Review of CO_2 emissions mitigation through prescribed burning

Caroline Narayan

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Publisher: European Forest Institute
Torikatu 34, FI-80100 Joensuu Finland
Tel. + 358 10 773 4300
Fax. + 358 10 773 4377
Email: publications@efi.int
http://www.efi.int

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Abstract

Forest fires have the potential to feed back to global climate change because of the emissions of carbon dioxide and other greenhouse gases. The amount of biomass burning over the past 100 years has increased dramatically and is now recognised as a significant global source of atmospheric emissions. The techniques that are used to reduce the risk of destructive wildfires, such as prescribed burning, also have the potential of mitigating carbon emissions in the context of the Kyoto Protocol. The current study reviews the importance of accounting for emissions from forest fires and shows that prescribed burning can be a means of reducing carbon emissions. However, very limited data are available on European scale to fully explore its potential. The limited studies suggest that significant reductions can be obtained and that prescribed burning can be a viable option for mitigating CO_2 emissions in fire prone countries. The present analyses show that the potential reduction attained by such techniques as a percentage of the reduction in emissions required by the Kyoto Protocol varies from country to country. Out of the 33 countries investigated, in only one the requirements of the Kyoto could potentially be achieved by applying prescribed burning, while three other nations showed a potential reduction of 4–8% of the Kyoto requirements. The majority showed a reduction of less than 2%. This implies that prescribed burning can only make a significant contribution in those countries with high fire occurrence. Over a five year period the emissions from wildfires in the European region were estimated to be 11 million tonnes of CO_2 per year, while with prescribed burning application this was approximately six million tonnes, a potential reduction of almost 50%. This means that for countries in the Mediterranean region it may be worthwhile to account for the reduction in emissions obtained when such techniques are applied.

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List of abbreviations

A	area of forest burned
B	biomass of the burned area
β	fraction of biomass consumed during burning
β_a	fraction of above-ground vegetation consumed during fires
β_g	fraction of forest floor fuels consumed during fires
C	carbon emitted during burning
C_a	average carbon of above-ground vegetation
C_g	average carbon of forest floor fuels
CH_4	methane
CO	carbon monoxide
CO_2	carbon dioxide
E_c	amount of carbon emissions
E_{fc}	emission factor of gas specie
EC-JRC	European Commission – Joint Research Centre
EFFIS	European Forest Fire Information System
ENSO	El Niño Southern Oscillation
EU	European Union
f_c	carbon fraction of biomass
FAO	Food and Agriculture Organisation
FIRESCHEME	Fire Information Systems Research in the Socio-Culture, History and Ecology of the Mediterranean Environment
FWI	Fire Weather Index
gCO_2/kg dry matter	grams CO_2 per kilogram of dry matter
GHG	Greenhouse gases
GIS	Geographical Information System
GPG	Good Practice Guidance
GtC	gigatonnes of carbon, 1 Gt = 1 x 10^9 t
GWEM	Global Wildfire Emission Model
ha	hectares
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land Use, Land-use Change and Forestry
MEACAP	Impact of Environmental Agreements on the Common Agricultural Policy
NMHC	non-methane hydrocarbons
Pg	petagram, 1 Pg = 1 x 10^{15} g
PgC/y	petagram carbon per year
tha^{-1}	tonnes per hectare
TEM	Terrestrial Ecosystem Monitoring
TgC	teragram carbon, 1 Tg = 1 x 10^{12} g
UNEP	United Nations Environment Programme
UNFCCC	United Nations Convention on Climate Change
UN	United Nations

1. OBJECTIVES AND OUTLINE

1.1 Introduction

Wildfires are increasingly becoming a major problem for many European societies. Traditional use and management of fire is well established in many regions of Europe where it has been used for many thousands of years to regulate natural ecosystems and land use systems. It is also well known that its misuse or its complete exclusion may result in catastrophic wildfires. There is a need for understanding this paradoxical nature of forest fires in order to avoid losses and destructions.

Forest fires are the most important damaging factor in the Mediterranean countries where between 300 000 to 500 000 ha of forests and other wooded land are burnt each year. During the summer of 2003 forest fires were particularly virulent, as the forests were exposed to very hot and dry climatic conditions, causing destruction, for example to about 400 000 ha of forest in Portugal and leaving even the well-equipped European regions like South-Eastern France with extraordinary difficult situations despite having thousands of fire fighters and extensive ground and aerial up-to-date equipment (Fire Paradox, 2006).

Therefore, the reduction of wildfire hazard and the sustainable development of natural and managed ecosystems in Europe require new practices in wildfire management. The understanding of the concept of the fire paradox is thus essential for finding solutions for integrated wildland fire management by considering various aspects of fire, from its use as a planned management practice (prescribed fire), to the initiation and propagation of unplanned fires (wildfires), to the use of fires in fighting wildfires (suppression fire). Prescribed and suppression fires will therefore set the limits for wildfires by controlling their spatial extent, intensity and impacts.

Among the destruction of livelihoods and habitats, one of the major consequences of forest fires is their potential impact on global atmospheric problems, including climate change. Only in the past decade have researchers realised the important contributions of biomass burning to the global budgets of greenhouse gases (GHGs), such as carbon dioxide (CO_2), methane, nitrous oxide, and other tracers, like tropospheric ozone, methyl chloride, nitric oxide and elemental carbon particulates (UNEP, 1999a). The amount of biomass burning over the past 100 years has increased dramatically and is now recognised as a significant global source of atmospheric emissions, contributing more than half of all the carbon released into the atmosphere (UNEP, 1999a).

This has important implications, meaning that there is a potential for emissions mitigation through effective fire management measures in the context of the Kyoto Protocol. The current report thus aims to provide a review of CO_2 emissions mitigation through prescribed burning by qualitative and where possible, quantitative analyses of the amount of CO_2 emissions produced by wildfires and prescribed burning in Europe. The objectives of the report are outlined in the next section.

1.2 Objectives

The current report aims to: ***review the potential of CO_2 emissions mitigation through prescribed burning.***

The report involves two different activities, the first comprises a review and analysis of contributions by wildfires and by prescribed burning to the overall emissions in Europe in CO_2 equivalents, and the second concerns a review and analysis of the potential of prescribed burning and suppression fires to mitigate emissions in the context of the Kyoto Protocol.

1.3 Project framework

This study was undertaken within the framework of the EC-funded FP6 project "Fire Paradox", an integrated project aiming to create scientific and technological bases for new practices and policies under the Integrated Wildland Fire Management in Europe, thus allowing the development of strategies for their implementation at the European level. The project is completely focused on fire paradoxes, from its negative impacts to its positive effects, from wildfires to managed fires (prescribed and suppression fires).

1.4 Report outline

The current report comprises six chapters, structured as follows: **Chapter 2** provides a literature review of forest fires in Europe with the focus on CO_2 emissions; **Chapter 3** outlines the methodology applied for estimating emissions and the data needs for the estimates; **Chapter 4** reports on the results; **Chapter 5** provides a summary and discussion, with conclusions and outlook in **Chapter 6**.

2. LITERATURE REVIEW

2.1 Introduction

Fire has always been and continues to be an integral part of land use and agriculture around the world. In many ecosystems fires are natural, essential and ecologically significant forces, responsible for organising the physical and biological attributes, shaping landscape diversity and influencing energy flows and biogeochemical cycles, particularly the global carbon cycle (IFFN, 2003a and 2003b). While some forest ecosystems have evolved positively in response to frequent fires from natural and human causes, maintaining the dynamic equilibrium responsible for high biodiversity, others are negatively affected, resulting in the destruction of the forests or long-term site degradation (Goldammer, 1998 and 1999; FAO, 2005a).

Forest fires result from a combination of factors that vary markedly from country to country. These range from burning and clearing of forests for agricultural lands, increase in exploitation of natural resources, rural development, droughts related to El Niño Southern Oscillation (commonly known as ENSO – for further explanations see UNEP, 1999b) events and natural disasters, such as lightning. In many northern countries and particularly in Western Europe, forest fires are mostly due to arson, poor forest management, rural depopulation and negligence, while in southern and eastern parts deforestation and severe climate conditions are the main culprits.

This chapter contains a literature review of biomass burning and the related emissions of GHGs, focussing on forest fires, in particular wildfires, suppression fires and prescribed burning. The aim of the review is to provide an overview, and where appropriate, in-depth information on these types of burning, their role in and within forest ecosystems and the associated losses. More importantly, the review focuses on carbon emissions from forest fires mainly in Europe but also provides some indication on global emissions. The current review is targeted towards, firstly, showing the importance of accounting for emissions from forest fires, and secondly, showing that prescribed burning could be a means of mitigating carbon emissions in the context of Kyoto Protocol. The latter point is further elaborated in the report with data analysis and quantification of emissions from different fire types.

2.2 Emissions from forest fires

Annually, fires consume millions of hectares of the world's forests, with loss of human and animal lives, as well as biodiversity, burned and degraded real estate and private properties, extensive economic damage in destroyed wood and non-wood forest resources, high costs of fire suppression, and damage to other environmental, recreational and amenity values (FAO, 2005a). Another major consequence of forest fires is their potential impact on global atmospheric problems, including climate change. The amount of biomass burning, as reported in *GEO-2000* of UNEP (1999a), has increased significantly over the past 100 years and is now recognised as a significant global source of atmospheric emissions, contributing more than half of all the carbon released into the atmosphere. Table 2-1 summarises the estimates for the release of carbon (in units of teragrams of carbon per year, TgC/year, where 1 teragram equals 10^{12} grams or 10^6 metric tonnes) into the atmosphere from biomass burning for different ecosystems.

Table 2-1. Biomass burning: global estimates of annual amounts and the resulting release of carbon into the atmosphere.

Source of burning	**Biomass burned (Tg dry matter / year)**	**Carbon released (TgC / year)**
Savannahs	3 690	1 660
Agricultural waste	2 020	910
Tropical forests	1 260	570
Fuel wood	1 430	640
Temperate and boreal forests	280	130
Charcoal	20	30
World total	8 700	3 940
For comparison: Global carbon emissions from fossil fuel burning, cement manufacture and gas flaring		6 518

[Source: Andreae, 1991]

The most recent estimates show that the amount of vegetation biomass burned annually is in the magnitude of 9 200Tg, or 92 billion tonnes (Andreae and Merlet, 2001).

Apart from emissions of various gases fires lead to a loss of benefits from total economic value components. The value of losses of wood forest products resulting from forest fires is usually estimated by using either the replacement costs or the value of burnt wood (Merlo and Croitoru, 2005). However, as the focus of the present report is on GHG emissions, economic losses due to forest fires will not be discussed here.

While fires are important for forest ecology, continued intense burning can have drastic ecological consequences, such as soil degradation, contamination of lakes, nutrient loss, erosion and loss of landscape. The next section describes this paradoxical nature of forest fires.

