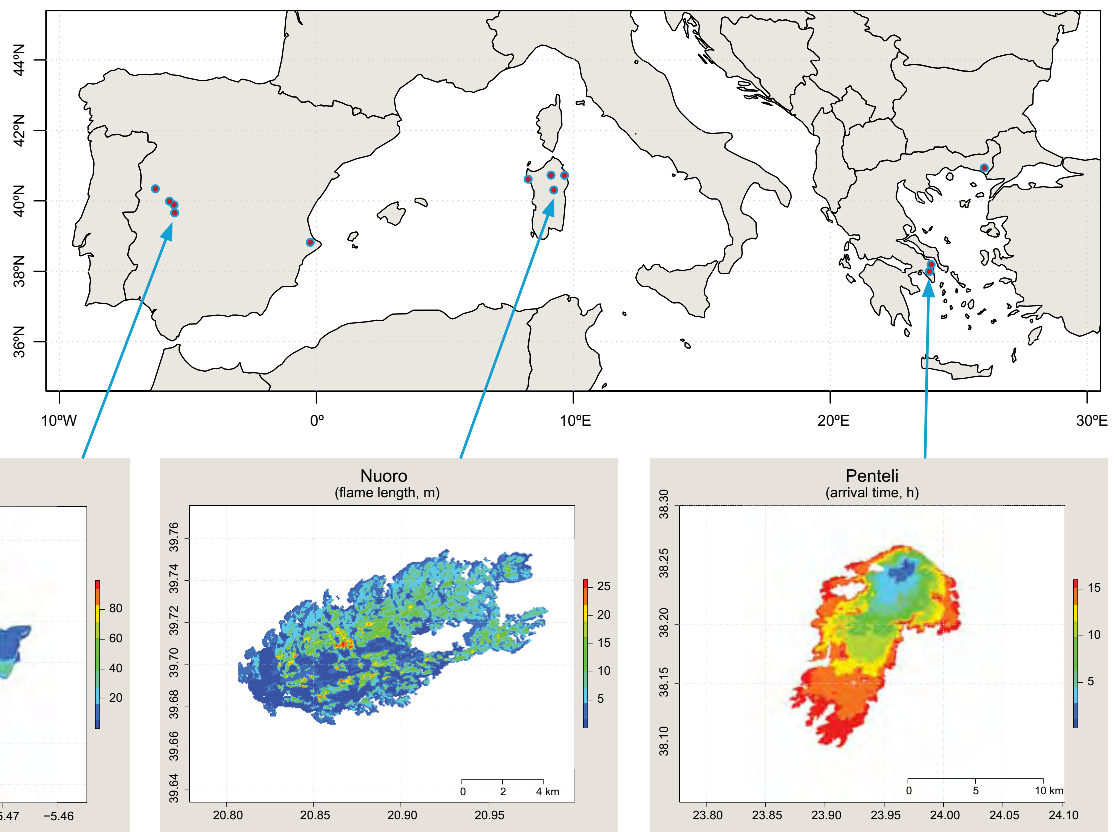
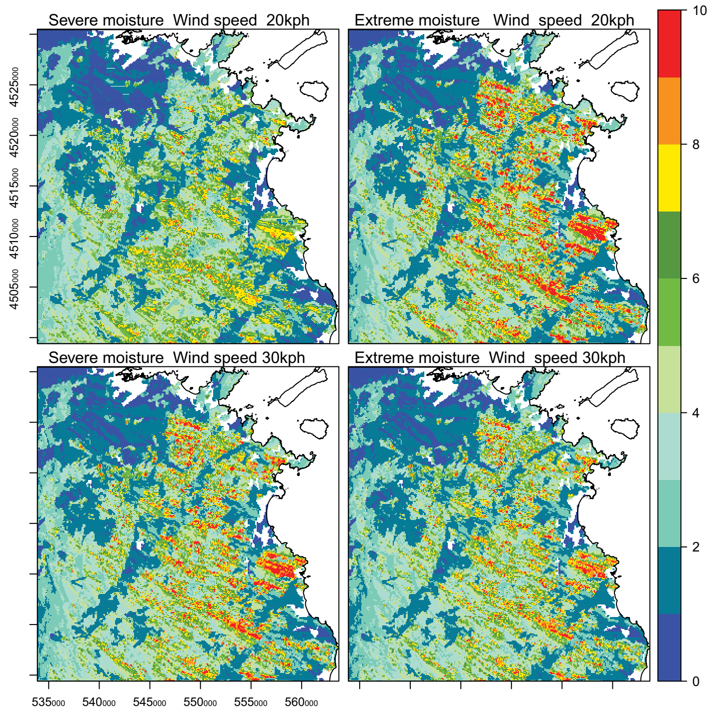
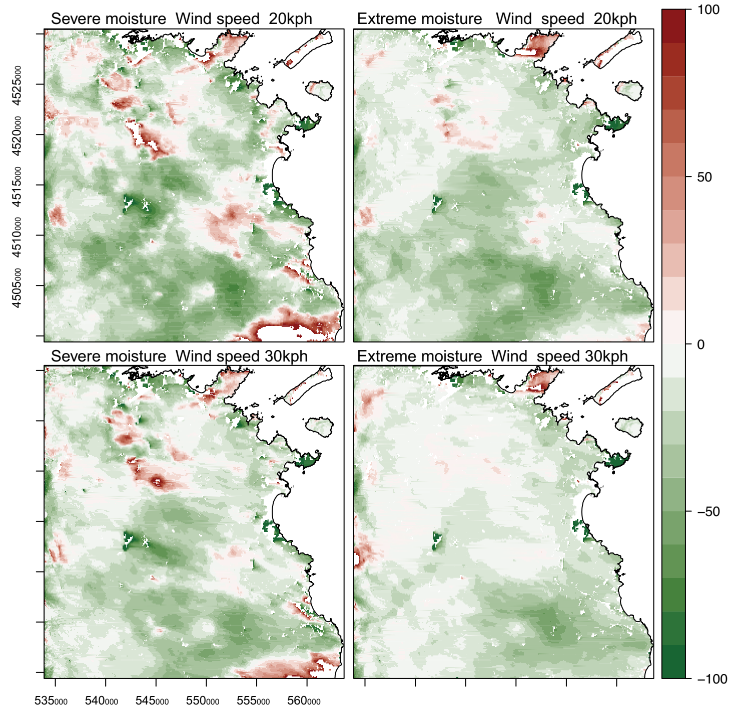


Fig. 10.1: Location of the sites across the Mediterranean Europe, in which fire behaviour models were tested for specific fire events, using standard and customized fuel models and high resolution wind field data.





Top left - Fig. 10.2: Maps of the North Sardinia (Italy) study area showing FlamMap flame length (m) estimates using different scenarios of fuel moisture and wind speed; the fuel model map was derived from 1977 land cover and land use data.

Top right - Fig. 10.3: Temporal variation (%) of FlamMap burn probabilities calculated between 1977 and 2000 in the North Sardinia (Italy) study area using different scenarios of fuel moisture and wind speed. The burn probability is the chance that a pixel will burn considering one ignition in the whole study area.

The approach: Two fire spread simulators based on the Rothermel's model (FARSITE and FlamMap) were used in different configurations. The first configuration was devoted to the model calibration and validation using a set of case studies, based on real fires which covered an East-West transect along the Mediterranean basin (Fig. 10.1). The second configuration was devoted to apply wildfire simulators using a probabilistic approach, in order to predict the effects through time of the main key factors affecting wildfire likelihood and intensity. For the predictive objective, two time periods were used to provide input data for simulations: the past conditions of land use and key factors between 1950 and 2000, and the future conditions, from the present to 2070. Spatial and temporal variations in wildfire size and area burned probabilities, derived from simulated fire perimeters, and fire intensity, derived from simulated flame length, were evaluated and associated to the key factors, analysing the anomalies induced by both land use and climate weather.

Achievements: The modeling activities performed at different temporal and spatial scales confirmed the efficacy of wildfire simulators as tools in wildfire analysis and prediction. The calibration at local scale (Fig. 10.1) highlighted that both wind field data and accurate custom fuel models are critical in predicting wildfire spread and behaviour. Increased accuracies in simulated fire perimeters and behaviour were obtained using custom fuel models, in particular in shrublands and broadleaf forests, while in grasslands and conifer forests the standard fuel models provided good results. Moreover, the use of fluid dynamic computational models allowed to produce more accurate wind fields for the simulations, and therefore to increase the reliability of the predicted outputs. The application of simulators in a probabilistic configuration considering past conditions of land use and other key factors (Fig. 10.2, Fig. 10.3) highlighted, in recent time steps, both significant reductions in wildfire size and increases in wildfire intensity, in comparison with simulations performed in '60s and '70s. Changes of land use affected considerably this trend, as the main variations in wildfire likelihood and intensity were observed where shrublands and forests increased their coverage; in some cases, the expansion of urban areas also played a role in wildfire size reduction. The application of wildfire simulations to future scenarios showed that increased drought led to reduced fuel moisture and increased fire intensity. Future changes in land use projected a limited but generalised increase of sclerophyllous vegetation and forests, and then a potential increase in fire intensity.

Lessons learned and implications: The first step toward a definition of uniform approaches in landscape wildfire risk assessment would be the adoption of powerful tools to predict wildfire probability and intensity. Wildfire simulators can provide data, maps, and guidelines that can be used with different planning strategies, from tactical and strategic planning of wildfire management, to firefighter training, to even real-time firefighting. The experience of FUME modeling activities confirms that wildfire likelihood and behaviour should be studied and monitored over time, so that policy makers and management agencies can plan investments and activities and evaluate the responses at fine scale, even in a perspective of future climate changes and/or other changes.

Dehesa de Solanillos (Guadalajara, Spain). Photo: J.M. Moreno

Topic 11

Calculating future fire danger under climate change

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Fire danger indices, like the Canadian Fire Weather Index (FWI), are used by fire agencies to forecast fire potential in an area based on a few instantaneous meteorological variables. Changes in fire danger due to climate change are calculated using future climate projections from General Circulation Models (GCMs). However, their outputs do not have the required temporal or spatial resolution to reliably provide local/regional future FWI estimates. There are two basic downscaling techniques to address this problem: dynamical (based on the use of Regional Climate Models, RCMs) and statistical. In FUME, we applied both techniques in Europe to this aim.

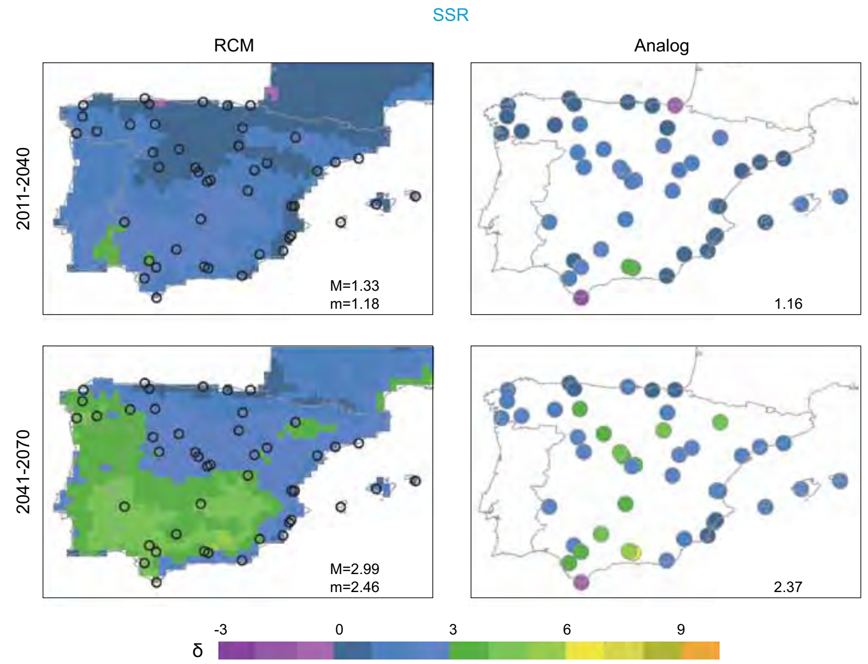

Fig: 11.1: Projected fire danger scenarios (Seasonal Severity Rating for the fire danger season, JJAS) in the Iberian Peninsula, in terms of anomalies (delta) of the current climate conditions (1970-2000) for the periods 2011-2041 and 2041-2070. Spatial mean values are indicated at the bottom of each panel. In the case of the RCM projections the spatial mean of the whole domain represented is indicated by the capital M, and the mean at the point locations coincident with the place-based observations by the m. Projections correspond to the annual fire danger values according to the ECHAM5-r3 GCM, applying both statistical downscaling (points) on the weather station data, and dynamical downscaling (RCM simulations of the KNMI-RACMO2 model) at the same point locations. From Bedia et al., 2013.

Implications for policy and management

- *Earlier calculations of future fire danger using RCM-based FWI not based on instantaneous data or the appropriate proxy may have rendered spurious results, particularly for extremes, and should be viewed with caution.*
- *Future fire danger projections predict important increases in FWI magnitude, length of the fire season and in extremes over large extensions of Europe.*
- *FWI is projected to increase where fires have been prevalent until now, but also in other regions where these were not common because of reduced fire danger.*
- *Both dynamical and statistical downscaling scenarios consistently point to an increase in fire danger in the Euro-Mediterranean area during the 21st century, and both can be used for calculating adaptation needs during this period.*

The problem: Determining future fire potential requires calculating fire weather danger indices, like the Canadian Fire Weather Index (FWI), in a future climate. The FWI builds upon instantaneous meteorological records (wind, humidity, temperature, precipitation). Dynamical downscaling allows computing future fire danger at regional scale (~14-50 km). However, RCM data are usually stored at a daily temporal aggregation, which can produce misleading projections. Regarding statistical downscaling, the combination of variables with different distributional properties for the generation of FWI implies that the technique chosen must consider the need for a physical and spatial consistency between them in order to obtain reliable local FWI projections. An objective in FUME project was to apply various methods, including a specific methodology for statistical downscaling, to calculate future FWI in Europe.

The approach: We tested the sensitivity of FWI to both instantaneous and daily mean input data (Herrera et al., 2013) by analysing their effect on mean and extreme fire danger scenarios and on the climate change signal using RCM-based future projections. This permitted identifying possible problems with the use of daily mean data. We then tested several proxy variables and used the optimal variable combination (see Bedia et al., 2014) to calculate future fire danger projections for the Mediterranean basin, considering the spatial pattern and magnitude of different FWI-derived fire danger indicators in future climate conditions. We use the Iberian Peninsula and Greece as representative Mediterranean areas to investigate the application of statistical downscaling methods to FWI, because it was possible to obtain sufficiently long, high-quality historical meteorological observations. We then analyzed the performance of the method, which guarantees physical and spatial consistency of the downscaled variables, regardless of their statistical properties.

Achievements: Future fire potential based on the FWI can be reliably calculated using available future climate projections. However, the use of daily data (as previously used in several studies), which is the only one stored in most public future climate databases, can produce spurious results. Although the mean seasonal fire danger indices might be corrected to compensate for systematic biases, fire danger extremes cannot be reliably transformed to accommodate the spatial pattern and magnitude of their respective instantaneous versions, leading to inconsistent results when projected into the future. To avoid this problem, an optimal proxy variable combination was successfully applied in FUME for calculating future FWI, relying on RCM outputs commonly available in most databases. A robust assessment of future fire danger projections was undertaken by disentangling the climate change signal from the uncertainty derived from a multi-model ensemble of state-of-the-art RCMs. We document an increase in fire danger over large areas of the Mediterranean and Central-Eastern Europe, accentuated towards the latest part of the century. Increases are particularly high in the Iberian Peninsula, Greece and Turkey. Both statistical and dynamical projections exhibit a similar pattern of fire danger increase in the first half of the 21st century. Yet, the two methods diverge during the second half of the century because the inability of the statistical method used (analogues) to extrapolate beyond the observed historical records. The multi-model range for future FWI projections was remarkably low, indicating the consistency of the future fire danger scenarios. Variability was larger (i.e., more uncertain ranges) for threshold-dependent indicators (i.e., values above a certain value).