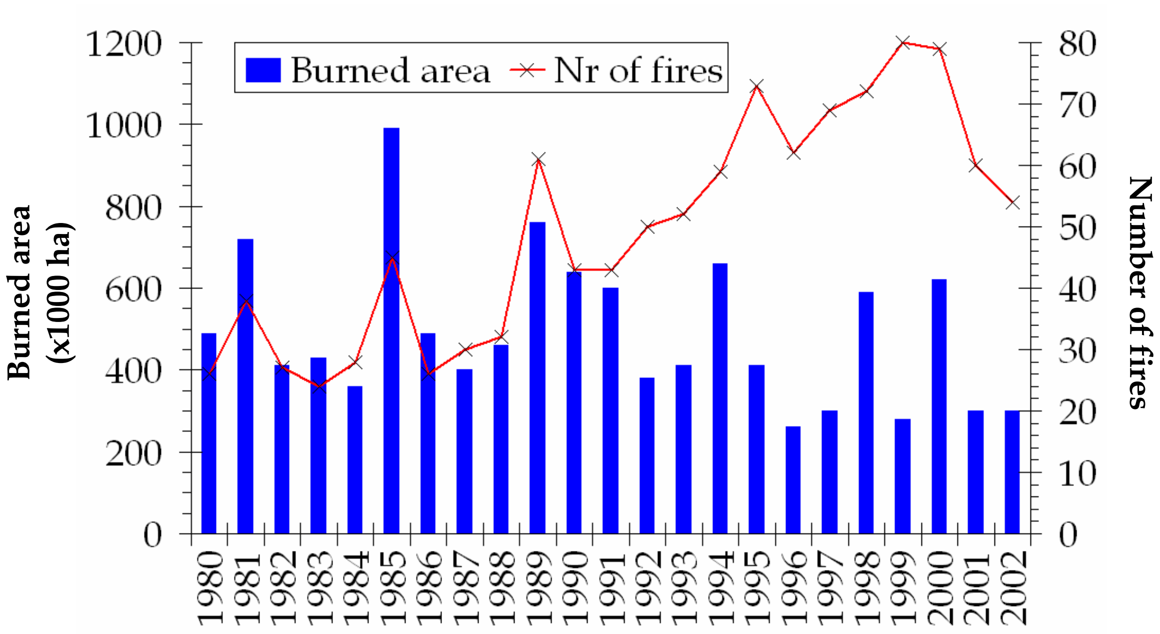
2.3 Forest fires – a paradox

Generally, fires can be grouped into prescribed, or controlled fires, and wildfires.

1. Wildfires

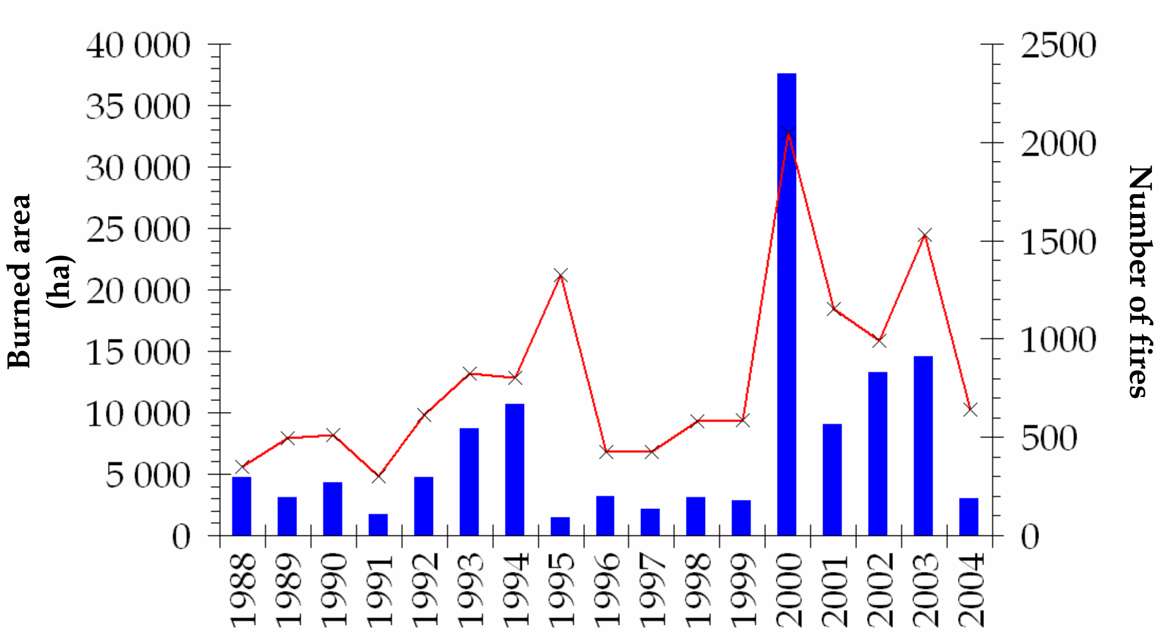
A wildfire (also known as a forest, vegetation, grass, brush, bush or hill fire) is a natural event that burns a variety of vegetation types ranging in age, size and density. The characteristics of wildfires are highly variable, with varying fire temperature, quantities of biomass available, thoroughness of the combustion and impact on the forest stand (IPCC, 2003). Among wildfires, ground-level ones are less intensive and their impact on trees less severe than crown fires. Common causes of such fires include lightning, human carelessness and arson. Drought and failure to prevent small fires are major contributors of extreme forest fires. Some of the important environmental factors for the occurrence of wildfires include weather, fuel property, amount of combustible material, ignition source and topography (Liu, 2004).

Fire statistics of the European Union (EU) Mediterranean Region and the Balkan Region countries show fluctuating behaviour in the number of fires and the burnt area in the last couple of decades (Figures 2-1 and 2-2), the variations being attributed to various conditions under which the reported fires occurred.



[Source: European Commission. Forest fires in Europe – 2002 fire campaign]

Figure 2-1. Annual average burned areas and number of fires from 1980 to 2002 in the five EU Mediterranean Member States (France, Greece, Italy, Portugal and Spain).



[Source :FAO, 2006]

Figure 2-2. Annual average burned areas and number of fires from 1988 to 2004 in the seven countries in the Balkan region (Albania, Bulgaria, Croatia, Republic of Macedonia, Slovenia, Serbia and Montenegro and Turkey)

FAO (2001) reported that the average annual number of forest fires throughout the Mediterranean basin is close to 50 000, twice as many as during the 1970s. However, owing to the varying databases an accurate picture of the overall increase is not easy to obtain. Table 2-2 gives an indication of the increase in forest fires from the beginning of the 1970s for the countries where data have been available, according to the FAO (2001) report.

Table 2-2. Increase in forest fires and area burned in the Mediterranean basin from early 1970s.

Country	**Average annual number of forest fires**		**Average annual accumulated area burned (ha)**	
	During 1970s	**Until 2000**	**During 1970s**	**Until 2000**
Spain	1 900	8 000	50 000	208 000
Italy	3 000	10 5000	43 000	118 000
Greece	700	1 100	12 000	39 000
Morocco	150	200	2 000	3 100
Turkey	600	1 400	No data	No data
Former Yugoslavia[1]	900	800	5 000	13 000

[Source: FAO, 2001]

Furthermore, fire risk analyses and forecast for Europe, undertaken by the European Forest Fire Information System (EFFIS) at the European Commission Joint Research Centre (EC-JRC), predict extending risks outside of the peak fire seasons. Figure 2-3 shows the trend of monthly averages of fire risk level in Europe estimated using the Canadian Fire Weather Index (FWI) for the years 2003 to 2006, from May to September - the peak fire season. The figure shows that while the higher northern latitude forests mostly have low to very low risk, the Mediterranean region has high to very high risk.

[1] Deviates from the general trend

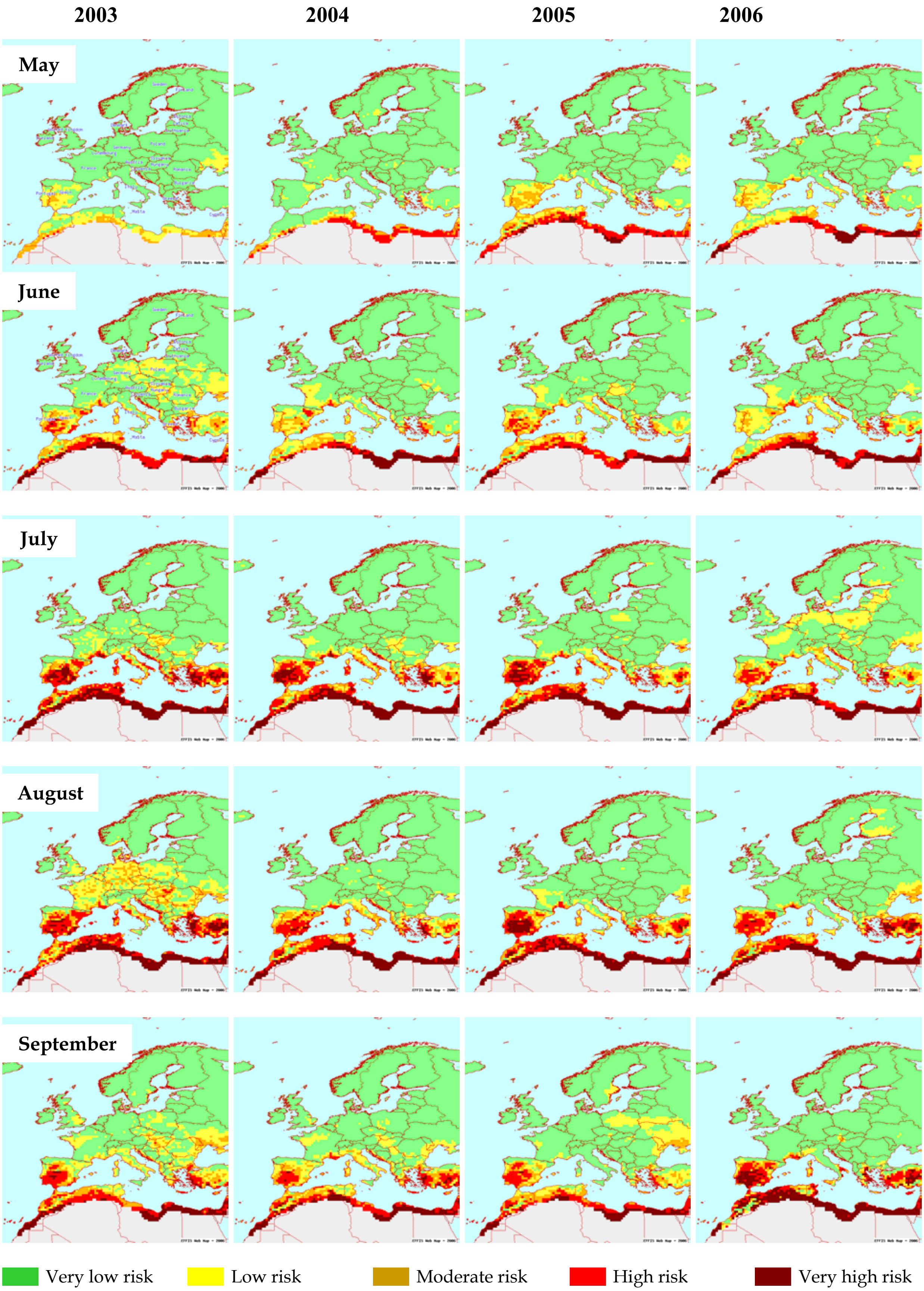


Figure 2-3. Monthly averages of fire risk level estimated with 1-day forecast using the Canadian Fire Weather Index (FWI). (Source: EFFIS, JRC**)**

The monthly averages shown on the maps may flatten out the local peaks, especially for countries in the Mediterranean, such as France or Italy. However, the fire risk trend for the different months can clearly be seen for the different years. While the peak summer months – June, July and August – show a mixture of low to moderate, and high to very high risk, May shows a significant increase, from low, in 2003, to high and very high by 2006. September also shows increasing risk.

The maps show a prolongation of fire risk period, whereby the likelihood of fire occurrence is not necessarily restricted to the summer months, but rather starts early and goes to the end of summer. It is, however, important to keep in mind factors such as local weather conditions (Johnson and Miyanishi, 2001), fuel availability, amounts and types of fuel, and moisture content of the fuel that largely influence the occurrence and intensity of fires.

A burning forest fire is a complex combustion process in which the flaming front is heating and then igniting unburned woody and herbaceous fuels (Johnson, 1992). Fires not only affect the flora and fauna, and emit a complex mixture of particles and gases to the atmosphere but also have effects on the soil, soil pH, hydrology, nutrients and organic matter. Studies have shown that while fires add nutrients to the soil and help in the regeneration of vegetation, too frequent and intense wildfires lead to reduced soil fertility (Perry, 1994), reduction in microbial biomass through direct heating and destruction of microbial cells (Choromanska and DeLuca, 2002; Hart et al., 2005), mortality of a majority of above-ground biomass causing reduced plant uptake of nutrients (Grady and Hart, 2006), and increase in possible leaching losses of nitrogen (Prieto-Fernandez et al., 1993).

Wildland fires (as well as prescribed burning, discussed in (2)) are one of the critical processes in the global and regional carbon cycle. Emissions from such disturbances directly affect the carbon cycle by increasing the atmospheric CO_2, and in a less indirect fashion, by altering carbon sequestration by terrestrial ecosystems. Commonly used methods for estimating wildfire emissions include Geographic Information System (GIS) based models, emissions and/or atmospheric transport models using different levels of spatial and temporal resolution, *in situ* measurements, satellite remote sensing and estimations from other measured parameters, such as area burned, fuel load and fuel consumed (Seiler and Crutzen (1980); Ward and Hardy (1991); French et al. (2003); Lü et al. (2006); Fraser and Li (2002); Fraser et al. (2000); Soja et al. (2004); Andreae and Merlet (2001); Zhang et al. (2003); Liu (2004); Schultz (2002); Hoelzemann et al. (2004)).

Recent increases in wildfire activity and fire risk level in Europe have prompted intensified discussions on preventing or effectively managing destructive wildfires. For example, the Food and

Agriculture Organisation of the United Nations (FAO), with collaborating partners[2] are committed to a multi-stakeholder process to prepare a *Fire Management Code* (FAO, 2006a) – a voluntary and legally non-binding documentation, directed towards land-use policy makers, planners and managers in fire management – aimed at providing more holistic approaches to fire management (IFFN/GFMC, 2006). A second draft of the *Code* was released in July 2006 and awaits feedback from Governments by 31 October 2006 to strengthen the *Code*.

Although global in scope, the elements of policy level and senior managers of sub-regional, regional and global organisations (whether government or non-governmental) could prove beneficial for Europe whereby countries could work together in, for example the implementation of policies for better and more effective management of forest fires, hence work collectively towards effective mitigation of CO_2 emissions.

Open vegetation fires are typically dynamic fires in which a moving fire front passes through a fuel bed, with all combustion types[3] being present at any given time and their combined emissions being released into smoke plume (IFFN, 2004a). To better manage wildland fires becoming uncontrolled devastating fires, fuel management has been deemed important. It is a known fact that while complete exclusion of fires lead to counter effects in the forest ecosystems, such as high fuel accumulation, which in turn leads to high intensity fires, and hence an increase in area burnt, and high cost of suppressing such fires, effectively managing the accumulating dead and live fuels reduces damage from wildfires, as well as reduces the stature of the developing under-story when burning conditions are not severe (Liu, 2004; Piñol et al., 2005; Pollet and Omi, 2002; Agee and Skinner, 2005; Baeza et al., 2002; Grady and Hart, 2006; Perry, 1994; Stocks, 1991; Myers, 2006).

In some parts of Europe, mainly in the Mediterranean countries, not only fuel management technique has been implemented and used, but also the effects of such techniques on, for example trees, forest floor, soil and breeding bird population have been investigated, though not on a very wide scale (Fernandes and Botelho, 2004; Moreira et al., 2003; Úbeda et al., 2005).

The increasing number of wildfires since the 1970s and the extension of the fire season have prompted an increase in interest for the prevention of wildfires by effective fuel management. The most common

[2] Collaborating partners providing inputs on an "in kind" basis, with FAO undertaking the overall coordination, technical inputs, include members of the International Liaison Committee, 4th International Wildland Fire Conference, Seville, Spain, 2007; USDA Forest Service; Global Fire Monitoring Centre (GFMC); UNISDR Global Wildland Fire Network; The Nature Conservancy; and other experts from private sector, International Governmental Organisations (IGOs) and Non-Governmental Organisations (NGOs) (IFFN/GFMC, 2006)
[3] Combustion of individual fuel elements proceeds through a sequence of stages – ignition, pyrolysis, flaming+pyrolysis, glowing+pyrolysis (smouldering), glowing and extinction – each with different chemical processes that result in different emissions. For a brief review see (IFFN Nr. 31, 2004), and for detail description of the processes during the combustion of biomass see (Lobert and Warnatz, 1993; Yokelson et al., 1997).

fuel reduction treatment applied is prescribed burning. Despite being an established practice, it is a technique that is banned in some European countries. The next section highlights the use of prescribed burning, not only as wildfire hazard abatement but also as a potential mitigation of CO_2 emissions from forest fires.

2. Prescribed burning

Prescribed burning is a controlled application of fire to vegetation in either their natural or modified state, under specified environmental conditions, which allow the fire to be confined to a predetermined area and at the same time to produce the intensity of heat and rate of spread required to attain planned resource management objectives (IFFN, 2004a). Prescribed fire is a fuel management technique that temporarily reduces damage from wildfire by removing a portion of the accumulating dead fuels, such as duff[4] and logs on the forest floor, hence facilitates fire suppression efforts by reducing the intensity, size and damage of wildfires (Liu, 2004; Fernandes and Botelho, 2003). Significant types of prescribed fires include: (i) land clearing fires in the course of forest conversion, (ii) slash-and-burn agriculture, (iii) post-logging burning of harvest residues (slash), and (iv) low-intensity prescribed fire for fuel load management (IPCC, 2003). In contrast to wildfires, the average fire intensity of prescribed burning is controlled, the burning conditions are more uniform and the emission factors less variable (IPCC, 2003).

A comprehensive review of the effectiveness of prescribed burning in fire hazard reduction was conducted by Fernandes and Botelho (2003), while Hesseln (2000) reviewed the economic aspects. Although most studies have largely focussed on the effects of fuel treatment as a preventive measure for intense wildfires, extensive studies have also been done on the effects of prescribed burning on other aspects, such as effects of high temperatures, vegetation recover rates, chemical and biological effects, and development of models as tools for forecasting, risk assessment or impact studies (Zeleznik and Dickmann, 2004; Baeza et al*.,* 2002; Thies, et al*.,* 2006; Pollet and Omi, 2002; Hille and Stephens, 2005; Ryu, et al*.,* 2006; Garten Jr., 2006; Valette et al*.,* 1994; Marco et al*.,* 2005; Silva et al*.,* 2006; Sieg and Wright, 1996; Herr et al., 1994; Guerrero et al., 2005; Massmann and Frank, 2004; Úbeda et al., 2005)

While extensive literature is available on specific studies regarding the effects of prescribed burning, literature, as well as data on GHG emissions from such fires is sparse. Emissions from forest fires have been estimated or measured under the broad category of "forest fires", as part of country-based forest inventory reporting. Therefore data that are available, in most if not all cases include emissions

[4] Layer consisting of fermentation and humus horizons of decomposed litter and organic matter (Johnson & Miyanishi, 2001)

from forest fires in general, without being classified as wildland, prescribed burning or suppressed fires. Some studies have also used a wildland fire emission model on global scale, such as GWEM – Global Wildland Fire Emission Model – to estimate fire emissions on the global scale, using land cover maps, emission factors and other satellite input data (Hoelzemann et al., 2004). However, such model-based studies do not distinguish between different types of fires, and in particular, do not include emissions from prescribed burning. This in part is due to lack of data, as well as the complexity of modelling.

Several European projects, such as FIRE TORCH (www.cindy.ensmp.fr/europe/firetorch/index.html; 1998–2000), EUFIRESTAR (eufirestar.org; 2001-2003), EUFIRELAB (eufirelab.org; 2003–2006), and other European-scale research have studied various aspects of prescribed burning, for example operational issues and standardisation of management data collection and storage, risk assessment at wildland-urban interface, and as a management tool for biodiversity and ecosystem functioning. The studies have also shown that this fuel management technique is acceptable and has economical and ecological advantages. However, the reports indicate that foresters are not receptive to see it as a management tool and as a consequence prescribed burning is used either locally or sporadically in Portugal and Spain, for example, but is not allowed in Greece and most of Italy, as well as some eastern European countries like Belarus, where it is banned by law.

The FIRE TORCH project, which finished in 2000, formed an important contribution with regards to prescribed burning as a management tool in the Mediterranean region. The project focus was on analysing the opportunities for prescribed fire development, modelling environmental effects, development of a decision support system for the different stages of a burning operation, as well as contributing to the technical know-how and training of personnel. Among the deliverables of the project, of particular importance, as far as prescribed fire emissions are concerned, are the following reports:

(i) prescribed burning field forms

Based on the experiences of countries like France, Portugal and Spain, this report defines the parameters important for the practice of prescribed burning, organisation of these parameters in a rational way and to design the methods for collecting these elements at the European level. The report describes the European standardised data collection process that was chosen within the FIRE TORCH project (Rigolot and Gaulier, 2000a). Although the focus is on the Mediterranean region, similar standard methodology can be adapted for other regions of Europe;

(ii) modelling tool to assist in prescribed burning management

This report describes the modelling tool developed within the framework of FIRE TORCH, describing the links between environmental conditions, fire behaviour and fire effects that are important for prescribed burning operation, aiming for assisting a manager in planning and evaluating a burn operation in order to attain certain objectives (Fernandes et al., 2000b). As with the other reports, a similar management guide could be prepared for other regions;

(iii) prescribed burning guide

This guide, although prepared for operational use in fuel reduction burns in maritime pine stands (*Pinus pinaster*) in north and central Portugal, and north-west of Spain, can also be tested in other regions where maritime pine, as well as other pine species exists (such as, *P. sylvestris, P. nigra, P. pinea, P. halepensis*). However, the report draws attention to all extrapolations to other fuel types and weather patterns, which should be made with caution (Fernandes et al., 2000a). Despite the specific nature of the guide, sections describing for example, the estimation of fuel loading and moisture, prescriptions for weather, fuel moisture, ignition and fire behaviour – parameters that seek to optimise fuel reduction while maintaining site quality and minimising tree damage – could be adapted for other species characteristic of other regions in Europe.

The above-mentioned reports may provide a good foundation and prove valuable in establishing a standardised approach towards the estimation of CO_2 emissions from prescribed burning in other regions of Europe. Although this fuel reduction technique is either not widely practiced, or is done in moderation or even banned by law, having a standard methodology at national levels could nevertheless be useful in case where the technique is legalised, or becomes a common practice.

Table 2-3 shows a compilation of countries where prescribed burning is practiced, whether as an established management technique or on experimental scale, and whether or not it is legal. The information provided is extracted mainly from the IFFN (2001, 2004) and Forest Management working papers of FAO (2006b, c, d).

As seen from the table, the only European country where prescribed burning is a well-established technique is France, where it has been expanding substantially for almost a decade, and now involves 6 000 to 10 000 ha, depending on weather conditions (FAO, 2001). The costs depend on the conditions under which the operation is carried out, which in all cases is relatively low, ranging $US40–80 per hectare for treeless land in foothill areas to $US160–800 per hectare for clearing land with large trees before burning (FAO, 2001).

Table 2-3. Country-based prescribed burning situation in Europe.