Quintos de Mora (Toledo, Spain). Photo: J.M. Moreno

Lessons learned and implications: Future fire danger might have been miscalculated due to the limitations of available future climate projections. This is particularly relevant for the calculations of extreme values. However, future fire danger can be reliably calculated using an adequate set of proxies most often available in databases. Dynamical and statistical downscaling techniques should be regarded as complementary rather than alternative approaches. Statistical techniques, however, have limitations for the last decades of 21st century. Yet, both can be used for fire danger calculations in the coming decades in which adaptation will be needed. Fire danger is projected to greatly increase over large parts of Europe, including Eastern Europe, where fires until now have not been prevalent.

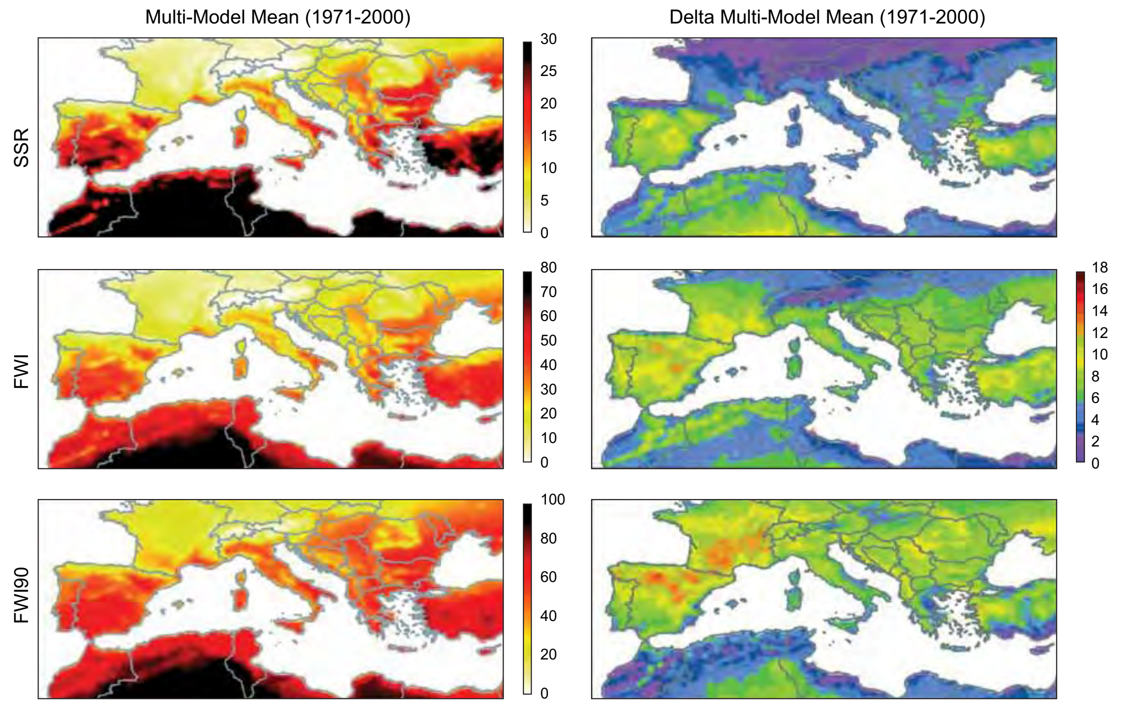

Fig: 11.2: Control (1971–2000) and future projections (deltas, 2071–2100) of FWI, 90th percentile of FWI (FWI90) and seasonal severity rating (SSR) for the Mediterranean for the period 2071–2100 according to the multi-model ensemble of five RCM-GCM couplings from the EU-funded project ENSEMBLES, corresponding to the SRES A1B emissions scenario for the fire season (JJAS). Delta values (right panels) are calculated as the anomalies of the future scenario with regard to the multi-model ensemble mean of the current climate values (left panel). From Bedia et al., 2014.

Topic 12

Fire and weather relationships: future projections

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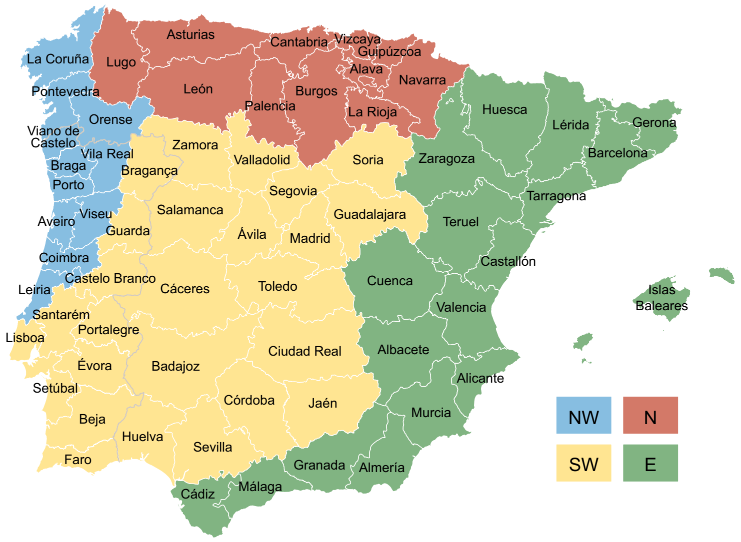
Wildfires are a major hazard in Western Mediterranean, and responsible for large areas burned every year. We analyzed fire records in Iberia (Portugal and Spain) for the 1981-2005 period and organized a comprehensive joint Iberia database. Results show that summer burned areas in Iberia result mainly from meteorological forcing factors: 1) appropriate previous climatic conditions; and 2) favourable circulation patterns during the fire season that induce extreme temperatures. We then evaluate the impact in fire activity associated with the projected trends of warming and drying consistently obtained with Regional Climate Models (RCM) in the Mediterranean.

Implications for policy and management

- *A common pan-European fire dataset, as derived here for Iberia, is needed to study the Mediterranean fire regime and identify pyro-regions.*
- *Further statistical models should be developed for other European regions using pre-fire season climate conditions, coupled with in-season fire weather information.*
- *Climate projections point towards an important decrease of precipitation in most Mediterranean areas accompanied by a significant increase in average temperatures and heat wave frequency.*
- *Models based on meteorological parameters estimate a potential increase of burned area in Iberia of up to 3 times of current values, disregarding other constraining factors.*

The problem: It is widely accepted that weather and climate play a key role in fire spread in Southern Europe. In this context several research groups have determined the role of meteorological variables in the months prior to the fire season (e.g., high temperatures or lack of precipitation), as well as during the fire season in modeling total burned area. However, most of these approaches have not been applied to climate change scenarios using multiple runs based on different RCM. There is a clear need for this type of outlook on potential changes in total burned area.

The approach: This relation between meteorology and wildfires was expressed with simple statistical models using meteorological indices as predictors (Trigo et al., 2013), to: 1) reproduce the inter-annual variability of burned areas (BA); 2) extend this modeling approach into climate change scenarios (Pereira et al., 2013). This approach was developed for the Iberian Peninsula, starting by regionalizing the available fire data for the Portuguese and Spanish provinces for 1981-2005. It is possible to distinguish four clusters in Iberia with different intra-annual variability of Normalized Burned Area (Fig. 12.1). While most of Iberia essentially has fire activity during summer months, northernmost sectors have a bimodal annual cycle, with a secondary peak around March. Results obtained show that up to 70% of the inter-annual variability can be explained by these simple models (Pereira et al., 2013), particularly for the two Western Iberian regions (Trigo et al., 2013).



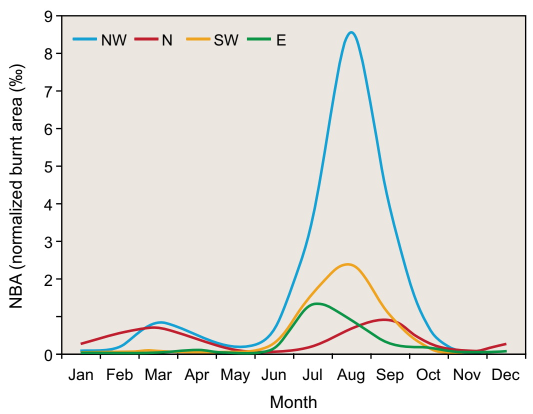


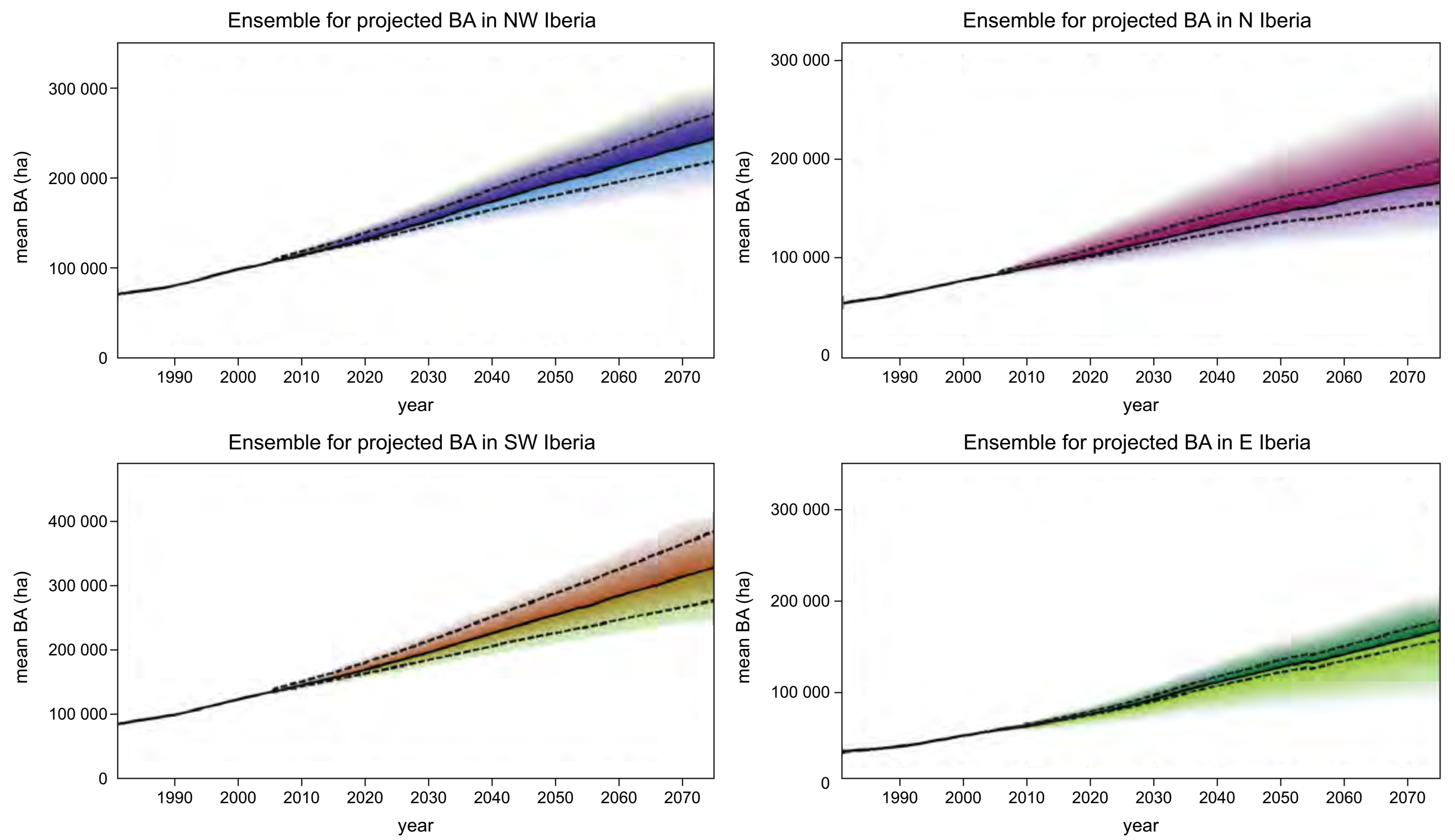
Fig. 12.1: Spatial extension (left) and mean monthly series of Normalized Burned Area (right) of the 4 clusters considered inside the Iberian Peninsula. These clusters correspond to relatively homogeneous fire regimes for the 66 Administrative Regions (AR) of Iberia, as derived by Trigo et al. (2013). The Normalized Burned Area is defined as the quotient between the amount of Burned Area in each of the AR and the area of the AR (both in hectares).

View of Andilla fire (July 2012, 12 000 ha; Valencia, Spain). Photo: A. Vilagrosa

Achievements: We have shown that fire activity in Western Mediterranean is essentially driven by specific meteorological conditions during summer that favour the spreading of fires. Moreover, we provide evidence that such conditions can be enhanced by the existence of stressed vegetation as a result of pre-fire season climatic conditioning. We have also shown that these relations can be well expressed using very simple statistical models based only on meteorological parameters such as usual climatic elements, weather type classifications or fire indices. The fact that such models can explain most of the burned area and fire risk variability for present climate raises the prospect of applying them to future outlooks of the Iberian climate; thus trying to quantify future fire danger and potential burned areas in the 21st century. This was achieved using simulations by RCM from the ENSEMBLES project to the four sub-domains considered in Iberia. Our projections show that the models predict a significant potential rise in the amount of burned areas in all clusters as the 21st century progresses (Fig. 12.2). Two main conclusions can be derived from the upward trends that arise from future burned area projections: 1) fire danger, i.e., meteorological conditions that favour fire ignition will be much more frequent, as the average temperature rises and the frequency of heat waves increases; and 2) vegetation vulnerability due to hydric stress in the pre-fire season is also expected to be more significant, obviously enhancing the potential for the occurrence of large wildfires.

Lessons learned and implications: The establishment of appropriate regionalizing analysis requires the use of reliable fire databases, regardless of political borders. The inter-annual variability of burned area in Southern Europe is highly dependent on climate variables during both the pre-fire and fire season itself. Climate projections point towards an important decrease of precipitation and number of wet days in most Mediterranean areas accompanied by a significant increase in average temperatures and frequency of heatwaves. Models based on meteorological parameters estimate a potential increase of burned area in Iberia of up to 3 times in the present climate, disregarding other constraining factors and nonlinear feedbacks.

Fig. 12.2: Ensembles of projected mean burned area (BA) for the period 1981-2075 in the four Iberian clusters. The solid line represents the mean of all 16 considered simulations. The upper dashed line represents the mean of the simulations that use fixed reference climatology, while the lower dashed line represents the mean of the simulations using moving reference climatology. Darker and lighter shades represent ensemble uncertainties of the previous simulations and where obtained using inter-quartiles. A 25-year moving average was applied to all series.



Topic 13

Measuring and modeling fuel change in relation to drought

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Climate change could lead to increased frequency and intensity of drought events affecting fuel flammability, through its moisture content and dead-fuel loads, which are two major components controlling fire behaviour. We measured fuel moisture content in a wide-range of plant species across the Mediterranean basin. Seasonal plant moistures were compared to drought indices. Vulnerability to necromass production was assessed by measuring cavitation, and long-term fuel amount adjustments were explored across a precipitation gradient. We found that the Drought Code (DC) index is a good index to capture the fire season, but should be complemented with species functional traits. Prolonged droughts may enhance fire risk but plant and ecosystem-level adjustments may act as strong mitigators.

Implications for policy and management

- *Plant species differ in their seasonal variability in live fuel moisture content and their vulnerability to cavitation, so managers must know the species characteristics to understand their system sensitivity to climate extremes.*
- *Seasonal course of sensitivity can be modeled by the DC, but local adjustments must be considered based on local vegetation.*
- *Necromass needs surveying because it will potentially become a key variable for fire ignition propagation.*
- *Managers should be alerted to species changes favouring reduced moisture and increased necromass production.*
- *Fire hazard may increase during several decades before decreasing in some regions due to fuel limitation.*

The problem: The projected increased temperature and drought (Giorgi and Lionello, 2008) should affect fuels through fire behaviour factors: seasonal water status, fuel load, and live/dead ratio. We hypothesize non-linearity and specific responses, critical for accurately predicting fire frequency, intensity and burned areas. We used rainfall interception and gradient analysis to capture extreme events, and considered mixed species ecosystems with contrasted water use strategies to answer these questions: 1) to what extent generic weather-derived drought indices can be reliable tools for fuel moisture projections, 2) how species can promote differentially branch mortality and dieback, 3) how leaf area and plant density adjustments might mitigate these processes.