Region	Country	Yes	Experimental/ Limited	No	Comments
Balkan	Albania				No information
	Bulgaria				No information
	Croatia				No information
	Greece			✓	Forbidden by law although have limited and spatially restricted fuel management; most efforts spent on fire suppression
	Republic of Macedonia				No information
	Serbia & Monte Negro	✓			Practiced by law
	Slovenia				No information
	Turkey			✓	Fire management relies on early detection, fast initial attack and powerful suppression; no information on prescribed burning
W. Europe	Austria				No information on prescribed burning in the available statistics; forest fires cause no major damage except in years with exceptional fire weather
	Belgium		✓		No information on prescribed burning
	Denmark		✓		On dune heaths for restoration purpose; generally forest fires are not a problem
	Germany		✓		Only recently a variety of projects on prescribed burning are underway for heathland restoration, biodiversity maintenance, glassland and pasture restoration, and improving black grouse habitat
	Luxemburg		✓		No information on prescribed burning
	Switzerland				No information on prescribed burning but fuel reduction on roadsides in sensitive areas are done as a preventive measure
	The Netherlands		✓		Main interest is on nature reserves and military training areas; main objectives are to conserve particular heathland plant species, black grouse and certain insects; there is no recent fire statistics; no systematic data collection
	United Kingdom	✓			Used more frequently on private land than on publicly owned land; practiced to improve habitat of woodland grouse
E. Europe	Belarus			✓	Banned by law
	Czech Republic				No information on prescribed burning; low forest fires per year, therefore it is estimated that these are not a major problem

Region	Country	Yes	Experimental/ Limited	No	Comments
	Estonia				No information on prescribed burning
	Latvia				No information on prescribed burning
	Lithuania				No information on prescribed burning
	Poland			✓	It is acknowledged that fire can be a potential management tool, but there is a lack of knowledge and expertise
	Slovakia				No information on prescribed burning; average size of fire has generally been low, even in more severe fire seasons. It is therefore estimated that since most fires are human-caused, prevention should concentrate on increasing awareness of fire risk
Scandinavia	Finland	✓			Currently used as a management tool although fire is not regarded as a problem due to low number of fires and effective suppression
	Norway		✓		Mainly used as a tool in restoration activities, to regenerate logged clear cuts
	Sweden			✓	Fire is not considered a serious problem today and area burned annually is rather small; there is no official collection of forest fire statistics; awareness about fires has increased among foresters and public but there is no action taken when it comes to prescribed fire as a tool. This is due to lack of practitioners, anxiety over risk of escape and lack of resources. However, prescribed fire is required for forest products certification.
Mediterranean	Algeria				No information on prescribed burning
	Cyprus				No information on prescribed burning
	France	✓			A well-established technique
	Israel				No information on prescribed burning
	Italy		✓		In some parts it is not allowed, Forest protection in Italy mainly rely on fire suppression
	Morocco				No information on prescribed burning
	Portugal		✓		Not practiced on a wide scale; used only sporadically
	Spain		✓		Used sporadically

[Source: IFFN (2001, 2004a and 2004b); FAO (2006b, c, d)]

In other parts of the Mediterranean region prescribed burning is used marginally (such as in Italy, Portugal and Spain) or not at all (Greece and Near-Eastern Mediterranean countries), and where it is in use, it has been reported that the administrative authorities found it to be less costly than the suppression of wildfires resulting from various causes (FAO, 2001). In most other countries around Europe (Northern, Western and Eastern Europe) prescribed burning is increasingly used mainly for landscape management, restoration, maintaining or improving habitat conditions and nature conservation.

Forest fires in Europe tend to be more common in the Mediterranean region (Portugal, Spain, South of France, Italy, Greece and Cyprus), contributing 94% of the total burned area in Europe, according to an analysis of the 1975-2000 statistics by the European Forest Institute (Xanthopoulos et al., 2006).

Very limited but useful studies have also been conducted whereby comparison of emissions from wildfires and prescribed burning has been made. The results of one such study, conducted in maritime pine stands in Portugal, indicated that it was reasonable to assume that on the long term prescribed burning emissions would be lower than the emissions from wildfires, if the wildfire return interval is roughly below 40 years (Fernandes, Pers. Comm., 2006). Table 2-4 shows the results of their study for CO_2 emissions.

Table 2-4. Relative CO_2 emissions and unit of burned area in maritime pine for six fire scenarios.

Scenario	% Area burned	% Fuel moisture content Surface fine dead fuel	Duff	% CO_2 emissions
Wildfire	90% crown fire	3	10	100
Wildfire	60% crown fire	5	10	87.4
Wildfire	30% crown fire	7	10	74.8
Prescribed fire (drier)		12	75	51.5
Prescribed fire (normal)		20	150	38.5
Prescribed fire (damper)		40	200	23.3

[Fernandes, Pers. Comm., 2006]

In their study, Fernandes and colleagues estimated relative emissions per unit area of maritime pine stands for six scenarios of wildfire and prescribed burning. The moisture content of the consumed fuel distinguished each scenario. The results in Table 2-4 were obtained using the FOFEM – First Order Fire Effects Model - software (Reinhardt, 2003). The release of CO_2 and other compounds from prescribed burning under normal conditions was defined in Fernandes and Botelho (2004) as 62% lower than the emissions from a more severe wildfire.

However, meaningful comparisons between the scenarios are only possible in the context of a fire regime. The wildfire regime in many regions of Portugal currently approaches a 20 year cycle. Assuming a pine stand with three prescribed fires during its life time (respectively at the ages of 15, 20 and 25 years), mean annual emissions over the 25 years period will amount to 58.4% of a wildfire. Only with a wildfire event every 43 years would the prescribed and wildfire emissions be equal (Fernandes, Pers. Comm., 2006). These results indicate that it is reasonable to assume that on the long term the emissions from prescribed burning will be lower than the emissions caused by wildfires if the wildfire return interval is roughly below 40 years (annual probability of fire = 0.025).

3 .Suppression fires

Suppression of forest fires can be defined as either refraining from all burnings near to forest areas as a precaution for the breakout of wildfires (fire exclusion), or it refers to all activities concerned with controlling and extinguishing a fire following its detection.

Short-term negative impacts, such as the perturbation of the hydrological regime, the increase of soil sensitivity to erosion, the loss of timber production, the decrease of wild fauna, the loss of leisure capacities and unwanted changes of the landscape, which may affect people living near burned areas, lead them to push for more effective fire suppression (Hadjibiros, 2001). Recent data on suppression fires is difficult to obtain in terms of human, physical and financial resources. However, in the United States for example, it was estimated that wildfire suppression expenditures on national forest land had increased over 35 years, and in 2000 and 2002 it exceeded US$1 billion (Donovan and Brown, 2005).

In a recent EUFIRELAB project report (Alexandrian et al., 2003) the suppression costs were identified as costs that include field camps, equipment use, loss of tools and supplies, mobilisation and demobilisation, and related logistic costs such as evacuations, emergency operations centres and debris removal. The cost of suppression measures reported is dominantly from studies and forest fire reporting from the US rather than Europe. It nevertheless provides some indication of the expenses associated with fire suppression. An important outcome that the authors draw attention to is the fact that fire size is in relation to the suppression costs, therefore is not completely an exogenous variable but rather costs and size are determined simultaneously.

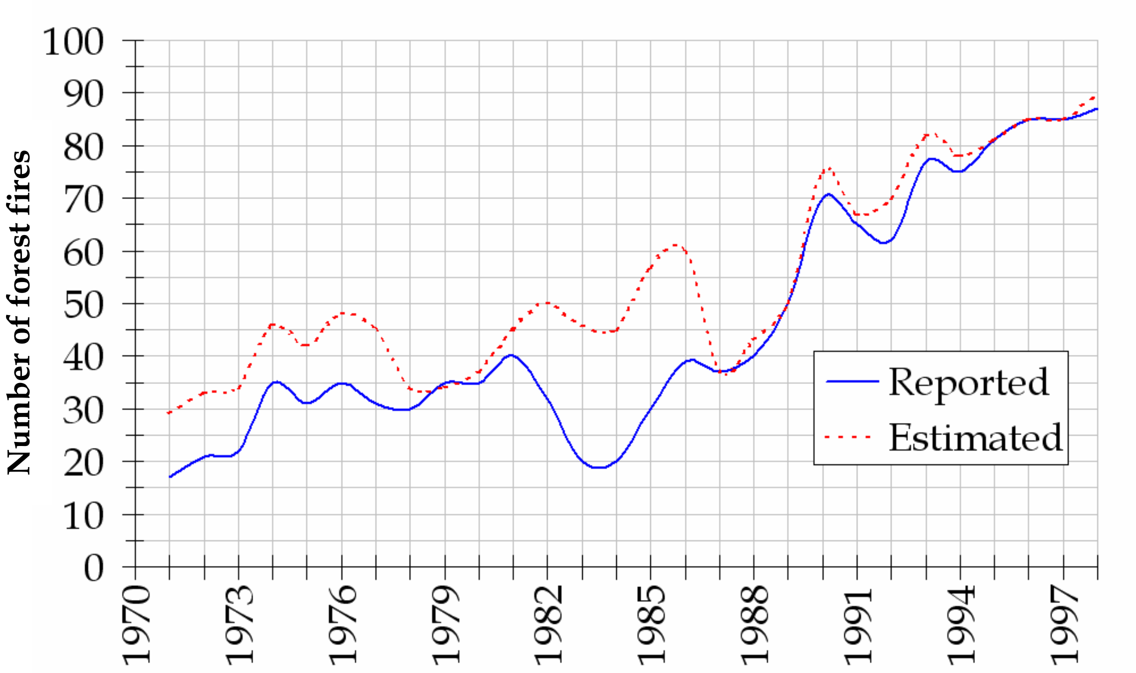
Fire suppression efforts can be effective at protecting lives, personal property and infrastructure but at the same time cause accumulation of fuel. Together with prolonged hot and dry periods severe drying of the fuels occur, and when fires start in these conditions they are more destructive and more expensive to control. By applying fuel management techniques such damages and wildfire severity can be minimised.

Because suppression fires are closely related to wildfire burning, the emissions from the two are difficult to separate. No literature has been found on emissions from suppression fires.

2.4 Forest fires in Europe

Fire disturbances form an integral part of the forest ecosystem, occurring either in natural or managed forests. However, information on the events of disturbances is scattered and incomplete. In the recent past forest fires have received increasing attention, leading most European countries to collect and report comprehensive statistics on forest fires. Figure 2-4 (taken from IFFN, 2002a) shows the trend in the number of forest fires in Europe from 1970 to 1998.

The growing concern about the increasing trend in fire occurrence and the subsequent vegetation, habitat, property and lives destruction has led to international cooperative initiatives in wildland fire science, management and policy development (IFFN, 2002b). A number of international and interdisciplinary fire research programmes have contributed to a better understanding of the impacts of fire on ecosystems, biogeochemical cycles, atmosphere and climate, as well as the development and improvement of the utilisation of space-borne sensors for wildland fire early warning, detection, monitoring and impact assessment, leading to enhanced capabilities to obtain detailed and comprehensive information on the extent of wildland fires occurrence and consequences (IFFN, 2002b).



[Source: IFFN, 2002a]

Figure 2-4. Total reported and estimated annual number of forest fires for 31 European countries[5] from 1970–1998.

The focus until now has been more towards fire reduction and management rather than on emissions. The overall interest in specific emissions of forest fires, in particular prescribed fires in Europe, was never very great. In the history of European fire research an earlier proposal for a pan-Mediterranean programme, discussed at the end of the 1990s (Fire Information Systems Research in the Socio-Culture, History and Ecology of the Mediterranean Environment – FIRESCHEME), was not realised due to this, and even here the emissions component was not of significant importance (Kraus, Pers. Comm., 2006).

Likewise, recent European fire projects mentioned earlier (FIRE TORCH, EUFIRELAB, FIRESTAR) did not investigate emissions from forest fires. The underlying reasons for a lack of interest in the atmospheric science community is due to the fact that the emission characteristics of European fires will not have significant differences from sites elsewhere where such experiments have been conducted (Kraus, Pers. Comm., 2006). However, the weather conditions, vegetation types, topography and fuel moisture would be different in the different regions of Europe, with the implications that the combustion types could be different and hence the emissions. In the highly

[5] The countries included are: Albania, Austria, Belgium, Bosnia Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, Macedonia, The Netherlands, Norway, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey, United Kingdom, Yugoslavia. For further information on the methods of data collection, see IFFN No. 27 (July 2002)

summarised Table 2-3 we can see the different objectives for which prescribed burning is used. In some cases, it is applied only occasionally, while in others there is a need for its recurrence. Depending on the specific aims of prescribed burning one would expect that the emissions would be different.

Furthermore, the limited small-scale studies on the comparison of emissions from wildfires and prescribed fires (for example, in Portugal – shown in the next section) show that the emissions from the latter are lower than the former (see Table 2-4). Unfortunately, there are not many such studies that have been reported for Europe. This somewhat hinders sound quantitative comparison of the emissions, not only between wildland and prescribed fires but also between the different regions in Europe. More so, due to the uncertainty in costs, expert training, other effects on the ecosystem and potential pitfalls (see for example, Myers, 2006), prescribed burning as a management tool has not been an easily embraced fire reduction management in all parts of Europe. But this could be changing, as the need for collective action and integrated initiatives becomes more apparent.

2.5 Prescribed burning – a solution?

In the past two decades the Mediterranean countries have registered a marked improvement in fire suppression resources that have limited the damages but at such high cost that the economical possibilities to increase those resources are nearly exhausted (FAO, 2005b). This indicates that the forest fire organisations need to find more effective approaches to fire management by improving strategies and technologies for fire prevention and mitigation.

The studies at the European scale cited so far indicate a pressing need for proper fuel management actions particularly in the Southern European forests. The focus of such studies has mainly been on various aspects of forest fires ranging from the investigations of the effects of prescribed burning on the ecosystem (for example on the roots, and soil), to alternative fuel management options, such as silviculture, mechanical treatment with or without physical removal of the residues, and chemical treatment (FAO, 2005b; Fernandes et al., 1999 and 2004). Prescribed burning is deemed an economical technique but one that requires specific training due to its nature, and when combined with controlled grazing it can be highly recommended[6] (FAO, 2005b).

Alexandrian and colleagues from the EUFIRELAB project (2003) reported on the economic effectiveness of fuel treatments (prescribed fires, thinning, pre-commercial harvesting and chemical

[6] Further information can be found in (Martínez *et al.*, 2001; Molina, 2000; Rodríguez Silva *et al.*, 2001; Vega *et al.*, 2001)

and mechanical treatments) as fire prevention measures. While the techniques are not guaranteed[7] to be cost effective, it is expected that over a long time they will eventually lead to not only lower costs of suppression and post-fire restoration but also reduction in smoke and wildfire-related property damage. The former (reduced smoke) coincides with the findings of the exercise by Fernandes and colleagues (Pers. Comm., 2006) on comparison of prescribed fire and wildfire emissions using different scenarios (see Table 2-4). Prescribed burning is not a new concept in Europe. It has been used over time in world-wide forestry for reducing fuel hazards, pre-commercial thinning, improving ecosystem diversity and wildlife habitat, restoration of entire ecosystems and preparation of seedbeds and sites for forest regeneration (Mutch, 1994; Deeming, 1990; Wagle and Eakle, 1979; Graham et al., 1990; Wade, 1993; van Leer, 2000; Burger et al., 1998; Covington et al., 1997; Elliot et al., 1999; Uggla, 1959; Braathe, 1974; Sykes and Horrill, 1981; Brose et al., 2001)[8].

A recent report from an on-going Sixth Framework Programme project MEACAP – Impact of Environmental Agreements on the Common Agricultural Policy (www.ieep.org.uk/projectMiniSites/meacap/), surveyed technical and management-based mitigation measures in forestry to reach the goals of emission reduction within the Kyoto Protocol through active forest management. The report (Schelhaas et al., 2006) is a compilation of an extensive list of measures detailing the ways in which forestry could contribute to either an enhanced sink or reduced emissions. Among other measures, the list includes prescribed burning as a means of reducing fuel loads and hence fire risk.

Fuel load in the forest is one of the determining factors for forest fire risk – the higher the amount of fuel at a site the greater is the risk for uncontrollable fires. As described earlier (Section 2 on Prescribed burning), prescribed burning is one way of reducing the amount of fuel on the ground by low-intensity controlled application of fires to ground vegetation and litter without killing canopy trees. The technique does not lead to complete exclusion of fires but reduces the intensity of possible fire breakouts that are likely to turn into wild uncontrolled fires, thereby enhancing fire-fighting possibilities. The main potential for prescribed burning is GHG mitigation through reduced fire risk.

Although technically demanding, in terms of financial costs and training, prescribed burning has been used in many places in Europe in the past but is currently not widely applied, or is banned from its use. It is a commonly used technique in most fire-prone areas in the US. However, in Europe the benefits of prescribed burning are increasingly being recognised, and there are places where it is used in moderation, or for very specific objectives, other than fuel load reduction (see Table 2-4). For the wider European region other than the Mediterranean, where its use is more pronounced, very few

[7] Cited from (Donovan and Rideout, 2003; Rideout and Ziesler, 2004)
[8] Cited in Hille, M. (2006)

common practical guidelines for prescribed burning exists (with the exception of for example, Scotland (see www.scotland.gov.uk/library3/environment/mbcd.pdf). Important documentation and databases also exist from previous projects, such as FIRE TORCH, that include guidelines specific for maritime pine stands, for example. Additionally, FAO recently drafted a Fire Management Code that sets out the framework of guiding principles and internationally accepted strategic actions to address the vital cultural, social, environmental and economic dimensions for all levels of fire management (FAO, 2006a).

Furthermore, in Module 12 of the current project a comprehensive guideline for the different aspects of fire addressing key techniques and strategies within the Integrated Wildland Fire Management is expected to be produced, together with the anticipated establishment of the "Fire Paradox" information management platform (see Fire Paradox, 2006).

With clear benefits of the technique there are also notable concerns, of which the two most important are (1) the possibilities of fire spreading to adjacent properties and, (2) smoke intrusions in populated areas. However, these concerns can be reduced by good management, such as limiting the application to certain weather and fuel situations (edis.ifas.ufl.edu/FR061). With ample support, research, training and the success of existing prescribed fire practices in Europe prescribed burning could prove a viable management tool for GHG emissions reduction.

2.6 Modelling of fire emissions

Emissions from wildland fires have gained the attention of the atmospheric chemistry modelling community since the 1980s. One of the first attempts to quantify wildfire emissions was by Seiler and Crutzen (1980) followed by others[9], such as Hao et al. (1990), Hao and Liu (1994), Cooke and Wilson (1996), Lobert et al. (1999), Galanter et al. (2000) and Lavoué et al. (2000). However, these estimates have been done on global scale using global fire emissions model, such as GWEM that uses data on satellite-observed burnt area, model-derived available fuel load, emission factors, burning efficiency and land cover classification schemes as inputs, to compute emissions from wildland fires (Hoelzemann et al., 2004; Hoelzemann, 2006).

In projects such as FIRE TORCH, modelling work involved the establishment of links between burning conditions of prescribe burning, fire behaviour and first order fire effects[10] (Fernandes et al., 2000b), while in EUFIRELAB project the behaviour of wildland fires was modelled (Morvan et al., 2001). In another report of EUFIRELAB fire emissions measurement was reported as part of data

[9] Cited in Hoelzemann (2006)

[10] Those that occur immediately after, and result directly from the fire

collecting procedures for modelling of fire behaviour (Miranda et al., 2003). However, the experiments conducted were primarily designed to study the effect of chemical retardants on fire progression and fire emissions in the scope of another European project.

In the current project modelling constitutes a significant part (Modules 2, 3, 5, 9) towards the development of the Integrated Wildland Fire Management concept (see Fire Paradox, 2006), whereby simulation exercises for training purpose will be performed, as well as integration and further development of past works initiated by other EU projects. Additionally, validation of models will be undertaken in accordance with fire experiments conducted in various natural conditions and by intensive use of observations during the monitoring of wildfires.

2.7 Fire emissions and the IPCC

The IPCC guidelines attempt to standardise national GHG inventories in order to serve the Kyoto Protocol in measuring and reporting of GHGs. The *Good Practice Guidance* of the IPCC covers managed forests, whereby forest management is defined as "the process of planning and implementing practices for stewardship and use of the forest aimed at fulfilling relevant ecological, economic and social functions of the forest" (IPCC, 2003). In the *Good Practice Guidance* two general types of biomass burning are considered: burning within managed forests and burning in the course of land use conversion. However, the basic approach for estimating GHG emissions are the same as in the *IPCC Guidelines* (Section 5.3 of IPCC, 2003), whereby a simple methodology is used to compute carbon release from burnt biomass as part of forest/grassland conversion. Shown in the following equation is the extended methodology, for all vegetation types, to estimate GHGs (CO_2 and non-CO_2) directly released from fires (IPCC, 2003):

$$E_{fire} = (ABCD) \times 10^{-6}$$

Where

E_{fire} = quantity of GHG released due to fire, tonnes of GHG

A = area burnt, in ha

B = mass of 'available' fuel, kg dm/ha (kg dry matter per ha)

C = combustion efficiency (or fraction of biomass combusted)

D = emission factor, g/kg dm

The combustion efficiency is a dimensionless parameter (see Table 3A.1.12 of IPCC, 2003). The rate and magnitude of emissions from prescribed burns and wildfires are related to biomass consumption, which is controlled by total biomass, fuel moisture, fuel distribution (fuel size and arrangement) and ignition patterns (Ferguson et al., 1998). Knowledge of the geographical and temporal distribution of burning is critical for assessing the emissions of gases and particulate matters to the atmosphere. The area burned and the severity, such as depth of burn and consumption of under-story vegetation and dead fuel, are important factors to consider in estimating carbon emissions from forest fires (Conard et al., 2002).

In previous reports and studies emissions from fires have not been given importance. They have been acknowledged though among other more obvious and immediate consequences and research, such as fire management, effects of fires, damage assessment, risk analysis and suppression techniques. Emissions have been investigated in the context of atmospheric pollution or health hazard, in some experimental cases, as well as limited *in-situ* measurements, but not in the context of mitigation for GHGs. At least no data or publication has been found on this.

The IPCC *Good Practice Guidance for LULUCF* (IPCC, 2003) broadens the scope of the coverage of emissions from burning for land management, particularly in the case of managed forest land, to include the effect of both prescribed and wildfires on CO_2 and non-CO_2 emissions. Burning for land management in crop- and grasslands is covered by the Agriculture sector of the *Good Practice Guide 2000* (*GPG-2000*), where guidance is provided to estimate emissions from prescribed burning of savannas and field burning of agricultural residues covered under the Agricultural sector. The *Good Practice Guidance* states that “when managed land is burned emissions resulting from both prescribed and wildfires should be reported so that carbon losses on managed lands are taken into consideration” (Chapter 3 of IPCC, 2003). Whether these guidelines are used at national levels for reporting GHG emissions from forest fires have not been explored in this report.

2.8 Emissions mitigation – Kyoto calls!

The Kyoto Protocol, negotiated in December 1997 and came into force in February 2005, is the first international treaty of the United Nations Framework Convention on Climate Change (UNFCCC) to limit GHG emissions. The Annex I countries (major industrialised nations) agreed to reduce their overall emissions by at least 5% below 1990 levels during the commitment period 2008 to 2012. However, emissions reductions vary between countries, with the greatest reduction of 8% within the EU countries, 7% in the USA and 6% in Japan, while the obligation to Russia is 0%. Some countries are allowed to increase their emissions, like Norway by 1%, Australia by 8% and Iceland by 10%, while EU countries can divide their reduction between the member countries. Shares between the Nordic countries have been agreed as follows: Denmark -21%, Finland 0% and Sweden +4%

(Karjalainen et al., 1999), where the positive and negative signs refer to the increment or reduction in emissions, respectively.

As of October 2006 a total of 166 countries and other governmental entities globally have ratified the agreement. This means that the countries commit to reducing their emissions of CO_2 and five other GHGs (methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride), or engage in emissions trading if they maintain or increase emissions of these gases.

Historically, humans have contributed to CO_2 emissions by burning fossil fuels and by converting forest lands to other uses. The Kyoto Protocol recognises the efficacy of forests and sustainable management as a vehicle for addressing climate change. For example, Article 2 states that each party in Annex I shall establish or expand policies and measures that promote sustainable forest management practices, while Article 3.3 provides credits for afforestation and reforestation, and associates debits for deforestation (Sedjo and Amano, 2006). However, of particular interest to this report is Article 3.4 that provides credits for increases in the carbon sequestered by forest management, under which prescribed burning falls. Possible measures under Articles 3.3 and 3.4 that can be undertaken in the forestry sector to contribute to the Kyoto Protocol are discussed in one of the latest reports from the MEACAP project (see Schelhaas et al., 2006). Another report from the same project provides a discussion on the potential impact that Kyoto Protocol might have on forestry in European countries (Cienciala et al., 2006), describing the potential and current position of forest management in the EU countries. However, the report does not mention any specific management task, making it difficult and unclear to deduce whether or not accounting for emissions from prescribed burning is included.