The approach: Fuel moisture and soil/plant water fluxes were investigated during several fire seasons at 3 study sites (Sardinia, France, Tunisia) and in several plant species. Measurements were taken in the natural environment or in a rainfall interception experiment simulating a 7 months dry spell. Measurements were tested against empirical and process-based models to simulate actual fuel moisture content. To capture the seasonal pattern of drought intensity and fire season length, we calculated the DC of the Fire Weather Index (FWI) and plant water content in the main shrub species using a water budget model. Changes in fine fuel amount were investigated through leaf litterfall and shoot elongation as a response to drought, and we made laboratory experiments for the vulnerability to cavitation susceptible to produce necromass. Regional scale information on tree dieback and adjusted tree density across drought gradients were used as indicators for long-term processes which are hard to capture experimentally.

Achievements: We found species-specific responses to seasonal changes in soil moisture. High-desiccating species severely adjust their moisture content across the season, while others keep hydrated throughout the year. Isohydric species could block their water flux early in the season while anisohydric species followed the soil water content, and in turn were more able to rehydrate after small rainfall events. All species reached minimum seasonal water content, but with values that were not extremely low; yet, they exhibited a prolonged live-fuel dryness period each year.

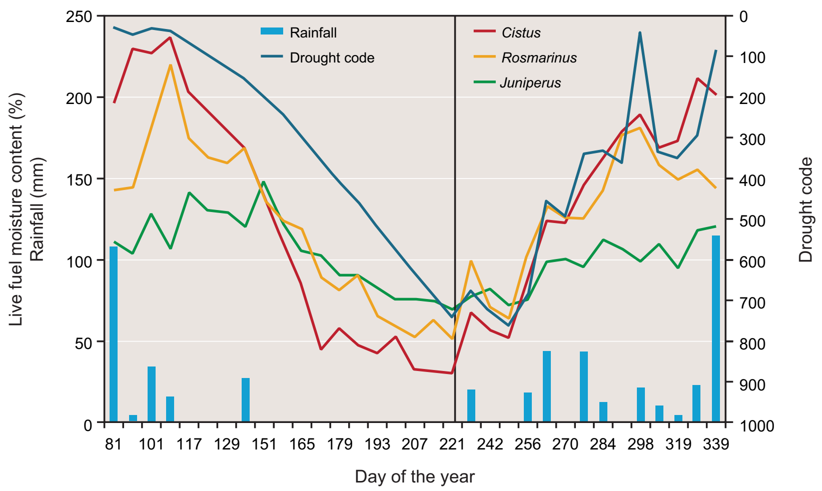

Fig. 13.1: Variation of the drought code (DC) for different types of Mediterranean plant species with contrasted water holding strategies. This figure shows that in the falling phase of moisture content (winter to spring) DC was not close to the live fuel moisture content and rainfall. It correlated much better during the moisture raising phase (mid-summer to autumn), thus suggesting that DC is more appropriate to identify the end of fire danger season rather than the date of starting. In some species less sensitive to drought (e.g., Juniperus) live moisture content is weakly correlated with DC.

A fair correlation between DC and live fuel moisture was established, but with the differences among species mentioned above (Fig. 13.1). DC was appropriate to identify the end of the fire danger season, with substantial correlation with fire occurrence. More complex process-based models can predict species responses according to functional strategies with mitigation feedbacks through leaf area adjustment limiting water loss.

We found that potential critical thresholds after extreme drought are possible. However, despite no major extremes in live fuel moisture during prolonged drought, critical thresholds could be reached when live fuel is converted into dead fuel able to desiccate down to extremely low values. Species experienced differential vulnerability to cavitation in relation to their hydraulic strategies (Fig. 13.2). Direct mechanisms for actual necromass production are still unclear for accurate predictions, but tree die-back was observed after extreme years in Southern France, leading to increased fire hazard. On the contrary, at the most southern bound of Mediterranean climate, significant tree density adjustments are observed as a long-term adjustment, leading to crown discontinuity preventing severe crown fires. Figure 13.3 summarizes short to long-term trends in fire risk associated to climate change in Mediterranean environments.

Lessons learned and implications: The DC is a useful generic indicator of live fuel moisture and thus of fire danger. However, adjustments considering plant functional types and leaf area adjustments would improve its value. Increasing dry spells lead to longer fire season. Under climate change, critical thresholds could be reached due to increased drought length, leading to enhanced necromass load, which could exponentially increase fire hazard. In the long-term, as climate changes, sparser vegetation would likely develop as a result of recurrent droughts and heat waves. Such vegetation would better cope with drought, and would, likely, become less hazardous for fire occurrence.

Management implications of drought in a climate change context

- *The DC index should be adapted to soil water holding capacities and plant functioning for more precise assessments of regional fire risk and trend.*
- *Consider species differential functioning to identify key indicators for fuel combustibility.*
- *Warnings on necromass as a major variable for reaching critical thresholds in fire risk along time under climate change scenario.*
- *Consider tree density adjustment as a double benefit for tree water saving and durability and to reduce risk of severe fire spread.*
- *Manage fuels and landscapes: favour fire-smart management of forest landscapes and fuels, firewise and regional strategies.*

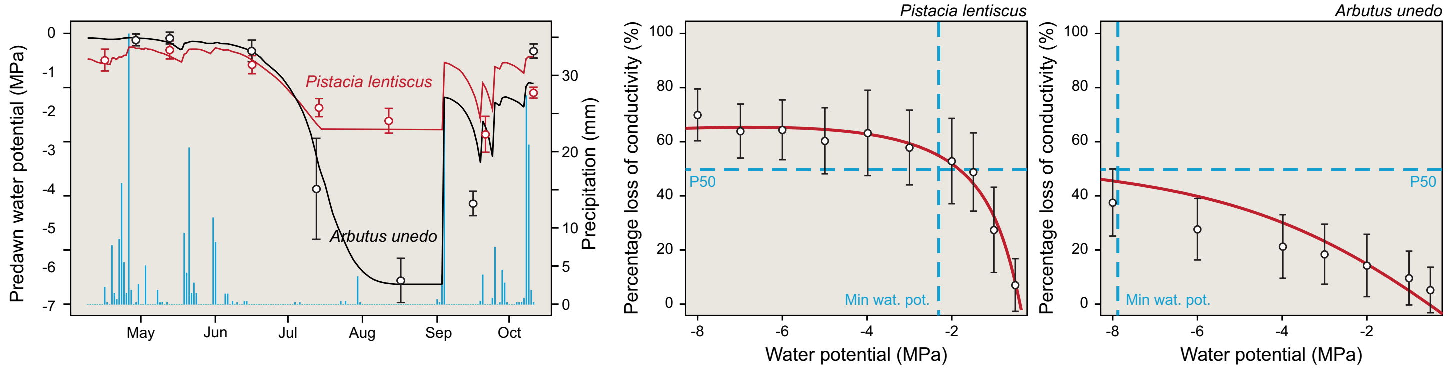

Fig. 13.2: Seasonal course of predawn water potential in relation to rainfall for Arbutus unedo and Pistacia lentiscus, two shrubby species with contrasted water strategies (left). Percentage loss of conductivity in relation to water potential for P. lentiscus and A. unedo (right). Differential vulnerability to cavitation is measured by the percentage of conductivity lost according to water potential. 50% loss of conductivity (P50) corresponds to field measurements of minimum water potential observed during the season.

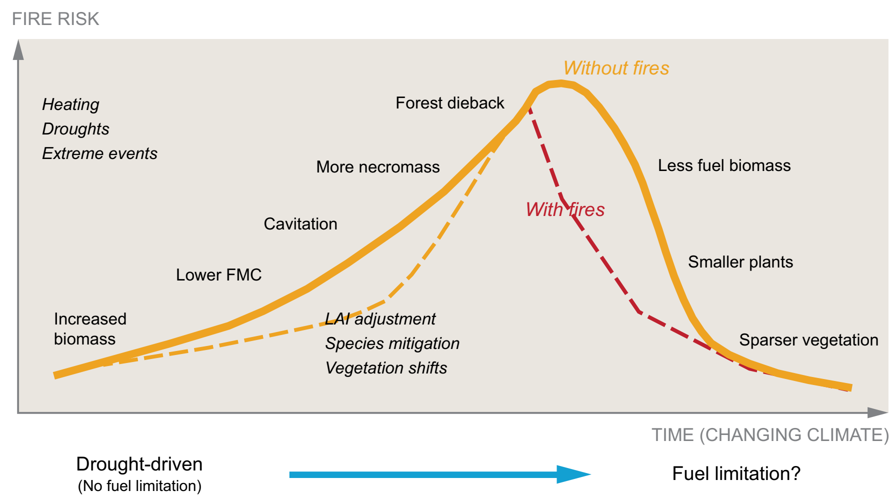

Fig. 13.3: A possible model for future fire risk in Mediterranean fertile environments (such as France, Spain, or Italy) indicates that fire could shift from drought-driven as today (i.e., fires depend mostly on fire weather since fuel biomass is sufficient) to increased fire occurrence or intensity during several decades due to climate change (mitigated by different adaptive strategies of vegetation), then to fuel-limitation in the long-term because vegetation will decrease in biomass and become sparser. The leaf area index (LAI) characterizes the extent of a species canopy.

Topic 14 Modeling vegetation and ecosystem responses to climate change and fire regime

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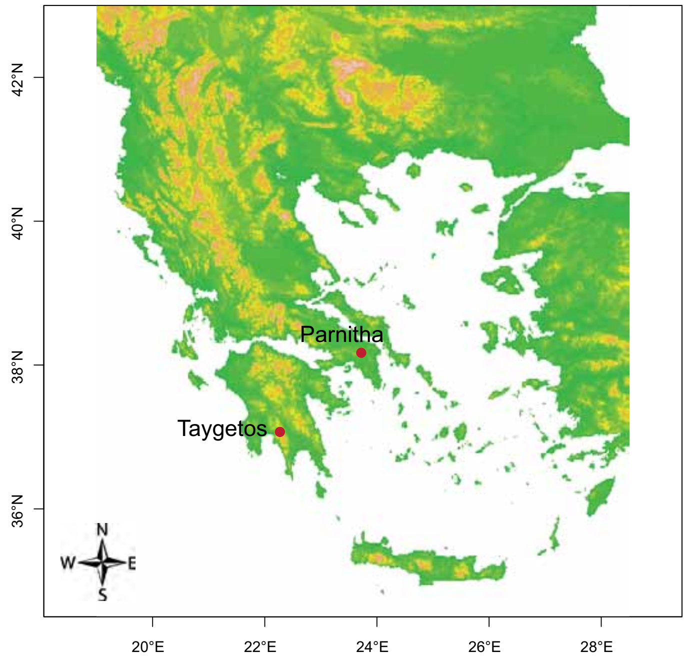
Climatic fire danger will likely increase because more droughts and heat-waves are caused by climate change. Climate change can shift fires from occurring only rarely to regularly in ecosystems not until now adapted to fire. We applied dynamic vegetation-fire models to investigate these future responses. The future of fire in Mediterranean-type ecosystems depends strongly on changes in vegetation productivity, thus fuel availability, if burned area increases as much as fire danger. Temperate ecosystems might be exposed to Mediterranean-like fire regimes. In high altitudes, Mediterranean trees might migrate up-hill and cause feedbacks between diversity and fire under climate change.

Implications for policy and management

- *Influence of climate change and atmospheric CO_2 on vegetation growth have a larger impact on future fire than human-caused ignitions.*
- *Changing fire management with respect to fire ignition has probably little influence on reducing fire in Western and Southern Europe, but is key in Eastern Europe.*
- *Vegetation productivity is important in future fire regimes in the Mediterranean, for which precise climate change conditions might be decisive for crossing an ecological tipping point.*
- *Eastern Europe will require more support in fire monitoring and management given predicted substantial increase in fire across all climate change scenarios.*

Fig: 14.1: Location of 2 Greek sites to which the GREFOS gap model was applied (map shows elevation [m]).



The problem: Current projections of future fire activity are derived from projections of future fire danger. Under current climate conditions, fire ignition and fire size were correlated with fire danger. This relationship might only hold true under future climate conditions, if vegetation productivity is unchanged. If vegetation is degrading under climate change, there might be less fuel and thus less biomass lost in fires. In temperate and boreal ecosystems as well as mountainous regions, fires occur but a lot less frequent. If climate change increases drought and heat-waves here, fire regimes might intensify and prevent typical forests from re-growing.

The approach: We applied the dynamic vegetation-fire models LPJ-GUESS-SIMFIRE and LPJmL-SPITFIRE, and the Greek forest gap model GREFOS to future climate and socioeconomic scenarios. We used scenarios of climate and human population change from the 4th and 5th IPCC assessment reports as input to our models. To understand the role of climate, atmospheric CO_2 and anthropogenic influence, we conducted factorial experiments to quantify each factors' contribution to the overall changes. We applied the dynamic vegetation-fire models to Europe and Northern Africa to allow investigating large-scale changes at annual to decadal time scales. The forest gap model was applied to 2 mountainous sites in Greece, which were devastated by the disastrous fires in Greece in 2007 (see Fig. 14.1). We used the model results to quantify changes in fire regimes and vegetation responses at the local and continental scale.

Achievements: Results of the application of the vegetation-fire models to two sets of climate scenarios of the 5th IPCC assessment report shows that: 1) fires are simulated to more than double in the temperate and boreal zone, where 3 out of 4 scenarios show similar trends (Fig. 14.2); 2) simulated changes in the Mediterranean basin are qualitatively very different and spatially heterogeneous with less agreement between the 2 large-scale models.

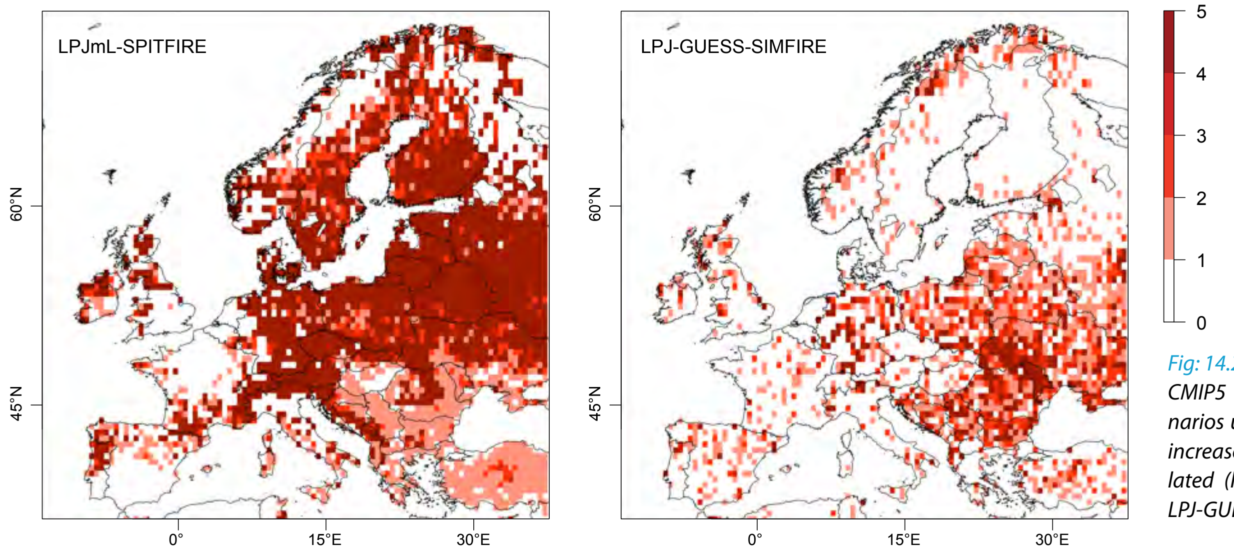


Fig: 14.2: Agreement across CMIP5 RCP8.5-SSP5 climate scenarios under which at least 100% increase in fire emissions are simulated (left: LPJmL-SPITFIRE, right: LPJ-GUESS-SIMFIRE).