Under the Kyoto Protocol the EU countries were given credit for 15% of the net growth for their managed forests, with no credits associated with unmanaged forests (Sedjo and Amano, 2006). This approach, according to Sedjo and Amano (2006), assumes that active management is responsible for 15% of the incremental addition in the forest growth. This gives some indication of the contribution of carbon sequestration by European forests. Again, not much is reflected from this assumption regarding CO_2 emissions from managed and unmanaged forest fires.

2.9 Knowledge gaps identification

Forest ecosystems are dynamic, constantly being affected by the weather conditions (temperature, precipitation), forest structure (tree species, composition, age structure, and density), forest management and natural disturbances (insect outbreaks and fires). With increase in forest fires in

Europe in recent years, accounting for carbon emissions has become increasingly important, firstly to assess the contribution of the GHG to the atmosphere according to the Kyoto Protocol, and secondly to try and curb such emissions by adopting appropriate measures. In light of the frequency of forest fires, which is predicted to increase, larger high-intensity wildfires would result that may produce higher CO_2 to the atmosphere and act as a feedback loop in global warming (Goldammer, 1998). Their increasingly devastating consequences and GHG emissions mitigation in the context of the Kyoto Protocol, makes it crucial to account for emissions from forest fires.

While Europe, particularly the regions that are prone to forest fires, has the potential for prescribed burning in mitigating CO_2 emissions, very limited data or no data is available on European scale to fully explore this possibility. This can be attributed to a number of reasons, such as the lack of interest in emissions measurements from prescribed burning, as well as limited research on emissions in limited number of areas, which may not necessarily be representative of all European regions. Additionally, irregular occurrence and the specific reasons for which they are conducted make it unviable to keep a record.

Despite the knowledge on the number of forest fires, areas affected and the associated losses, it is unclear how much of CO_2 emission is contributing to the atmosphere at national level in Europe from managed and unmanaged forest fires. While estimates of wildfires on global scale have been made, data from prescribed burning is lacking.

In an attempt to partially bridge this gap and to demonstrate the importance of prescribed burning in mitigating CO_2 emissions from forest fires, the current report tries to estimate and compare emissions from wildfires and prescribed burning using a simple model and data gathered from inventory reports and other published literature sources. This analysis will be presented in the following chapters.

2.10 Concluding remarks

The literature review shows a dire need for research on GHG emissions comparison from prescribed burning and wildfires. Numerous literatures have been found on the effects of prescribed burning but not on emissions from such management practice. Although studies have shown advantages resulting from good fire management techniques, whether or not emissions are reduced remain to be explored more comprehensively. The only example from Portugal has shown that there is reduction in fire emissions with better fire management. However, this single study cannot be taken as being representative of other European regions.

3. METHODOLOGY AND DATA NEEDS

3.1 Introduction

Biomass burning is one of the most immediate direct carbon-releasing agents, which converts living or dead biomass into carbon-containing trace gases, such as CO_2, carbon monoxide (CO), methane (CH_4) and non-methane hydrocarbons (NMHC) (Lü et al., 2006). Fire-induced emissions have significantly contributed to the variations of the atmospheric concentrations of carbon-containing trace gases (Wotawa and Trainer, 2000; Schimel and Baker, 2002; Langenfelds, et al., 2002; van der Werf et al., 2004)[11] and many efforts have been made to estimate the magnitude of such emissions at regional, national and continental scales (Wong, 1978; Crutzen et al., 1979; Cahoon et al., 1994; Conard and Ivanova, 1997; French et al., 2000; Andreae and Merlet, 2001; Korontzi et al., 2003; Liu, 2004)[11].

To quantify emissions from vegetation fires four types of parameters are commonly used: the amount of fuel that is available for burning and the percentage of fuel that is actually burned over a specific time period (i.e. carbon density and fraction of carbon consumed), area burned and emission factors (cf. Section 2.7). The amount of fuel that is burned in a given region and the fraction of fuel burned depend on vegetation density, fuel composition and dryness, and meteorological parameters such as wind speed, humidity and temperature (Schultz, 2002).

3.2 Methodology

Figure 3-1 summarises the steps required to evaluate emissions from a fire.

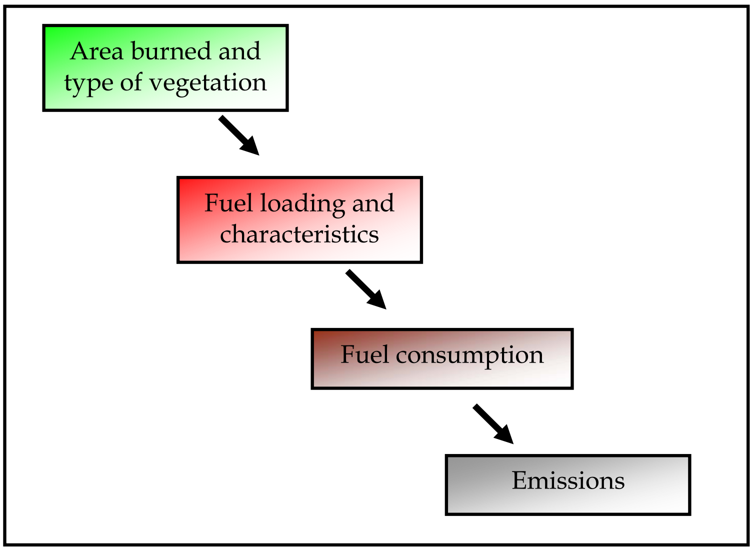


Figure 3-1. Steps required for evaluating fire emissions (Source: Battye and Battye, 2002)

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[11] Cited in Lü et al. (2006)

The estimation of emissions from fires is usually based on the commonly used Seiler and Crutzen model (1980):

$$C = ABf_c\beta \qquad (1)$$

Where

C is carbon emitted

A is the total area burned (ha)

B is the biomass (t ha^{-1})

f_c is the carbon fraction of the biomass

β is the fraction of biomass consumed during biomass burning

The burning of forest floor fuels such as litter, lichen and organic soils are not taken into account in equation (1). As a result the estimated carbon emissions from this equation is deemed lower than the real values, as these floor fuels are believed to be different from those of the above-ground vegetation that contribute to the carbon emissions of forest fires (Lü et al., 2006). In their study Lü and colleagues modified equation (1) as follows:

$$C = A(C_a\beta_a + C_g\beta_g) \qquad (2)$$

Where

C_a is the average carbon of above-ground vegetation (t ha^{-1})

β_a is the fraction of aboveground vegetation consumed during fires

C_g is the average carbon of forest floor fuels (t ha^{-1})

β_g is the fraction of forest floor fuels consumed during fires

Thus the amount of specific trace gas emissions (in this case, carbon emission, E_c) during fires was calculated using:

$$E_c = CE_{fc} \qquad (3)$$

where E_{fc} is the emission factor, in weight of gas released per weight of carbon burned for the gas type. Lü et al. (2006) in their study assumed that parameters β_a, β_g and Ef_c are closely related to the forest types.

For reasonable quantitative analysis of CO_2 emissions from the different types of forest fires (here, wildfires and prescribed burning), it is important not only to compute but also to compare the emissions resulting from these fires. However, due to lack of sufficient information and available data on prescribed burning, the current report presents estimates of forest fire emissions based on existing databases and published literature, and uses the results of Fernandes and colleagues (Pers. Comm., 2006) to illustrate the potential of prescribed burning in mitigating fire emissions in the European region. Equation (1) was thus modified as follows for the computation of emissions from prescribed burning:

$$C = ABf_c\beta \times 0.38 \qquad (4)$$

assuming a 62% reduction in emissions compared to a more severe wildfire (cf. Table 2-4). However, this reduction factor applies to a single fire event only, while over a longer period the reduction in emissions that can be obtained depends on the fire regime (see Chapter 2) and is likely to be lower. In order to compute the long-term reduction in emissions, an estimate has to be made of the frequency at which prescribed burning needs to be applied, as well as the reduction in the number of wildfires that is obtained. Based on Finney (2001, 2003), it can be assumed that a typical prescribed fire regime in which it is applied annually to 5% of the total forest and shrubland area, or alternatively 5-10% annual area of prescribed fire in relation to the area currently burned by wildfires, leads to a landscape where 20% of it is at any given moment adequately fuel managed on strategic locations. This will correspond to a rough decrease in area burned by wildfires of 50%. The total emissions under prescribed burning are then the sum of the emissions from prescribed fires and the emissions from the remaining wildfires.

3.3 Assumptions

In the current report Seiler and Crutzen's model is employed to estimate emissions from wildfires. Information from Table 2-4 was used to estimate emissions from prescribed burning, with the following assumptions:

- The carbon fraction is taken as 45% of the biomass
- An emission factor of 1569 gCO_2/kg dry matter is used, from Andreae and Merlet (2001). The factor was converted to tonnes of CO_2 per tonne of dry matter using the conversion 1 tonne = 1000 kg
- Biomass applies to burned area
- Burning efficiency is taken as 50%, after Seiler and Crutzen (1980)
- As many vegetation types may in fact not represent a wildfire problem, it is assumed that prescribed burning is applied annually to 10% of the area currently burned by wildfires

- Under normal moisture conditions of fuels (20%), emissions from prescribed burning are 62% lower than wildfire emissions (Fernandes et al., Pers. Comm. 2006). Thus the amount of emissions produced by the prescribed burning activity assumed above is computed using equation (4)
- Based on Finney (2001, 2003), such prescribed fire regime is assumed to lead to a decrease in the area burned by wildfires of 50%

The current estimates are therefore not only based on the amount and the moisture content of the fuel but also on the area burned under a typical prescribed fire regime. Note that the result that was obtained in this way is only a very rough estimate, based on a single case study in Portugal with conditions that may not apply to other fuel types in Europe. But in the absence of any relevant information this could give at least some indication of the order of magnitude that could potentially be reached by applying prescribed burning as a mitigation measure.

3.4 Data needs

The data used in the present report were in part obtained from the national inventories or derived from reports and published literature. The main sources have been published data in the International Forest Fire News (IFFN), EFFIS and Terrestrial Ecosystem Monitoring (TEM) database and published FAO reports.

The parameters generally used in emissions estimations are: above-ground biomass, forest floor biomass, forest area, burned forest area and the emission factor for CO_2, which is defined as the amount of a compound released per amount of dry fuel consumed. For emissions inventories emission factors are either computed, as explained in Andreae and Marlet (2001), or default IPCC values (www.ipcc-nggip.iges.or.jp/EFDB/) are used. In this study, the emission factor for CO_2 derived by Andreae and Merlet (2001) was used.

4. RESULTS

4.1 Introduction

To illustrate the current state of prescribed burning in different European regions, Figure 4-1 shows a summarised graphical representation of the data presented in Table 2-3 (Chapter 2).

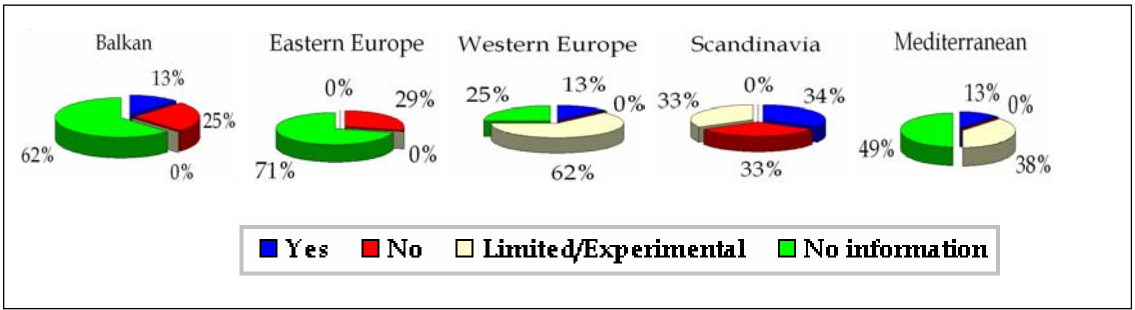

Figure 4-1. Summary of prescribed burning situation in Europe.