When comparing changes in climatic fire danger and fire ignition to changes in area and biomass burned results show that: 1) when forests continue to persist under high emission scenarios (i.e., most intense climate change) future biomass burned follow the increasing trend in fire danger (LPJ-GUESS-SIMFIRE) in Eastern Europe and the Mediterranean region; 2) when rather sparse vegetation productivity and open shrublands are simulated (LPJmL-SPITFIRE), fuel availability is too small to allow for more biomass burned despite increasing fire danger.

Changes in vegetation and fire are less intense under the 2°C-target climate change scenario. However, similar regions as under the intense climate change scenario are affected, i.e., parts of Eastern Europe would still face intense changes in fire and related vegetation responses. Moderate climate change means maintained fuel production continues to fuel fire.

The more intense climate change, the earlier Mediterranean pines migrate up-hill and the more dominant they become in Greek mountains (Fig. 14.3). These feedbacks between fire and climate change prevent the cold-adapted fir from regeneration and can cause changes in tree dominance and an intensified fire regime.

Lessons learned and implications: The projected fire increase in Eastern Europe seems to be robust as two vegetation-fire models show similar pattern under 3 out of 4 intense climate change scenarios. This means that a region becomes vulnerable to increasing fire, which has not yet the socioeconomic capacity to adapt or is lacking sufficient funding to implement an appropriate fire monitoring and management scheme. Increasing the habitat of Mediterranean-type conifers to high altitudes might extent the fire problem to regions that are difficult to manage and not fire-adapted. Whether the Mediterranean region is facing similar increases is more uncertain and depends strongly on the future pathway of vegetation dynamics.

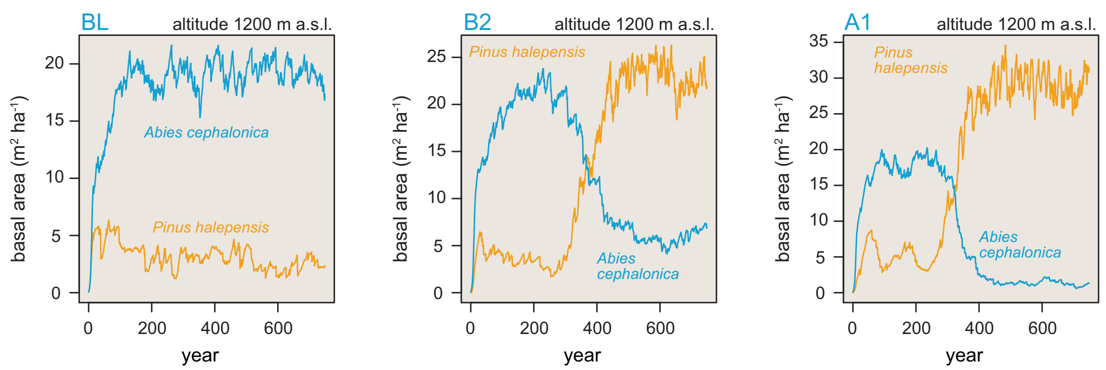


Fig: 14.3: Changes in basal area [m^2 ha^{-1}] of conifer species at 1200 m altitude as simulated by the GREFOS model for current climate (left), moderate climate change (central, SRES-B2 scenario) and high climate change (right, SRES-A1 scenario).

Topic 15

Threats of projected changes in fire regime for newly affected areas in Europe and Northern Africa

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Under climate change conditions, climatic wildfire danger could also increase in ecosystems not dominated by fires until now. This increasing trend could lead to more area burned in the future. We have developed an algorithm to map new fire-prone areas in Europe and Northern Africa that identifies grid points where a rare fire event is becoming the mean at the end of the 21st century. When applying the model to simulated changes in future fire regimes it revealed that these new fire-prone areas would be found mostly in Eastern Europe. Depending on the climate scenario and vegetation-fire model used, it could also extend to central and South-Eastern Europe.

Implications for policy and management

- *Simulated results differ in terms of scenario and vegetation-fire model used, but all show highest changes in some parts of Eastern Europe.*
- *The regions identified as new fire-prone areas might need to step up their efforts for monitoring, management and prevention of wildfire.*
- *Projected changes might require far-reaching knowledge transfer on how to set up such systems and harmonisation of policy strategies to the new fire situation.*

The problem: Under climate change projections, very productive forests might face more frequent and intense droughts or heat waves that are outside their current fire regime. If wildfires increase in a particular region to, e.g., Mediterranean levels, it would pose a threat to the affected ecosystem as it would increase vegetation vulnerability. Biodiversity is affected because changes in vegetation composition and biomass storage as carbon lost in fires increases. Using simulated changes in wildfire regimes, under which scenario do rare events become the mean in the future and in which region?

The approach: Two vegetation-fire models used (LPJ-GUESS-SIMFIRE and LPJmL-SPITFIRE) were driven by 6 climate change scenarios of the 5th IPCC assessment report to simulate area and biomass burned. These models were run at the continental scale at a grid with a cell size of 0.5° x 0.5° longitude-latitude. The vegetation-fire models applied in these experiments simulate changes in vegetation and fire including their bi-directional feedbacks. A grid cell was defined as a new fire-prone area, when the mean burned area simulated for 2071-2100 was larger than the 90th percentile of area burned between 1981 and 2010 in the same grid cell. These areas were identified by applying the algorithm in the post-processing of simulated data. If continuous regions can be identified, widespread effect on eco-regions could be concluded. Using the percentile approach considers the relative change in fire, which makes up the damage and endangers ecosystems resilience to an intensified fire regime.

Achievements: The range in climate change projections is large, thus the resulting extent of the regions most affected. Simulation results for Eastern Europe show strongest impacts under upper-bound climate change scenarios, i.e., RCP8.5-SSP5. How much this extends to central Europe or the Balkan countries or Northern Mediterranean areas depends on the climate scenario used and the vegetation-fire model applied. This also applies to the extent of the new fire-prone areas. Under scenarios of high climate change impact, e.g., HadGEM2 scenario, the new fire-prone area covers central and Eastern Europe, the Southern boreal region and parts of the Balkan Peninsula (Fig. 15.1, upper left). When less intense climate change is projected the size of the new fire-prone area is smaller, the Southern boreal zone is not included (Fig. 15.1, upper right). When using a prognostic fire model such as SIMFIRE, more grid cells are identified as new fire-prone areas (Fig. 15.1, bottom row). In the boreal and arctic zone the results must be regarded as statistical noise because current fire occurrence is too small to provide a meaningful parameterisation for a prognostic fire model. Depending on the climate scenario, the new fire-prone area detected by LPJ-GUESS-SIMFIRE was also found in Eastern Europe and partly in the Mediterranean basin. Even when applying the approach to climate scenarios closer to the 2°-target (RCP2.6-SSP1), Eastern Europe is still identified as new fire-prone area, though the size of the region is much smaller.

Old Pine woodland in La Adrada (Sierra de Gredos, Ávila, Spain). Photo: B. Pérez

Cone of Pinus brutia (Mount Carmel, Israel). Photo: J.M. Moreno

Narcissus triandrus subsp. pallidulus (Anchuras, Ciudad Real, Spain). Photo: J.M. Moreno

Lessons learned and implications: Eastern Europe is identified as the potential new wildfire-prone area, a region that has not been on the radar of fire science or fire management. If climate change goes un-abated, this region might have to become a focus of fire-ecological research as well as of fire management and protection. Differences in climate scenarios and vegetation-fire models can be refined by reducing uncertainty in parameterisations of the fire models used. Notwithstanding, both model approaches identify a similar region, which might have to increase its adaptive capacity to a rising fire problem.

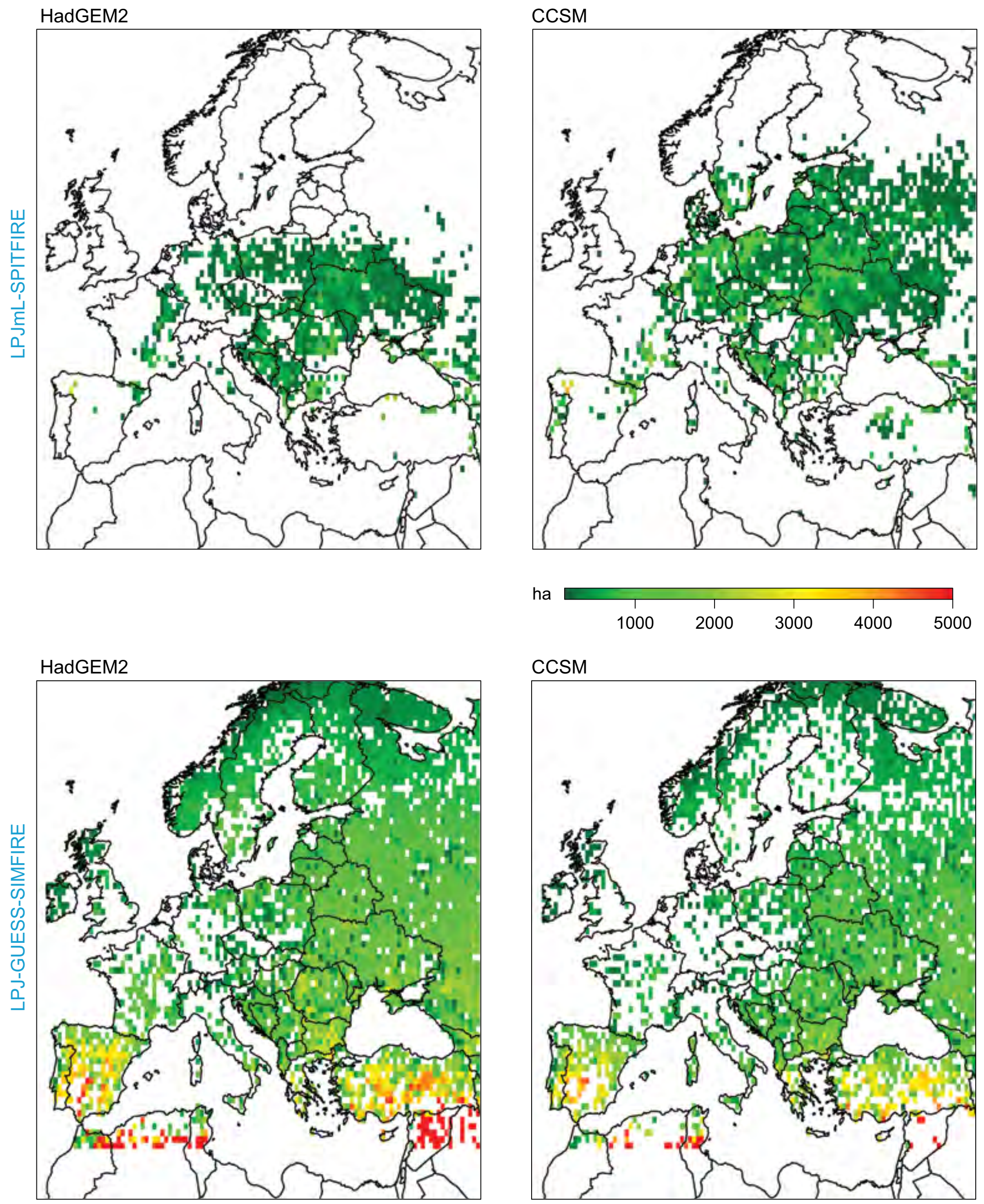

Fig. 15.1: Average future burned area [ha] in regions identified as new fire-prone areas in Europe and Northern Africa. Simulations by the LPJmL-SPITFIRE model (top row) and the LPJ-GUESS-SIMFIRE model (bottom row) under the intense climate change scenario of the 5th IPCC report (RCP8.5-SSP5) from the HadGEM2 climate model (left column) and the CCSM climate model (right column).

Topic 16 Germination sensitivity of Mediterranean species to changing climate conditions

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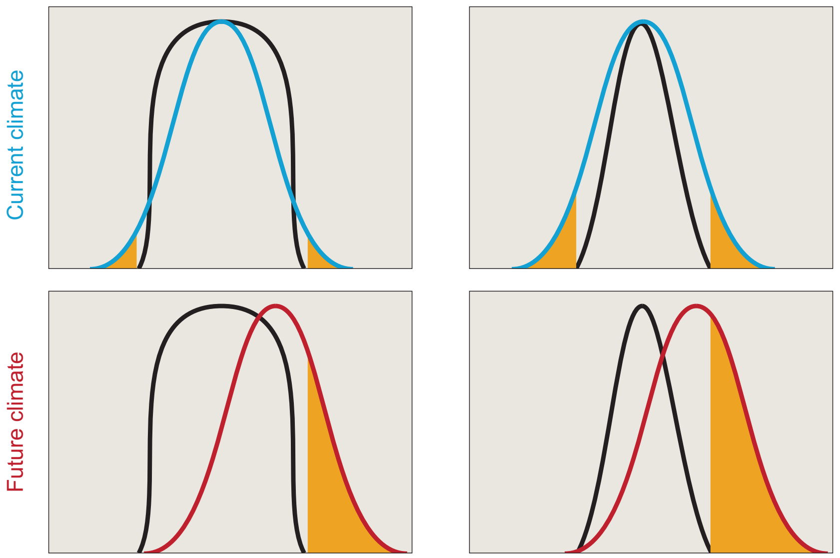
Many plant species in Mediterranean ecosystems regenerate after fire by seeds (seeders); thus, seed germination is crucial for species persistence and the stability of plant communities. In this chapter, results of experiments conducted to determine the germination sensitivity of Mediterranean species to environmental conditions simulating different precipitation and temperature conditions, under the perspective of climate change, are presented. Results obtained prove that climate change can affect species germination across the Mediterranean region. However, germination responses are species dependent, and vary between sites, which makes it difficult to anticipate particular projections for a given species at a specific place.

Implications for policy and management

- *Regeneration by seeds of Mediterranean species will suffer from changing environmental conditions such as water availability and temperature.*
- *Species and populations show idiosyncratic germination responses to environmental factors, making generalizations and extrapolations difficult.*
- *For management purposes, there is a need to know how local conditions have shaped seed germination responses.*
- *In restoration plans, use of seed from local provenances and knowledge of the local responses of seed sources is imperative.*

Fig. 16.1: Schematic representation of species with wide and narrow germination niche breadths (black lines) as a result of different germination sensitivity to the current environmental conditions (blue lines). A change in conditions (red line) with climate change, can have very different effects on species, depending on their niche breadth. In orange is represented the environmental range not exploited by the species, that is where germination is not possible. While broad niche species would be little less affected, narrow niche species would be greatly so.

The problem: Post-fire plant regeneration in fire-prone Mediterranean areas is frequently based on seed germination, which is a complex process influenced by various factors, among which temperature and water availability are most relevant.



As environmental conditions change with global warming, this can impose serious problems for seed germination and, consequently, for the maintenance of plant communities and species persistence. There exists a high variability in germination patterns in response to a given variable; some species show wide germination niche breadths while others can germinate only under narrow conditions (Fig. 16.1). Thus, it is highly important to know the germination niche breadth of species to identify those most vulnerable to changing climate conditions.

The approach: Germination sensitivity of Mediterranean species to different temperature, water and fire conditions was investigated in laboratory experiments using seeds collected across transects comprising various environmental conditions (Fig. 16.2). Germination sensitivity to water stress, with and without fire-related cues, was determined in four species from a range of sites encompassing a large portion of the Mediterranean basin. Additionally, the effect of water stress and fire-related cues was studied on the seed germination of *Cistus ladanifer*, a most widespread species in the Western Mediterranean. In this case, seeds were collected at the same site but in plants that had been exposed to different drought treatments, allowing thus to test the possible maternal effects on the germination response (Parra et al., 2012). Furthermore, the effect of varying temperature conditions was evaluated in two *Cistus* and two *Labiatae* woody species selected along an altitudinal gradient in Central Spain (Chamorro et al., 2013). Finally, cold stratification effect on germination patterns of four Mediterranean conifers was evaluated along a latitudinal gradient in Greece, taking into account intra-specific variability by using seed material from discrete provenances.

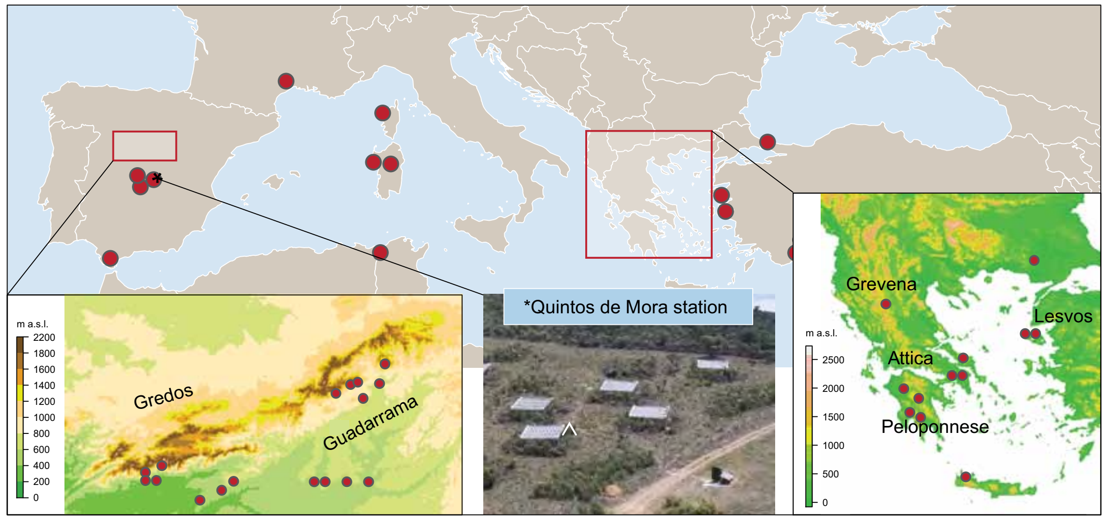


Fig. 16.2: Study sites where seeds were collected for four germination experiments analyzing the germination sensitivity to different factors such as fire-related cues, water stress, temperature regimes or cold stratification across the Mediterranean region, an altitudinal gradient in central Spain, a latitudinal gradient in Greece, or in a manipulative rainfall exclusion experiment at Quintos de Mora (Central Spain).

Achievements: Seeds from different provenances showed different germination responses to water stress and fire related cues. Overall, water stress decreased final germination and germination speed. Additionally, water stress interacted with fire related cues in hard-coated seeds (*Cistus monspeliensis*, *C. salviifolius*, *Calicotome villosa*), where final germination proved to be more sensitive when water stress was coupled with fire-cues. One species (*Erica arborea*) was little sensitive to water stress. Water stress may indirectly affect seed germination through maternal environmental conditions, that is, through the water stress experienced by the mother plant during seed maturation. Mother plants of *Cistus ladanifer* subjected to high levels of drought produced less viable seeds and with lower germination than non-drought plants.

Temperature is particularly interesting in mountain regions, where both temperature regimes and duration of cold-stratification can control germination. Final germination of hard-coated seeds (*Cistus ladanifer*, *C. salviifolius*) was determined by fire related cues, while other factors, such as temperature or altitude, were not as decisive. On the other hand, final germination of soft-coated seeds (*Lavandula pedunculata*, *Thymus mastichina*) were more sensitive to temperature conditions by itself or interacting with the altitude of provenance of the seed. Finally, seed chilling increased the final germination solely for the thermophilous *Pinus brutia*, but accelerated germination for other species (*Abies cephalonica*, *Pinus nigra* and *P. halepensis*). Seed provenance altitude was important as it switched the sign of final germination-stratification correlation from negative to positive, i.e. stratification appeared to enhance final germination for high altitude species (Table 16.1).

Lessons learned and implications: Germination of Mediterranean species showed some generalized response patterns to environmental cues, but sensitivity to these varied among species and populations. Thus, it is important to know species germination responses to the local conditions. Additionally, complex interactions with fire-related cues appeared, indicating that constraints for regeneration can be different with or without fire. Finally, consequences of changes in environmental conditions, such as water stress, can be appreciated directly in current seed germination but also indirectly in subsequent years through maternal effects which led to less viable seeds with lowest germination capacity.

Table 16.1: Summary of results of the various experiments.

Experiment 1. Sensitivity to water stress across a geographical gradient				
Species	**Sensitivity to water stress**	**Population effect**	**Water stress* Fire effect**	**Germination range**
C. monspeliensis	yes	yes	yes	narrow
C. salviifolius	yes	yes	yes	narrow
C. villosa	yes	yes	yes	narrow
E. arborea	no	yes	no	wide

Experiment 2. Sensitivity to water stress across a local change rainfall			
	Sensitivity to rainfall manipulation treatment	**Sensitivity to water stress**	**Response range**
Fruit production	no	-	wide
Seed production	no	-	wide
Seed mass	no	-	wide
Seed viability	yes	yes	narrow
Germination	no	yes	narrow

Experiment 3. Sensitivity to temperatures across an elevation gradient				
Species	**Sensitivity to temperature**	**Elevation effect**	**Elevation* Temperature effect**	**Germination range**
C. ladanifer	yes	no	no	wide
C. salviifolius	no	no	no	wide
L. pedunculata	yes	yes	yes	wide
T. mastichina	yes	no	no	narrow

Experiment 4. Sensitivity to cold stratification across a latitudinal gradient				
Species	**Sensitivity to stratification**	**Population effect**	**Elevation* Stratification effect**	**Germination range**
A. cephalonica	yes	yes	yes	wide
P. nigra	yes	yes	yes	wide
P. brutia	yes	yes	yes	wide
P. halepensis	yes	yes	yes	wide

Topic 17

Vegetation and ecosystem responses to fire under drought

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Summer drought is projected to increase with global warming. Drought impacts at the post-fire regeneration phase can be long-lasting. We studied the effects of drought on post-fire ecosystem responses by manipulating rainfall before and after fire in shrublands of Spain and Tunisia. Plant hydration was higher after fire, even under drought. Yet, drought affected plant populations in a differential way: seeders were sensitive to drought, but not resprouters. Drought reduced growth and the recovery of some plant species, leading to increased abundance of herbs. Effects on soil nutrient content were short-lived, but important effects in soil functionality were also detected.

Implications for policy and management

- *The differential vulnerability of seeders and resprouters to fire and drought can have important consequences for biodiversity conservation in a changing climate.*
- *Reduced vegetation growth under drought, together with enhanced nutrient availability after fire, but reduced nutrient uptake, can increase the impact of other extreme episodes on ecosystems processes (i.e., intense rain and nutrient losses).*
- *Predictability of vegetation regeneration after fire and drought will be reduced, which could affect the desired objectives of management plans.*
- *Increased risk due to higher abundance of herbs in the first few years after fire in drought exposed systems needs to be considered, because a new fire can have cascading effects on the system.*

The problem: Summer drought is a feature of the Mediterranean climate. Total precipitation and timing are projected to change with global warming, increasing summer drought. Additionally, drought frequency, intensity and magnitude are also projected to increase with global warming. Drought can negatively impact plants and soil processes, notably in the first years after fire. Impacts at the early stages of recovery after fire could be long lasting. The combination of high temperatures and drought can promote large fires. Hence, large areas may be regenerating after fire under drought conditions. Understanding drought impacts on post-fire regenerating ecosystems is critical to anticipate future climate change impacts on Mediterranean ecosystems.

The approach: Drought impact was studied on two shrublands (Spain and Tunisia). The Spanish site had a combination of seeders and resprouters (Box "Regeneration strategies after fire"), while the Tunisian site was dominated by resprouters. Various levels of reduced annual precipitation and drought duration were implemented in the field, producing summer droughts compatible with projections under climate change. The levels of summer drought implemented varied from 2 (normal drought, July-August) to 7 months (April-October) without rain. Drought was implemented since one year before fire, and continued for up to four years after fire. A system of fully automatic, remotely controlled (Spain) (Parra et al., 2012) or manual (Tunisia) shelters was used to exclude rain for the desired periods. Additionally, an irrigation system was set (Spain) so that specified levels of rain were implemented for a nearly-full control of rainfall (Fig. 17.1). Ecosystem responses (plant and soil) were monitored after fire.

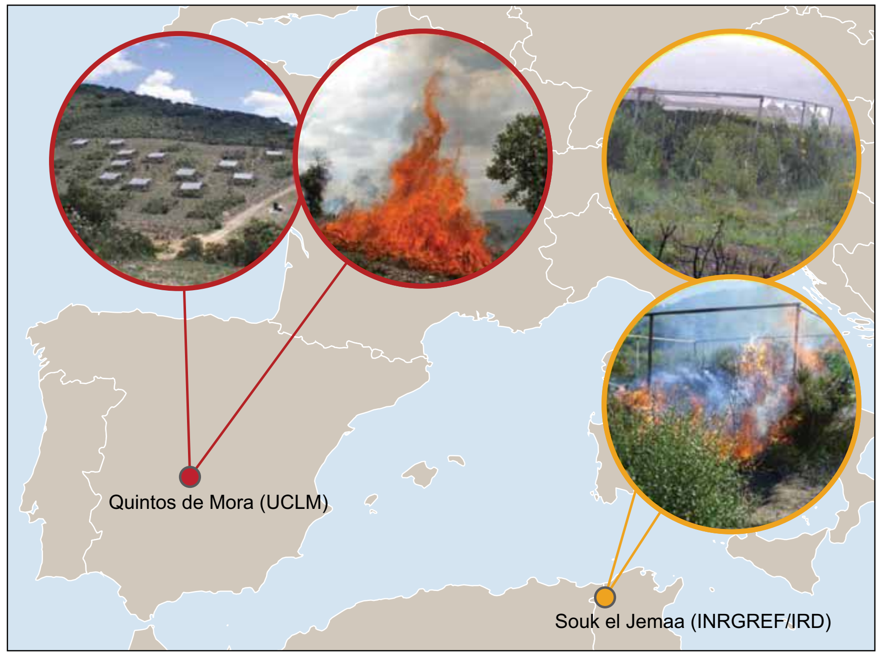

Fig. 17.1: Location of the study areas and pictures showing the systems for rainfall manipulation and details of the experimental burning at both sites.

From left to right:

Los Yébenes (Toledo, Spain).

Phillyrea angustifolia resprouting (Quintos de Mora, Toledo, Spain).

Cistus ladanifer (Quintos de Mora, Toledo, Spain).

Photos: A. Parra

Achievements: Plant hydration during the first years after fire was higher in burned than unburned plots, and much independent of drought (Fig. 17.2a) because reduced leaf area and preserved rooting systems. Species differed in water use strategy; drought avoidant species (resprouters) could cope with prolonged drought and drought tolerant (seeders) quickly responded to small summer rainfall events. Regeneration by resprouters was 100%; drought did not affect this process (Fig. 17.2b). Regeneration by seeders was affected by drought, so that fewer emergences and subsequent fewer recruitments were produced in drought-treated than non-drought treated plots (Fig. 17.2b). Recruitment in seeders was tightly dependent on emergence; hence, weather patterns in the first season after fire can determine the future vegetation. Nevertheless, the level of recruitment after three years of most severe drought was greater than the number of plants existing before fire. Hence, even under severe drought, recruitment in seeders was sufficient to replenish pre-fire levels. Plant growth was, however, smaller the higher the drought. Reduced canopy development allowed a greater abundance of herbs, causing a delayed recovery of the plant community towards the pre-fire situation (Fig. 17.2c). Soil nutrient availability (N, P, K) was initially affected by both burning and drought, but effects practically disappeared by the third spring after fire. Short-term changes in soil nutrients due to fire or drought did not affect plant nutrient concentration. Nevertheless, future changes in soil nutrient availability are possible, due to shifts in the main drivers of nutrient cycling: microbial community structure and functionality (Fig. 17.2d).

Lessons learned and implications: Post-fire environments maintain increased plant moisture, even under drought because of reduced leaf-area and preserved root systems. Yet, drought can impair the composition of the plant community, seeders being more vulnerable than resprouters. Vegetation compositional change can further affect the functioning of the ecosystem. Additionally, higher abundance of herbs can increase flammability during the first years after fire. A fire during this time could have critical consequences for seeders. Because recruitment of seeders is closely coupled to emergence and this to post-fire rainfall patterns, regeneration predictability will decrease with drought. Vegetation change, unpredictability and enhanced fire-risk during the first years after fire, can result in long-lasting alterations in the ecosystem.

Regeneration strategies after fire

Standing plants can either die or survive during fire. Plants that die can only recover their population from seeds stored in the soil or in the canopy that are not killed by fire. These are called seeders. Seeders germinate mainly in the first year after fire. Other standing plants are not killed by fire, and they resprout shortly after fire (weeks to few months) from buds in the roots, lignotubers or aerial structures. These are called resprouters. Resprouters can have seeds that survive the fire or not. Hence, they can recruit by both ways (seeding, resprouting) or only one (resprouting).

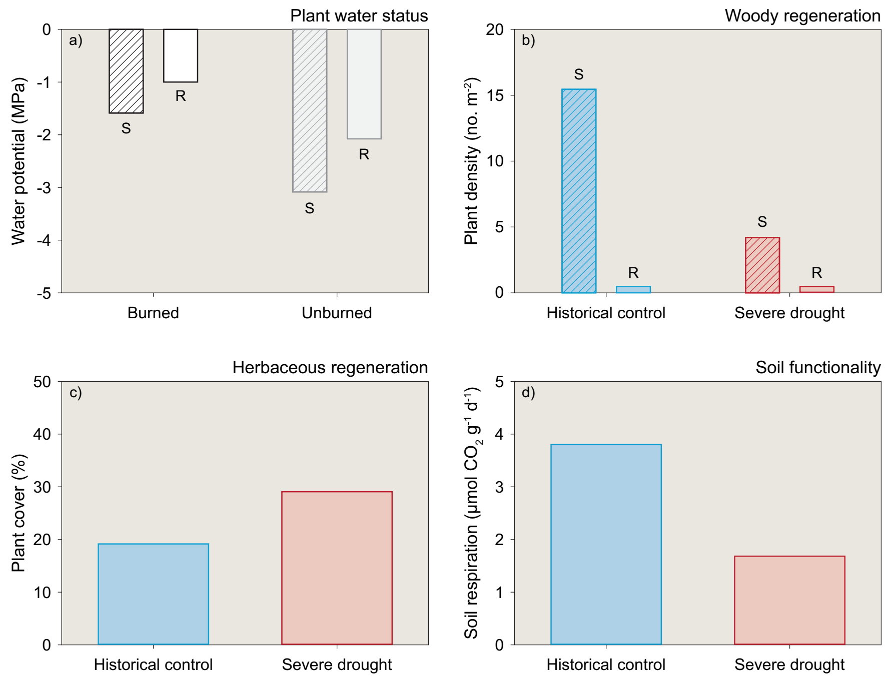

Fig. 17.2: Examples of the main results obtained for some relevant variables in Quintos de Mora experiment. a) Water potential during the first summer after fire in Cistus ladanifer (S) and Phillyrea angustifolia (R); b) plant density in C. ladanifer (S) and P. angustifolia (R) three years after fire; c) herbaceous cover three years after fire; d) soil respiration in spring three years after fire. Historical control: rainfall mimicked the long term in the area; severe drought: 7 months drought with total rainfall being at the percentile 1 of the long term records; S: seeder; R: resprouter.

Topic 18 Vegetation response to changes in fire regime

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In fire-prone areas, vegetation is usually resilient to fire. However, changes in fire frequency can compromise vegetation stability. We investigated the effects of fire in two contrasting fire frequency areas: high (Spain) and low (Greece). In Spain, plots were selected with a varied history (1-3 fires since 1976, and different burning period since last fire). In Greece, effects were investigated after a large fire in an area with little fire history. We found that increased recurrence changed the vegetation after fire. Vegetation also changed depending on the year burned after the last fire. Burning vegetation that had none or little fire history resulted in failures of some of the dominant tree species.