The figure shows that there is clearly no information on prescribed burning in most of the European region, with the Balkan, Eastern Europe and the Mediterranean having the highest percentage. This can be attributed to the fact that countries in the Balkan and Eastern Europe are not highly prone to severe forest fires and that the fire-fighting and suppression techniques, in their view, are sufficient to prevent wildfires getting out of control.

While Western Europe shows the highest percentage of experimental or limited prescribed burning occurrence, data on emissions have not been recorded, as the experiments were carried out for investigating other influences or effects of prescribed burning other than measuring emitted gases. Another possible reason for not recording emissions could be their irregular occurrences, for example in enhancing habitats for certain bird and other animal species.

Although more than 50% of the countries in the different European regions engage in using prescribed fires, none have kept records of emissions from their experiments.

4.2 Emissions estimations

Using equations (1), (3) and (4) and the assumptions outlined in Section 3.3 of the preceding chapter, forest fire emissions were computed on a country-basis where sufficient relevant data were available. The estimates are based on five-year averages of fire occurrences. In most cases the averages were taken over 1999-2003. Where data were not available from a common period, they were taken over 1997–2001.

Table 4-1 presents the resulting wildfire emissions as compared with the emissions from prescribed burning with assumed emission reductions applied under normal moisture conditions of the surface dead fuel and duff. The computations are based on the case study from Portugal. Table 4-1 shows only the data needed for emissions computation. A detailed table is presented in Appendix A.

Table 4-1. Wildfire emissions estimates in comparison with emissions from prescribed burning.[12]

Region	Country	Average burned area over 5 years (ha)	Biomass[13] (t/ha)	Wildfire without prescribed burning (million tonnes CO_2)	CO_2 released from: (million tonnes CO_2)		Reduction in CO_2 emissions when prescribed burning is applied (million tonnes CO_2)
					Prescribe fire	Wildfire with prescribed burning	
Balkan	Albania	2 569	58	0.053	0.002	0.026	0.025
	Bulgaria	19 487	76	0.523	0.019	0.261	0.243
	Croatia	29 697	107	1.122	0.043	0.561	0.518
	Greece	36 215	25	0.319	0.012	0.159	0.148
	Republic of Macedonia	10 236	24	0.087	0.003	0.043	0.041
	Slovenia	659	178	0.041	0.002	0.021	0.018
	Turkey	10 921	74	0.285	0.011	0.143	0.131
Western Europe	Austria	34	250	0.003	0.000	0.002	0.001
	Belgium	61	101	0.002	0.000	0.001	0.001
	Denmark	2	58	0.000	0.000	0.000	0.000
	Germany	511	134	0.024	0.001	0.012	0.011
	Luxemburg	2	101	0.000	0.000	0.000	0.000
	Switzerland	476	165	0.023	0.001	0.014	0.008
	The Netherlands	209	107	0.008	0.000	0.004	0.004
	United Kingdom	218	76	0.006	0.000	0.003	0.03
Eastern Europe	Belarus	2 523	80	0.071	0.003	0.036	0.032
	Czech Republic	442	125	0.019	0.001	0.009	0.009

12 Data presented in this table are derived from a number of literatures. These include: Andreae and Merlet (2001); Fernandes and Botelho (2004); Fernandes (Pers. Comm., 2006); Seiler and Crutzen (1980); Ward and Hardy (1991); FAO (2006b, c, d); EC-JRC (2005); FAO (2000); UNEC (2002)

13 Represents above-ground biomass, extracted from FRA2000 (FAO, 2000)

Region	Country	Average burned area over 5 years (ha)	Biomass[13] (t/ha)	Wildfire without prescribed burning (million tonnes CO_2)	CO_2 released from: (million tonnes CO_2)		Reduction in CO_2 emissions when prescribed burning is applied (million tonnes CO_2)
					Prescribe fire	Wildfire with prescribed burning	
	Estonia	4 137	85	0.124	0.005	0.062	0.057
	Latvia	6	93	0.000	0.000	0.000	0.000
	Lithuania	238	99	0.008	0.000	0.004	0.004
	Poland	49 534	94	1.644	0.062	0.822	0.760
	Slovakia	785	142	0.039	0.002	0.019	0.018
Scandinavia	Finland	615	50	0.011	0.000	0.005	0.005
	Norway	940	49	0.016	0.001	0.008	0.008
	Sweden	2 263	63	0.050	0.002	0.025	0.023
Mediterranean	Algeria	29 497	75	0.781	0.029	0.390	0.361
	Cyprus	3 483	21	0.026	0.001	0.013	0.012
	France	30 631	92	0.995	0.038	0.497	0.460
	Israel	3 469	3	0.004	0.000	0.002	0.002
	Italy	76 891	74	2.009	0.076	1.004	0.929
	Morocco	3 118	41	0.045	0.002	0.023	0.021
	Portugal	173 802	33	2.025	0.077	1.012	0.936
	Spain	118 715	24	1.006	0.038	0.503	0.465
Total for all countries				**11.369**	**0.431**	**5.684**	**5.254**

Overall, Table 4-1 gives an indication of the magnitude of the maximal emissions reduction when prescribed burning is applied under normal moisture conditions of the surface fuel. On average, roughly five million tonnes of emissions could potentially be reduced. This is a very crude estimate for the entire European region, which in reality have very different local environmental conditions and fuel characteristics. Additionally, the table shows that in Western Europe and a few Eastern European nations, where fire is hardly a problem, emissions are comparatively low, both for wildfires, as well as for prescribed burning. A summary of the trend is shown in Figure 4-2, whereby the Mediterranean countries dominate the release of emissions, with Poland being the only exception.

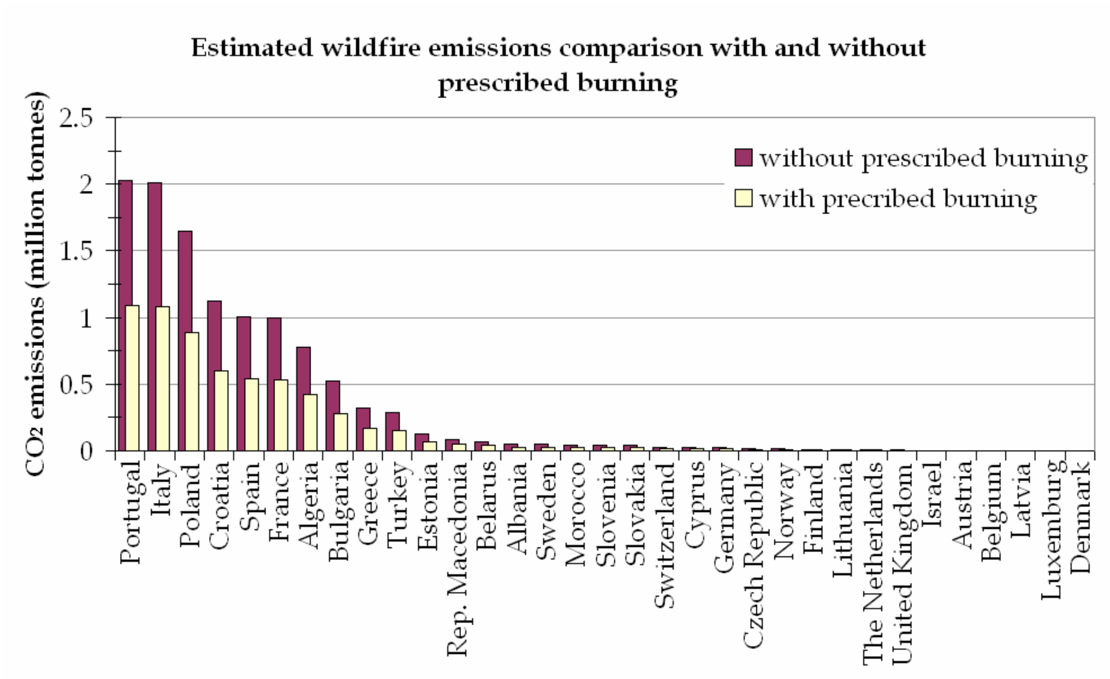

Figure 4-2. Estimated wildfire emissions as compared with estimated total emissions under prescribed burning assumed under normal conditions of 20% fuel moisture content.

The results, to some extent, also suggest that while prescribed burning leads to a reduction in CO_2 emissions, it may not be worthwhile to implement it as a mitigation technique for every European nation. Rather, it would be more practical for those nations where fire occurrences are high and are problematic in terms of damage to livelihoods and economics. In these countries, not only devastating fires can be prevented but also mitigation of CO_2 emissions under the Kyoto Protocol can be achieved. Table 4-2 presents the percentage of reduction in emissions required under the Kyoto Protocol that can potentially be achieved by applying prescribed burning.

Table 4-2. Potential CO_2 emissions reduction obtained by applying prescribed burning,[14]

Region	Country	Estimated emissions reduction[15] (million tonnes CO_2)	Kyoto targets for European countries[16] (% above or below 1990 levels)	1990 CO_2 emissions[17] (million tonnes CO_2)	Amount of emissions reduction required by Kyoto (million tonnes CO_2)	% reduction achieved with prescribed burning application under normal fuel conditions
Balkan	Albania	0.025	-	-	-	-
	Bulgaria	0.243	8	72.996	5.839	4.136
	Croatia	0.518	5	8.598	0.429	120.551
	Greece	0.148	25	81.065	20.266	0.726
	Republic of Macedonia	0.041	-	-	-	-
	Slovenia	0.018	8	-	-	-
	Turkey	0.131	8	-	-	-
Western Europe	Austria	0.001	13	49.953	6.494	0.021
	Belgium	0.001	7.5	117.650	8.824	0.011
	Denmark	0.000	21	54.597	11.465	0.000
	Germany	0.011	21	1001.616	210.339	0.005
	Luxemburg	0.000	28	-	-	-
	Switzerland	0.008	8	42.729	3.418	0.375
	The Netherlands	0.004	6	161.781	9.707	0.038
	United Kingdom	0.003	12.5	593.235	74.154	0.004
Eastern Europe	Belarus	0.032	8	90.629	7.250	0.454
	Czech Republic	0.009	8	163.281	13.063	0.069
	Estonia	0.057	8	-	-	-
	Latvia	0.000	8	2.094	0.168	0.053
	Lithuania	0.004	8	-	-	-
	Poland	0.760	6	-	-	-
	Slovakia	0.018	8	58.131	4.651	0.391

[14] Shown for countries where 1990 CO_2 emissions data were available
[15] Following from Table 4-1, the amount of emissions reduced after applying prescribed burning are computed based on normal fuel conditions
[16] Data obtained from www.pewclimate.org/
[17] Data obtained from UNFCCC (2006). The emissions here are defined as total anthropogenic CO_2 emissions, and include emissions/removals from land use, land-use change and forestry

Region	Country	Estimated emissions reduction[15] (million tonnes CO_2)	Kyoto targets for European countries[16] (% above or below 1990 levels)	1990 CO_2 emissions[17] (million tonnes CO_2)	Amount of emissions reduction required by Kyoto (million tonnes CO_2)	% reduction achieved with prescribed burning application under normal fuel conditions
Scandinavia	Finland	0.005	1990 level	35.305	2.824	0.178
	Norway	0.008	8	20.157	1.613	0.466
	Sweden	0.023	4	34.313	1.373	1.694
Mediterranean	Algeria	0.361	8	-	-	-
	Cyprus	0.012	8	-	-	-
	France	0.460	1990 level	367.983	29.439	1.561
	Israel	0.002	-	-	-	-
	Italy	0.929	6.5	354.575	23.047	4.027
	Morocco	0.021	8	-	-	-
	Portugal	0.936	27	46.727	12.616	7.415
	Spain	0.465	15	205.535	30.830	1.507
Total for all countries					**478.769**	

Figure 4-3 visualises the information in Table 4-2. It should be noted that the high potential reduction for Croatia (121%, possibly attributed to the low reduction requirement of 5% – 0.429 million tonnes – and the low 1990 emissions level of 8.598 million tonnes CO_2, see Appendix B for details, in combination with a high fire incidence) is removed from the plot in order to see the comparisons for other countries.