Implications for policy and management

- *Changes in fire regime due to increased fire frequency caused by climate change or other factors can compromise vegetation stability to fire even in highly resilient vegetation types.*
- *Pre-fire assessment of fire related plant traits of the dominant vegetation elements is needed to locate the most vulnerable vegetation types.*
- *Estimating future impacts of increased fire frequency requires a detailed cartography of fires; at least since the 1970's, when fires became frequently in the Northern Mediterranean region.*
- *Post-fire management of burned vulnerable forests should aim at the preservation of unburned islands, because they are vital for ensuring tree species colonization that failed to regenerate after fire.*

The problem: In fire-prone areas, the vegetation is considered resilient to fire (see Box opposite). However, resilience is compromised when fires occur at intervals too short for the vegetation to recover its capacity to withstand another fire. Climate change, among other factors, is expected to increase fire frequency, thereby increasing fire recurrence. A fire regime of increased fire frequency can affect vegetation stability, and become a major factor of vegetation change. This problem is important for low-, and mid-elevations pine woodlands exposed to frequent crown-fires, but also for high altitude, coniferous forests exposed to infrequent surface-fire episodes.

The approach: We conducted two studies: one in a high fire-frequency area; the other in an infrequent fire area. The first study was in an area covered by *Pinus pinaster* forests in Sierra de Gredos (Spain), with over 1000 fires between 1976 and 2009 (Fig. 18.1). Sites were selected by the number of fires experienced in this period (1 to 3 fires, [Rec1 to Rec3]) and year since the last fire (4 to 37 [YSLF]). The second study was conducted in an infrequently burned area (Mount Taygetos, Greece); a high altitude, cool coniferous forest stand, dominated by *Abies cephalonica* and *Pinus nigra* (Fig. 18.1). The short-term effects of fire were investigated in an area burned by a large fire in 2007. Floristic composition and regeneration of dominant tree species were monitored in sites located both at the edges of the unburned patches and in completely burned areas.

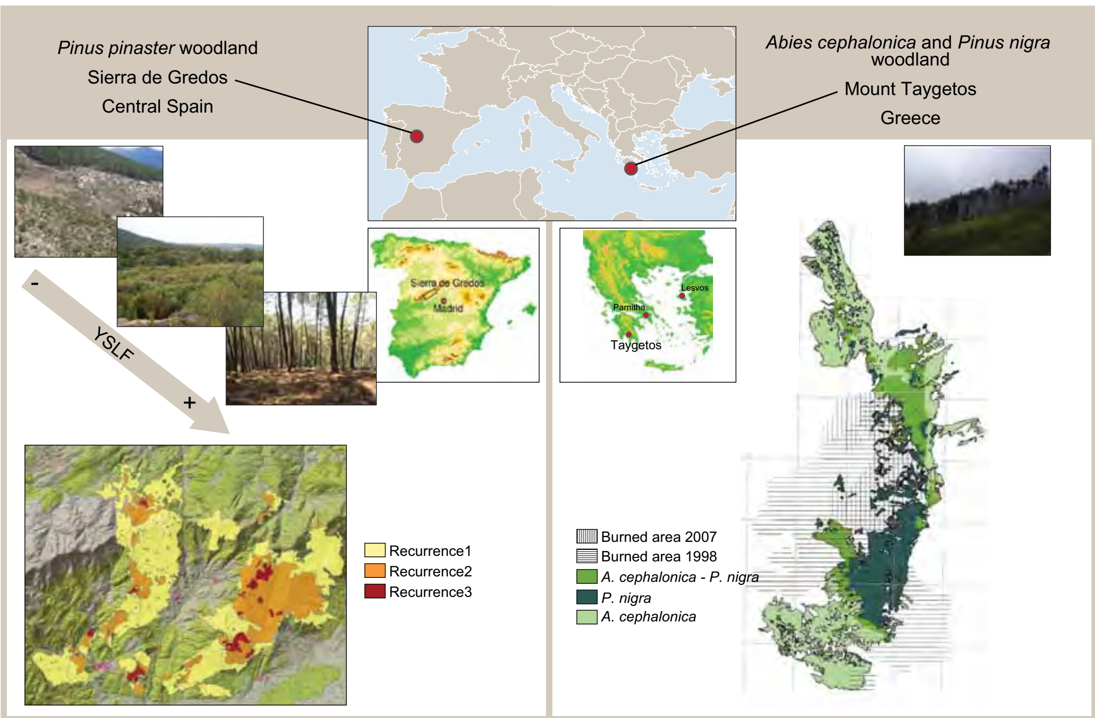

Fig. 18.1: Location of the study sites. A) Sierra de Gredos (Central Spain), a high fire frequency area dominated by Pinus pinaster, where fires had been mapped an plots selected comprising a range of years since the last fire, recurrence and fire return interval between 1976 and 2007; B) Mount Taygetos (Greece), a high elevation low fire frequency area dominated by Abies cephalonica and Pinus nigra, burned in 1998 and 2007.

Achievements: Years since the last fire (YSLF), fire recurrence and fire return interval differentially modified the various plant groups of the vegetation in *Pinus pinaster* woodlands (Fig. 18.2). YSLF controls the dominance of woody species, which increase with time, and affects herbaceous species richness and diversity, which decrease with time. When fire frequency increases (high recurrence), herbaceous species become more abundant, but the burned areas become more homogeneous (lower beta diversity). Woody species responded differently, and the highest species richness was obtained at intermediate recurrence, with lowest values at one or three burns. Finally, at medium fire return interval (10-20 yr) the herbaceous component increases in abundance and richness compared to shorter (<10 yr) or longer (>20 yr) intervals. At the longer interval, abundance of woody species became minimal.

In high altitude ecosystems newly affected by large crown fires, observed post-fire floristic changes are primarily related to the herbaceous component, as the key woody elements do not regenerate. *Pinus nigra* post-fire recovery depends almost exclusively on seed dispersal from neighbouring unburned patches while regeneration in the completely burned areas is practically inexistent. Environmental variables and microhabitat characteristics, such as presence of herbaceous species and other strong competitors, like ferns, fallen branches and trunks, can greatly affect *Pinus* density. On the other hand, *Abies cephalonica* fails to regenerate over the short-term, resulting in places where burned *Abies* stands are neighbouring with unburned *Pinus* stands, there being a high probability of *Pinus* intrusion to such *Abies* stands (Fig. 18.2).

Lessons learned and implications: We detected changes in vegetation because of changes in fire regime components, such as increased fire frequency. Vegetation responses vary depending on the traits of the constituent species. Vegetation change may be the first and most visible sign of a change in ecosystem properties. But other changes (i.e., soil), with additional implications, may follow and need to be investigated. Cartography of fires, necessary for detecting wildfire impacts due to recurrent burning is lacking. In large wildfire events (thousands of hectares), notably in protected areas with species little resilient to fire, it is crucial to identify sites that may require post-fire management actions due to anticipated regeneration failures.

Resilience

In Ecology, resilience is "the capacity of a system to experience shock while retaining essentially the same function, structure, feedbacks, and therefore identity..." (Walker et al., 2006). Resilient vegetation to fire is one that would maintain its structure, function and identity after fire. Fires would cause transitory changes that would disappear while the ecosystem slowly returns to its pre-fire condition. The capacity of an ecosystem to withstand fire is lowest right after fire, increasing with time until the regeneration potential has recovered. An ecosystem is vulnerable to another fire before a regeneration capacity threshold is reached. A fire during this time can irreversibly change it. Vulnerability decreases with time, as resilience builds up again.

Burned and unburned pine woodland (Sierra de Gredos, Ávila, Spain). Photo: B. Pérez

Pinus pinaster woodland
Sierra de Gredos, Central Spain

Variable	YSLF	Recurrence	Interval
Cover			
Total	**		
Woody species	**		*
Herbaceous species		**	***
Species richness			
Total	***		**
Woody species		**	
Herbaceous species	***		**
Herbaceous diversity			
H Shannon	**		
Whittacker index		*	

Abies cephalonica and *Pinus nigra* woodland
Mount Taygetos, Greece

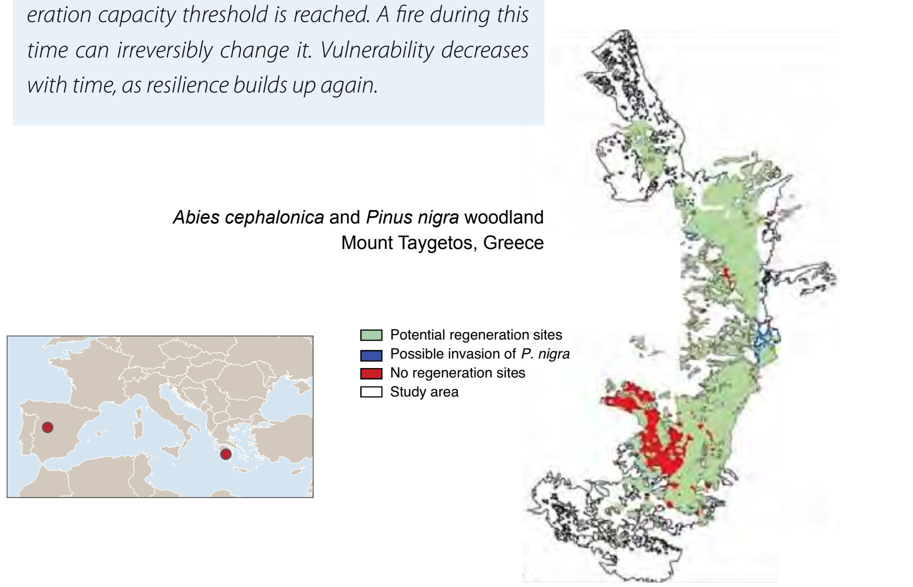

Fig. 18.2: Factors significantly affecting the vegetation in Sierra de Gredos (*) in relation to years since last fire (YSLF), fire recurrence and interval (table, left) and areas with regeneration failures or changes in the dominant species in Mount Taygetos as a result of fire (right).

Topic 19

Short-term post-fire vegetation responses to the legacies of past management

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The post-fire vegetation of Pinus woodlands may reflect the geophysical environment in interaction with past management. Understanding past management effects is important to anticipate post-fire vegetation. We tested this in two large fires in Spain (Guadalajara) and Turkey (Antalya). While the Turkish fire site was actively managed, the Spanish was not. Management history influenced stand structure, which determined fire severity. Where management was reduced (Guadalajara), we found, after fire, a major vegetation compositional change related to stand structure. Pinus regeneration was largely unpredictable (both sites). Geophysical variables determined some post-fire vegetation features (e.g., species richness). Stand structure (legacy of past management) and geophysical variables can help predicting some post-fire vegetation properties, although unpredictability in these systems is high.

Implications for policy and management

- *Effects of past management actions on stand structure must be considered for their ultimate effects on the post-fire vegetation.*
- *Stand structure strongly determined fire severity, in interaction with burning conditions and topography.*
- *Post-fire vegetation is the result of the interplay of pre-fire stand structure and geophysical variables in pine woodlands.*
- *Site-specific, local information is needed to anticipate post-fire vegetation, particularly to identify possible vulnerable areas subject to change due to fire.*

The problem: Forest fires affect areas with varied management history, including most recently reduced management. Once a fire occurs, it is important to know to what extent the post-fire vegetation reflects its past management. Knowledge of post-fire regeneration patterns, as affected by the interplay of past management, fire severity and the geophysical environment may help direct management actions to develop forest structures reducing fire impacts or identifying vulnerable areas after fire. This identification is more compelling given current trends to reduce active management. In such cases, fires could start a vegetation development process separate from management, with possible long lasting consequences.

The approach: We related short-term (3-4 years after fire) post-fire vegetation regeneration to pre-fire forest stand structure (proxy of past management history) and geophysical variables in Guadalajara, Spain (13000 ha, *Pinus pinaster* forest) and Antalya, Turkey (15000 ha *Pinus brutia* forest) (Fig. 19.1). The management history in Antalya was more intense and active than in Guadalajara. Pre-fire forest stand structure was reconstructed based on the remaining snags. At the Guadalajara fire, in addition, pre-fire stand structure was related to historical management using forest management plans from at least 50 years. In this site we also investigated how fire severity was affected by forest stand structure in combination with topography and burning conditions (weather, rate of fire spread). This was possible due to a detailed reconstruction of the progression of the fire front. Post-fire vegetation was studied by means of a comprehensive sampling scheme (Fig. 19.1).

Achievements: Management history-derived variables at the Spanish site were more important in explaining stand structure than geophysical variables. Pre-fire *Pinus* abundance was mostly influenced by its abundance in the past. *Quercus pyrenaica* (a broadleaf tree species) was more abundant in stands with a longer time since the last management plan, suggesting a colonization of the understory due to reduced management or abandonment. Fire severity was affected by the combination of forest stand structure, topographic variables and burning conditions; rate of fire spread being the most relevant. The three components of stand structure that more affected fire severity were tree height, fine biomass and tree size heterogeneity. Post-fire *Pinus* recruitment was mostly unpredictable by pre-fire stand structure in both fires. However, in the Guadalajara fire, *Quercus* regeneration was totally dependent on its pre-fire density, and became dominant over *Pinus* where it was already present before fire, suggesting a change in dominance as a result of fire (Fig. 19.1). On the other hand, geophysical variables were more important than pre-fire stand structure variables in explaining post-fire species richness, particularly in the Antalya fire (Table 19.1). Other vegetation features were not very predictable and variable among sites.

Lessons learned and implications: Current stand structure is a legacy of past stand use and management. Stand structure can be a main driver of fire severity. Stand structure at the time of fire was not a main factor of *Pinus* regeneration in either fire. However, changes in post-fire vegetation composition and dominance in the understory were accelerated by fire, and these were more important where management had been reduced (Guadalajara), leading to a major vegetation compositional change. Managers should consider down-stream effects (e.g., altered species composition) of current actions or their cessation.

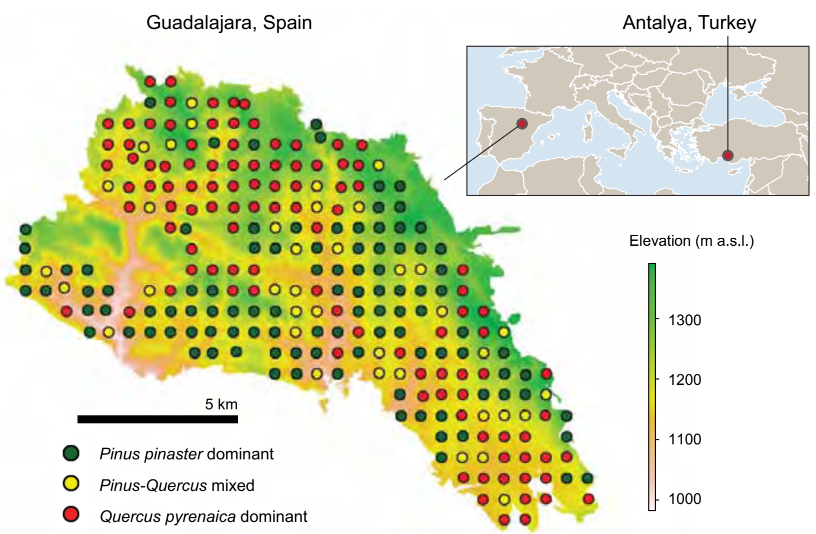
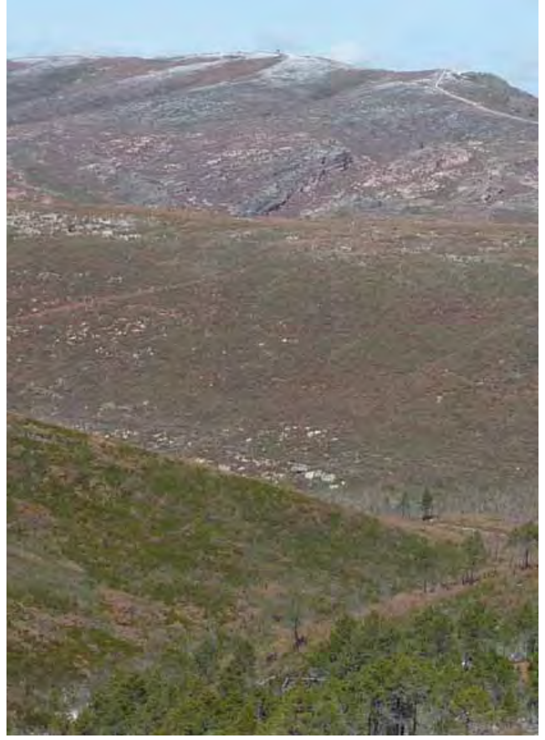


Fig. 19.1: Study sites in two very large fires in Guadalajara (Spain) (13000 ha) and Antalya (Turkey) (15000 ha) (top right, red dots). An intensive, regular sampling design was implemented for measuring pre-fire stand structure and post-fire vegetation characteristics. Larger map shows post-fire dominance of Pinus pinaster (green dots), Quercus pyrenaica (red dots) or mixed Pinus-Quercus dominance (yellow dots) in plots that burned as pine woodlands in the Guadalajara site.



Left: Quercus pyrenaica regenerating in former Pinus pinaster woodland (Guadalajara, Spain). Photo: I.R. Urbieta

Right from top to bottom:

Pinus pinaster woodlands with understory of Quercus pyrenaica (Ávila, Spain).

Log dams (Cuenca, Spain).

Quercus pyrenaica regenerating in former Pinus pinaster woodland (Guadalajara, Spain).

Pine woodland burned by surface fire (Cuenca, Spain).

Photos: I. Torres

Table 19.1: Proportion of explained deviance using model training data (Train) or left-out data in a cross-validation process (Cross-val) by Boosted Regression Tree models analyzing the influence of geophysical, stand structure or both sets of variables combined, on post-fire vegetation in large wildfires in Guadalajara (Spain) and Antalya (Turkey).

	Explained deviance (%)					
	Geophysical		Stand structure		Geophysical + stand structure	
Guadalajara fire	Train	Cross-val	Train	Cross-val	Train	Cross-val
No. pine seedlings	11	0	32	9	48	10
Ratio *Pinus/Quercus*	20	2	83	69	88	71
Species richness	24	9	-	-	37	10
Antalya fire						
No. pine seedlings	18	3	0	0	29	5
Species richness	75	43	30	4	73	41

Topic 20

Integrating pre and post-fire management to reduce fire risk: a comprehensive approach for fire management

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Management actions favouring stand resistance and resilience were developed in fire-prone pine forests from young to old stands. Young and dense stands were heavily thinned to reduce fuel load, and resprouting species introduced to promote resilience. In mature stands, various hardwood species were planted under different canopy conditions in dry and wet sites. Soil water and light availability showed a contrasted influence on growth and survival according to the sites. In mature stands, soil and vegetation treatments were applied to favour natural regeneration and oaks were sown to enhance diversification. Intense treatments (soil scarification, controlled burning of high intensity) showed better results.

Implications for policy and management

- *Active forest management is needed to increase resilience and must be adapted from young and dense to old and sparse pine stands.*
- *Intense thinning is recommended in young dense stands to reduce susceptibility to fire risk, and introduction of hardwood species is possible at the same time.*
- *Cover reduction by thinning of mature stands and introduction of resprouting hardwood species are recommended to increase resilience.*
- *In old pine stands on good soils, site treatments such as soil scarification or controlled burning of high intensity are adapted to favour the development of natural pine seedlings and introduced hardwood species.*

Fig. 20.1: Dense pine forest of Pinus halepensis naturally regenerated from a 1979 wildfire. This type of community shows a low productivity value and high risk of wild fires. In this community, reintroduction of hardwoods is difficult and seedlings will have problems related to intense competition for light and water. Photograph was taken in 2011.

The problem: In the Mediterranean, fires burn across landscapes resulting from previous land uses, including afforestation. Many shrublands, plantations or monospecific naturally regenerated forests growing in old fields show high fire hazard and low resilience after burning. After fire, not all areas will regenerate in a manner compatible with desired management objectives; burned areas can enter into degradation loops that must be avoided. This risk would be aggravated under the projected increased drought and more severe fire regime. Management actions favouring stand resistance and resilience are thus needed particularly in highly fire-prone systems such as pine forests.

Approach: We developed and tested three main forest management strategies to reduce fire risk and increase resilience of *Pinus halepensis* (Aleppo pine) forests along a South-North ecological gradient and differing in ages. The first strategy was clearing young and very dense pine stands (>100,000 stems/ha) at two densities (600 and 1200 stems/ha) in Northern Tunisia and Southern Spain. After brush chipping, oaks seedlings species (at 300 stems/ha) were also introduced to increase resilience. The second strategy aimed at increasing resilience of mature stands by introducing various resprouting hardwood seedlings (9 species in total) under three cover types obtained after thinning: dense cover (32 m^2/ha), medium cover (12-19 m^2/ha), and light cover (8-10 m^2/ha). The third strategy objectives were to regenerate old pine stands (90-100 years old) and to increase resilience by sowing oak acorns. Different site treatments were tested including prescribed burning of low or high intensity, chopping, chopping followed by soil scarification, and control.

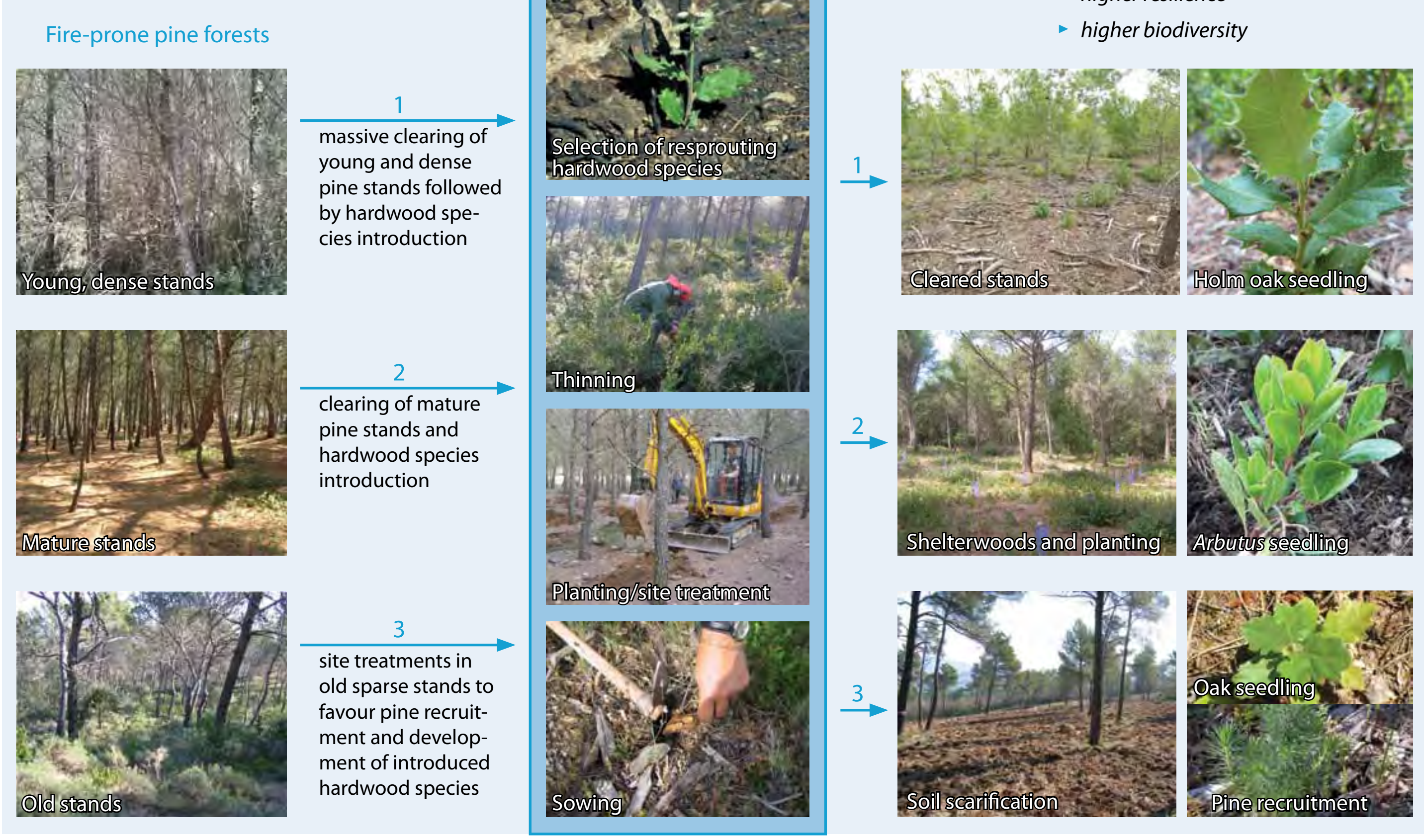
Achievements: The heavy thinning of young pine stands (first strategy) considerably reduced total, green, and dead biomass; total biomass dropping from about 60 tons/ha to 5 tons/ha. Vertical and horizontal fuel continuities were also greatly reduced leading to a reduced fire risk. While thinning also enhanced diameter growth (+3.5 cm in 4 years) of the remaining pines, it did not benefit height growth. Oak seedlings survival was higher in the treatments at 1200 pines/ha, probably because of a more pronounced shelter effect, while growth did not vary between the two thinning treatments. Results from the second strategy showed a slightly higher survival in dense stands in the drier Spanish site whereas it decreased significantly under the dense cover treatment in the wetter French site. However, in both sites relative diameter growth increased with cover openness, thus showing that light availability is also a crucial driver of growth under canopies of Mediterranean forests. However, a better performance of drought-resistant species was noted in the Spanish site and of shade-tolerant species in the French site. Soil moisture was also maximal in medium treatment at the French site. In the third strategy, site treatments creating the most pronounced disturbances of the soil and ground vegetation (scarification and fire of high intensity) were also the most adapted to favour pine recruitment and to enhance oak seedling survival. High intensity prescribed burning proved to be the most efficient treatment to survival, while scarification treatments induced the highest growth response.

Fig. 20.2: Thinning treatments on Pinus halepensis forest regenerated from a 1979 wildfire. This type of community shows a low risk of wild fires, high productivity and aesthetic value. Thinning works were performed 10-15 years after wildfire. In this community, hardwoods can be re-introduced. Photograph was taken in 2011.

Lessons learned and implications: Management actions must be adapted to each stage of the dynamics in fire-prone forests. Reduction of young stands density is recommended to reduce their extreme sensitivity to fire (Fig. 20.1). In mature stands, hardwood resprouting species can be introduced to increase resilience (Fig. 20.2). Management of the overstorey cover proves to be effective in controlling resources availability and in turn seedling survival and growth. In older and sparser stands, site treatments such as soil scarification or prescribed fire of high intensity, are needed to enhance development of naturally established or introduced seedlings.

Managing to increase resilience

Different forest management strategies (labelled 1 to 3) to change fire-prone monospecific pine stands of various ages to more resilient woodlands:



Topic 21

Restoring under uncertain climate conditions: options and limitations

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Climate change projections may dramatically increase the impacts of forest fires on ecosystems through more severe fire regime, increased drought, and heavy rains affecting post-fire vegetation regeneration and soil erosion. Post-fire management should select plant species and techniques able to increase ecosystem fire-resilience and improve tolerance to the projected increased drought. Developed techniques include improving plant water use efficiency, increasing water supply through soil preparation, and reducing water losses. However, the more severe change scenarios may produce dramatic ecosystem degradation, beyond the range of technical solutions for restoration. FUME has developed a structured approach for post-fire impact assessment and restoration under climate change.

Implications for policy and management

- *Ecosystems dominated by obligate seeder species, often old fields, require re-introduction of woody resprouters for reducing fire hazard and increasing fire resilience.*
- *Post-fire restoration in the perspective of climate change should consider fire-resilient, drought-tolerant species.*
- *Technical options were developed for increasing post-fire restoration success under climate change, including species and provenances selection, nursery seedling acclimation to drought, soil preparation to increase water supply, and microhabitat conditioners to reduce seedling water losses.*
- *A structured approach was produced for post-fire impact assessment and restoration under climate change (decision support system).*

Fig. 21.1: Seedling drought-induced dieback short after outplanting. CEAM.

The problem: Burned forests are exposed to ecosystem degradation and can damage downslope structures. Post-fire vegetation recovery rate is critical in controlling the risk of ecosystem degradation. Ecosystems with low presence of resprouting species are especially vulnerable. Projected increase of drought would hinder post-fire vegetation recovery, e.g., seed germination and/or establishment. Increased probability of heavy precipitation events would increase the risk of post-fire soil erosion and flash-flooding. The coincidence of mega-fires with extreme events may result in extended land degradation. The capacity of species to acclimate under changing climate is uncertain. More severe change scenarios may produce dramatic habitat degradation beyond the range of technical solutions for restoration.

The approach: Post-fire restoration should be considered for mitigating early post-fire risks and for enhancing ecosystem recovery. Vulnerable ecosystems require development of restoration approaches adapted to more severe fire regimes and increased drought, to avoid fire-degradation loops. This includes selection of drought-tolerant, fire-resilient species in post-fire restoration programmes in the Mediterranean. Drought is the main cause of seedling mortality in afforestation (Fig. 21.1). Therefore, extreme drought would reduce planted species survival and growth, especially if drought occurs shortly after plantation. Post-fire restoration techniques should adapt to increased drought (Fig. 21.2), improving the water status of introduced seedlings along the whole restoration process. Plant species in fire-prone ecosystems show different sensitivity to drought and various drought-tolerance mechanisms. We investigated successful plant functional traits related to drought resistance and to the ability to recover after fire that would increase plantation success and increase vegetation resilience (i.e., its recovery after fire).

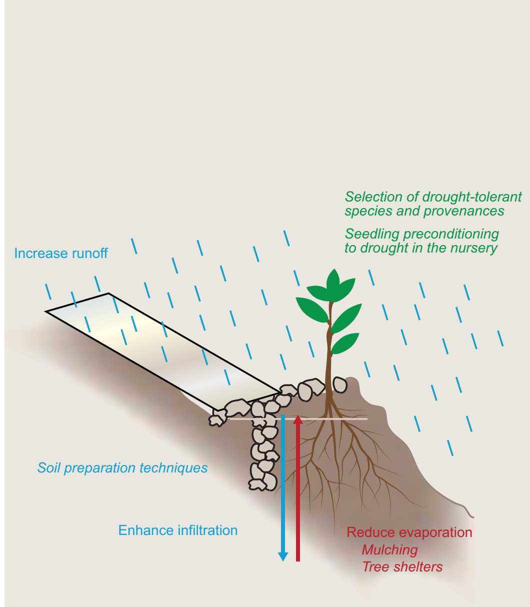

Fig. 21.2: Technical options to reduce water stress in plantations.

Fig. 21.3: Tree shelter. D. Fuentes, CEAM.

Achievements: Native Mediterranean sclerophyllous shrub and tree species quickly recover after fire by resprouting from protected buds (e.g., by cork in the case of cork oak, or from belowground buds). In addition, these species show higher leaf water content in summer and take much longer in accumulating dead, fine fuels than obligate seeder shrubs. Therefore, woody resprouters increase ecosystem resilience and produce less risky fuel load than obligate seeders. Technical options that proved successful in reducing water stress in plantations (Fig. 21.2) are:

1. Increase plant water use efficiency.

Selection of drought tolerant species and provenances: Most of woody resprouters have deep root systems allowing the plant escaping summer drought by exploring deep soil layers. Water use efficiency and resistance to xylem cavitation are critical morpho-functional plant traits used to assess drought resistance of the various species and provenances. Several native plant species and provenances have experimentally shown high tolerance to extreme droughts at the seedling stage and high capacity of recovery afterwards.
Nursery cultivation for the acclimation of seedling to extreme drought: Seedling pre-conditioning to drought by reducing irrigation in last period of nursery culture, the use of long containers favouring the development of tap root (e.g., in oaks) and the fast deep soil colonization after outplanting are techniques improving seedling survival in the field under drought.

2. Increase water supply through soil preparation techniques such as runoff harvesting (Fig. 21.2).

3. Reduce water losses (e.g., tree shelter and mulching). Tree shelter reduces seedling transpiration through reduced wind and increased air humidity inside the shelter (Fig. 21.3).

Lessons learned and implications: FUME developed a decision support system for helping decision making for burned areas management under projected future fire regimes (POSTFIRE-DSS, Fig. 21.4). POSTFIRE-DSS considers the short-term mitigation of post-fire damages on ecosystems and structures, and the long-term recovery of the ecosystem under increased drought. The application considers four time steps: 1) Preliminary assessment of damage, based on GIS; 2) Emergency actions; 3) Regeneration reinforcement, and 4) Forest restoration. Involvement of stakeholders in all phases of the restoration project is strongly recommended. Incorporation of monitoring and evaluation is also critical in restoration actions to face uncertainties on ecosystems responses to climate change.

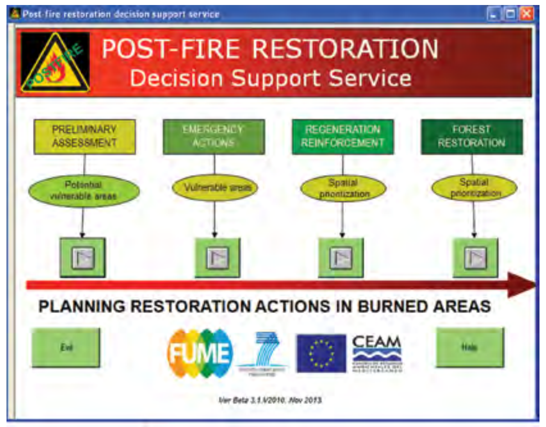

Fig. 21.4: Application for the decision-making process on post-fire restoration actions.

Topic 22

Perils in the adaptation of fire management to a changing world

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Future climate conditions point to a significant increase in wildland fire risk in many fire-prone areas, but particularly in Southern Europe and the Mediterranean region. Under these prospects, it is important to evaluate how well prepared fire agencies are to cope with the new conditions, what the potential damages are that future fires might cause, and what policy changes might be needed to address future fire management needs. To address these issues in FUME, we conducted a series of focus groups with stakeholders in Spain and Italy, to identify needs and gaps in science-technology transfer. Additionally, the economic impact of projected fire changes was estimated for Italy. A review of EU fire-related policies found that a disconnect exist between policy, science and management. It also revealed that fire costs and damages can greatly increase and that fire policies should be revised in a manner consistent with changing conditions.

Serranía de Cuenca (Cuenca, Spain). Photo: A. Velasco

Implications for policy and management

- *Public investments efficiency in wildfire research and wildfire management operations depend on resolving the disconnect problem between science, policy and management.*
- *Wildfire policy development needs to change with scientific development and operational applications.*
- *At the operational level, changing climate conditions, population growth and RUI expansion will likely necessitate more financial and firefighting resources in addition to more integrated fire management policies and incentives to private owners to invest in fire protection activities.*
- *To improve coordination between science and management, and to improve research and operational efficiency, it is best to involve agencies responsible for wildfire prevention and suppression in the research process from problem identification to operational tools implementation.*

The problem: Given changing climate conditions, demographic change and urbanization, a difficulty in dealing with wildland fire problem is re-establishing the connection between all institutions involved. Three main concerns were identified: 1) Climate change scenarios project increases in temperature and more frequent and extreme drought conditions, which could lead to significant increases in wildfire risk and fire loads in Southern Mediterranean basin countries; 2) Economic impacts associated with this increase in fire risk and load may move countries to not having enough social, financial and economic capital to address the problem adequately; and 3) The existence of a disconnect between science, policy and management.

The approach: The disconnect between science, policy and management was addressed by building a "bridge" of communication through several meetings between scientists and stakeholders and fire operation managers (see Fig. 22.1) (problem 3). An analysis of fire management plans in Mediterranean countries was used to identify strengths and weaknesses of current Fire Prevention and Fire-fighting planning instruments with respect to adaptation to future fire regimes (problem 1). Two additional important activities were conducted. One was an economic analysis of the current and potential impact at the national level of the present and future changes in fire regimes in Italy (problem 2). The other was a comprehensive forestry policy and fire prevention and control policy analysis at the European Union (EU) level to understand how the EU and its member states address the problems presented (all 3 problems).

Achievements: In our work we found the existence of a rift between science, policy, and managers. Stakeholders such as regional fire managers warn that the significant advances in science to deal with future fire regimes under changing climate conditions has not been properly transitioned into useful applications on the ground. Furthermore, a disconnect between the policy making, scientific and wildfire management communities was noted (see Fig. 22.2). A review of EU funding schemes for forest management reveals a lack of uptake of the measures and the absence of a sufficient logic in the area of forest fire prevention and action. The annual investments in wildfire protection in the EU are already very high and the projected increase in fire loads will necessitate additional financial resources. We used three cost categories to assess the economic implications of future fire events in the Mediterranean area (direct market losses from disrupted hectares of Mediterranean forest using as reference forestry sector shares of national value added; the total social cost of carbon emitted during fire events; and finally existence value losses) we found that for the Mediterranean area as a whole they range, depending on climate and economic scenarios considered, from $ 1.3 to 45.7 billion per year. These are conservative estimates as not all relevant impact categories (e.g., property and human life losses) were included in the analysis. Our studies show that in the "worst case" scenario the economic impact of wildfires amounts to an annual loss equal to 3% of Italy's GDP.

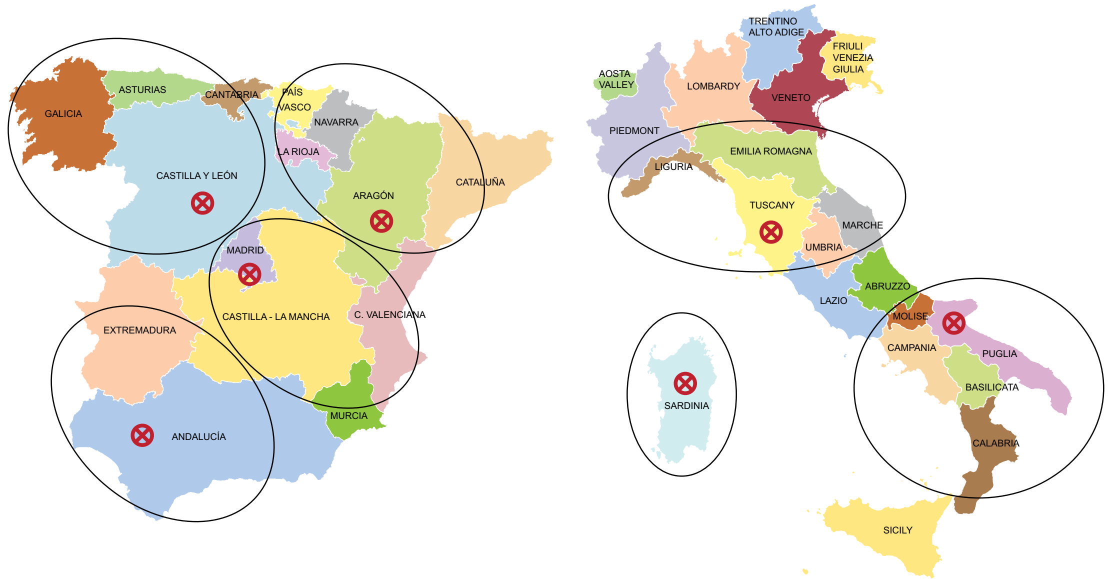

Fig. 22.1: Map showing locations of stakeholders meetings in Spain and Italy.

Lessons learned and implications: In addition to distinct differences in each sector objectives; there is a significant difference in the temporal work scale of each of the three sectors investigated (policy, science, and management) making knowledge transfer between them difficult. Consideration of main stakeholders' needs and existing scientific knowledge is important when developing fire policies. This implies that the EU could focus its support to better link scientific knowledge with firefighting and prevention tools. The economic consequences of projected increases in wildfires risk for the Mediterranean basin are significant ($1.3 to $45.7 billion per year), implying that integrating fire management into land management is cost effective.

Disconnect between science, policy and operations

"That new fire-climate fire model is very promising. It projects the dynamic climatic influence on fire into the future. As managers, we could then adapt to change by projecting our management response accordingly. But the reality today is that we cannot because the policies that guide us are not adaptive, they are prescriptive and we must work within those limitations."—Fire manager at a FUME stakeholders meeting

"This discovery you have shared is important! However, these research results must be translated into a form that can be made operational by managers. The construction and maintenance of the bridge between "validated science" and "operational tools" is often overlooked and under-resourced."—Fire manager at a FUME stakeholders meeting.

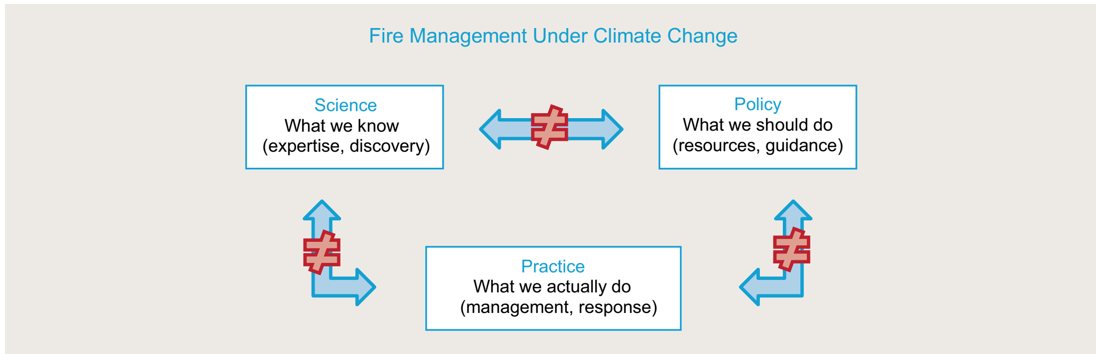

Fig. 22.2: Diagram showing disconnects between science, policy and operations as discussed by stakeholders.

Outlook and open questions

1. Fire regimes: The collection and recording of additional fire characteristics, such as fire type, intensity, severity, patchiness, requiring the use of spatially explicit datasets from remote sensing and GIS, should be pursued in future work to enable further exploration of patterns and processes affecting fires beyond the level of statistical summaries.

2. Trends in LULC: The role of the various drivers of change (socioeconomics and geophysical) on fire hazard and their impact on fire risk needs further investigation. This is more compelling as additional changes in climate and socioeconomics may affect increasingly closer areas to urban centers as additional low productive areas become unused.

3. Mapping fires: Free/low cost historical series of satellite images as well as future satellite programs (Sentinel) should be used to generate systematic information on fire affected areas in Europe at local/regional scales. Methods specifically adapted to Mediterranean areas that could improve the accuracy and reliability of these products should be explored.

4. Assessing burned landscape features: The relative importance of weather, socioeconomic conditions, vegetation or landscape features, and the way the combination of these parameters counterbalances or exacerbates their effect on fires should be thoroughly analysed. All these factors should be considered within a climate change framework because they are directly or indirectly related to climate.

5. Wild fire risk and the RUI: The relationship between RUI types and global risk must be generalized. Risk models in RUI must be integrated into RUIMap to draw risk maps in any context. Practically, the operational tools must be shared through web and mobile services in order to access any tool and any required GIS database.

6. Socioeconomics and fire relationships: Further research is needed on the historical interaction between human activity and wildfires to provide a comprehensive understanding of the relationship between socioeconomic changes and fire regime in Europe. Developing spatially explicit models to simulate future socioeconomic scenarios (including land use and land cover changes) is critical to obtain credible predictions.

7. Fire and weather relationships: As broad scale analysis may not reflect local situation, detailed studies on climate/weather and fires relationships at smaller scales are required, also coupled with vegetation responses to climate/weather extremes. Moreover, a crucial step forward in both short- and long-term planning activities would be gained through the implementation of long-range climate outlooks.

8. Disentangling the role of climate from other confounding factors in fire: Procedures to differentiate the role of the various factors affecting fire, in addition to climate, are a must to attribute climate change to changes in fire. Research should clarify the periods for which the various factors can be considered stationary to explore climate-fire relationships.

9. Modeling future LULC change: Shared protocols for data collection and harmonized LULC data for spatial resolution, temporal coverage and legends are crucial for integrating biophysical, biogeochemical and socioeconomic processes into models. At local scale, online tools able to directly provide representations of future RUI change scenarios on any local territory must be developed.

10. Fire hazard and fire modeling: The use of tools to assess fire likelihood and intensity at fine scale requires the availability of high spatial and temporal resolution data. There is a data gap in fuel characteristics and spatiotemporal ignition patterns that needs to be further investigated to increase wildfire simulations accuracy.

11. Calculating future fire danger under climate change: Euro-CORDEX is producing a new generation of regional climate projections at a very high resolution (0.11°), allowing the development of new fire danger projections. Further research is needed to properly integrate fire-vegetation feedbacks in climate modeling and to assess the performance of fire danger indices to predict actual fire activity.

Camino de la Guía, Sierra de Gredos (Navalonguilla, Ávila, Spain). Photo: B. Pérez

12. Fire and weather relationships in future climate: More confident modeling outlooks of fire risk in the future require the combination of both climatic and non-climatic components, such as land use and land cover, human activities and relevant feedbacks of fire and climate change on the ecosystem.

13. Fuels and drought: Collecting data for necromass and forest dieback in response to climate extremes is needed. The effect of live/dead fuels on shrub flammability should be clarified and compared to drought indices. Leaf area adjustments and live moisture in plants in response to soil moisture availability and increased CO_2 should also be studied.

14. Modeling ecosystem responses to changes in climate and fire regime: Improved simulation of interannual variability and extremes in climate models will allow vegetation-fire models to reproduce correct biome distribution and capture observed inter-annual variability of fire and vegetation productivity. Model inter-comparison across scales and by integrating dendrochronological data improves predicting vegetation responses to changing fire regimes and climate variability.

15. Threats for newly affected areas: The approach on new fire-prone areas needs testing against past shifts in fire regimes. For regions potentially affected, monitoring systems might be required as well as fuel models to assess fire management options. Vulnerability of boreal and temperate species and migration rates of fire-adapted species require assessment in these areas.

16. Germination and climate change: The Mediterranean basin is a biodiversity hotspot, with many endemic species; however our understanding of the regeneration niche of many species is still poor. Germination studies analyzing environmental changing factors and encompassing representative species from different provenances would help us identify the germination niche breadth of many species, in particular endemics.

17. Ecosystems responses to fire and increased drought: Extensive low-cost and simple manipulative experiments in mature and burned ecosystems, with comprehensive monitoring across levels (plants to ecosystem), complemented by process-based studies at particular locations, are a must. Thresholds for post-fire regeneration failures in relation to rainfall changes (total, patterns) differentiating seeders and resprouters is also needed.

18. Vegetation response to changes in fire regime: Critical thresholds below which plant community integrity cannot be sustained as a result of changes in fire frequency or other fire regime characteristics must be identified. This requires knowing plant traits regarding resilience. Events leading to tipping points in vegetation and degradative loops need to be researched.

19. Vegetation responses and the legacies of past management: The legacies of past management in determining burning characteristics, including fire severity, and post-fire vegetation in *Pinus* woodlands across the Mediterranean deserves further exploration. In addition to stand structure, forest surveys should include a comprehensive characterization of extant vegetation, differentiating plants by their resilience traits, and include soil seed bank regeneration potential.

20. Integrating pre-and post-fire management to reduce fire risk: a comprehensive approach for fire management: Acquiring a better knowledge of interactions – including resources repartition - among the tree canopy, the understorey and the naturally established or introduced seedlings need further research. Models simulating the development of the different vegetation layers could help to test the impact of different management options to improve resilience.

21. Restoring under uncertain climate conditions: options and limitations: More research is needed in the species and provenances adaptive and acclimation capacity to new fire regime and increased drought. Planning post-fire restoration should incorporate landscape ecology principles to facilitate species migration and reduce habitat fragmentation risks, and manage ecosystems in landscapes to improve fire prevention and to promote more resilient landscapes.

22. Perils in the adaptation of fire management to a changing world: The socioeconomic aspects of wildfire management are among the least addressed and researched high-impact issues at EU level. Research programs at EU member states and EU level could be implemented in response. Integration of science development with policy making and on-the-ground application of both policy and science knowledge is a must.

Outlook to the Hoz del Huécar (Cuenca, Spain). Photo A. Velasco

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Reception in the City Hall of Toledo (Toledo, Spain). Photo: Press Office of the Mayor of Toledo

SEVENTH FRAMEWORK PROGRAMME

GA N° 243888