It is important to keep in mind when interpreting Figure 4-3 that the reductions in emissions obtained here present only a rough estimate, assuming that a typical prescribed burning regime would be able to prevent half of the wildfire incidents. The actual reductions that can be obtained over a longer period may be much lower and depend on the fire regime, as explained in Chapter 2. Nevertheless, for a country like Portugal about 7.5% of the emission reductions required by Kyoto could be obtained with prescribed burning. A potential of about 4% may be achieved by two other nations while for the majority the potential reduction is below 2% of the Kyoto requirements. This implies that in most of the European countries the potential for prescribed burning as a mitigation technique is low. However, in countries with a high fire incidence, such as the Mediterranean region, prescribed burning could be a viable way of mitigating CO_2 emissions under the Kyoto Protocol.

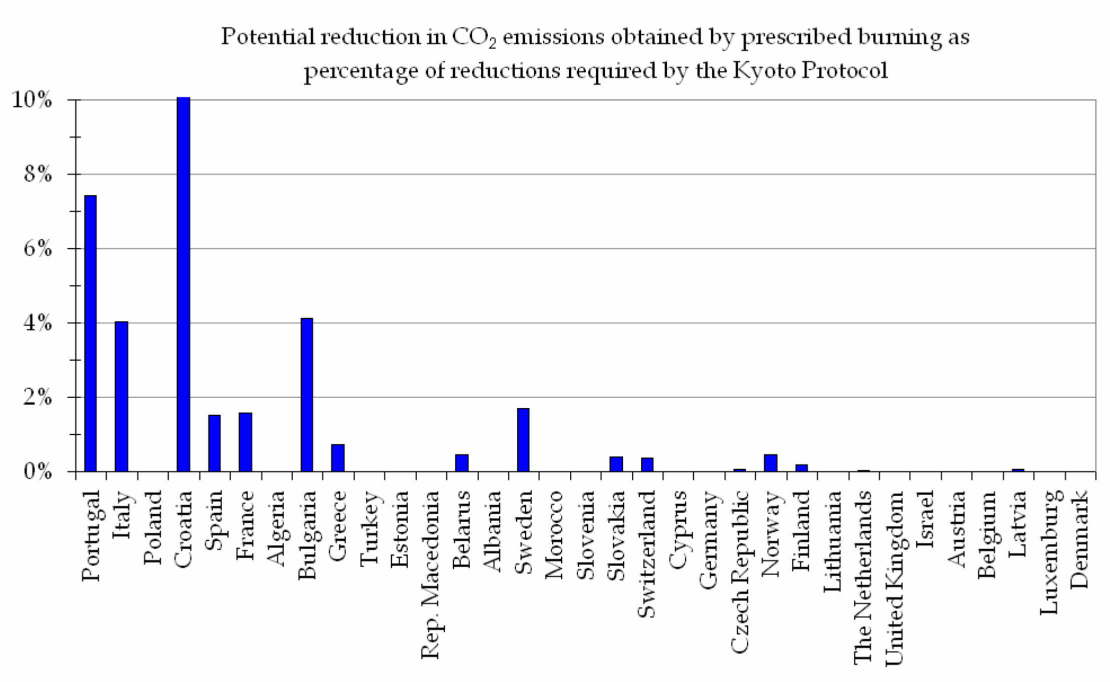

Figure 4-3. Potential CO_2 emissions reduction that could be achieved by prescribed burning, shown here as a percentage of reductions required by the Kyoto agreement.

5. SUMMARY AND DISCUSSIONS

Biomass burning is one of the major contributors of GHGs and particulate matter to the atmosphere (Ward and Hardy, 1991). Radke (1989) estimated that on a global scale 10 PgC/y of biomass are consumed, which includes all forms of biomass consumption, while Seiler and Crutzen (1980) estimated global biomass burning to contribute 2–3.3 Pg of carbon in the form of CO_2 to the atmosphere each year.

The present study attempted to quantify and compare CO_2 emissions from wildfires and prescribed burning in Europe contributing to the overall emissions. From the limited data that was available, it was estimated that over a five year period approximately 11 million tonnes of CO_2 was released annually from wildfires in Europe. Based on the outlined assumptions and the single case study of Portugal where wildfire emissions were compared with the emissions from prescribed burning, these emissions could potentially be reduced by almost 50% if prescribed burning would be widely used as a mitigation technique. In the current study, it was estimated that with a widespread application of prescribed burning under normal fuel moisture conditions, a reduction in emissions of up to five million tonnes could potentially be achieved.

However, studies have shown that both the nature and the amount of emissions from forest fires are directly related to the intensity and the direction of the fire, and indirectly related to the rate of spreading of the fire, which is affected mainly by the weather (wind velocity, ambient temperature and relative humidity), fuels (fuel types, fuel bed array, moisture content and fuel size), and topography (slope and profile). These conditions are highly variable, both in space and in time.

The estimations in the current study clearly show a lack of appropriate data for the different countries. Prescribed burning, for most of Europe, apart from the Mediterranean region, is not a regular practice and therefore records of emissions from these fires were so far not deemed important, or were assumed to be negligible. The current study could therefore only make a very rough estimate of the emissions from wildfires and from prescribed burning. Nevertheless, with the limited available data and some key assumptions where appropriate, the study has shown that there are countries in certain European regions where wildfires are common, and where prescribed burning would be useful not only for reducing damages and risks, but also for mitigating CO_2 emissions.

Similarly, the potential reductions in emissions shown in the study are marred by assumptions and severe lack of data. At this stage it can only be hypothesised that countries with devastating wildfires could mitigate CO_2 emissions by adapting prescribed burning. However, for most European countries it seems that the emissions reductions that could potentially be obtained with prescribed burning are insignificant compared to the requirements of the Kyoto Protocol.

6. CONCLUSIONS AND OUTLOOK

6.1 Conclusions

This report analysed the potential for prescribed burning technique for mitigating CO_2 emissions from forest fires. Prescribed burning is not a common practice within most of the European countries, either not being allowed (such as in the Mediterranean, where fires are frequent), or even banned by law. It is deemed by many that the emissions from such fires are negligible, resulting in a lack of measured data for quantitative analysis.

The stance of prescribed burning as mitigation for CO_2 emissions can be seen as a valid measure. The case study by Fernandes and colleagues (Pers. Comm., 2006) shows that in fire prone countries this could be a viable option for reducing emissions. For a site in Portugal they found that the emissions from prescribed burning under normal fuel moisture conditions can be 62% lower than for a more severe wildfire. However, the actual reduction that is obtained over a longer period of time depends heavily on the wildfire regime. Current analyses have shown that the potential reduction attained by prescribed burning techniques as a percentage of the reduction in emissions required by the Kyoto Protocol varies from country to country. Out of the 33 European nations from the five regions that were investigated, in only one (Croatia) the estimated reduction in emissions was high enough to fulfil the requirements of Kyoto, while three nations showed a potential of about 4–8% of the Kyoto requirements. In the majority of the countries, however, the estimated reductions were less than 2%. This implies that prescribed burning can only make a significant contribution in those countries with high fire occurrence.

Over a five year period the emissions from wildfires in the European region were estimated to be approximately 11 million tonnes of CO_2 per year, while with prescribed burning application this was estimated to be six million tonnes per year, a potential reduction of almost 50%. However, in most countries the reduction in emissions that can be obtained with prescribed burning is not significant compared to the requirements of Kyoto, with the exception of some countries in the Mediterranean region. The emissions that were calculated in the present study should be regarded as only a very rough estimate, hence the actual reductions that can be obtained will likely be lower.

While good support systems, such as fire ecology, fire science, fire models, fire danger rating systems and modern fire suppression systems (IFFN, 2004b) for prescribed burning have emerged in the recent past, its full realisation has yet to come. As concluded from the IFFN (2004) Report, the development of a good prescribed fire framework involving both prescribed fire projects, as well as stakeholders, will support not only a more targeted use of fire in the management of land in fire vulnerable regions of Europe, but also help inform policy makers about the factors that influence fire behaviour and consequent fire effects, hopefully leading to the creation of a more sustainable policy framework for prescribed fires in high fire risk regions of Europe. Even if mitigating CO_2 emissions may not be a convincing argument for applying prescribed burning, it can still be regarded as having an added value in its entirety.

6.2 Outlook

More research is needed specifically on GHG emissions quantification from prescribed burning in order to establish both for specific areas, as well as on a national scale or Europe-wide, and over a longer period of time, to what extent CO_2 emissions from prescribed burning are lower.

For most countries, this report estimated the potential of prescribed burning technique for CO_2 emissions mitigation to be rather low. However, there may be more reasons for applying prescribed burning to prevent wildfires, related to losses of biodiversity and of economic value, and for some regions in Europe, most notably in the South, it may prove to be a viable means to start accounting for the reduction in emissions that may be obtained at the same time.

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APPENDIX A: Detailed version of Table 4-1

Region	Country	Total Nr of fires over 5 years	Period considered	Average area burned over 5-year period (ha)	Biomass (t/ha)	Biomass consumed by fire[18] (t)	Wildfire without prescribed burning (million tonnes of CO_2)	CO_2 released from: (million tonnes CO_2)			Reduction in CO_2 emissions when prescribed burning is applied (million tonnes CO_2)
								Prescribe fire	Wildfire with prescribed burning	New total wildfire emissions[19]	
Balkan	Albania	2 781	1999–2003	2 569.4	58	74 513	0.053	0.002	0.026	0.028	0.025
	Bulgaria	3 709	1999–2003	19 486.8	76	740 498	0.523	0.019	0.261	0.280	0.243
	Croatia	2 132	1997–2001	29 696.6	107	1 588 768	1.122	0.043	0.561	0.604	0.518
	Greece	9 195	1999–2003	36 214.6	25	452 683	0.319	0.012	0.159	0.171	0.148
	Republic of Macedonia	1 959	1999–2003	10 236.4	24	122 837	0.087	0.003	0.043	0.046	0.041
	Slovenia	107	1999–2003	659.6	178	58 704	0.041	0.002	0.021	0.023	0.018
	Turkey	10 707	1999–2003	10 921.4	74	404 092	0.285	0.011	0.143	0.154	0.131
Western Europe	Austria	294	1997–2001	34.2	250	4 275	0.003	0.000	0.002	0.002	0.001
	Belgium	72	1997–2001	61.4	101	3 101	0.002	0.000	0.001	0.001	0.001
	Denmark	15	1997–2001	2.2	58	64	0.000	0.000	0.000	0.000	0.000
	Germany	6 012	1999–2003	511.0	134	34 237	0.024	0.001	0.012	0.013	0.011
	Luxemburg	13	1997–2001	1.8	101	91	0.000	0.000	0.000	0.000	0.000
	Switzerland	320	1997–2001	476.2	165	39 287	0.023	0.001	0.014	0.015	0.008
	The Netherlands	364	1997–2001	208.8	107	11 171	0.008	0.000	0.004	0.004	0.004
	The UK	1 024	1997–2001	217.8	76	8 276	0.006	0.000	0.003	0.003	0.003
Eastern Europe	Belarus	11 329	1997–2001	2 523.4	80	100 936	0.071	0.003	0.036	0.039	0.032
	Czech Republic	5 735	1999–2003	442.4	125	27 650	0.019	0.001	0.009	0.010	0.009
	Estonia	846	1997–2001	4 137.0	85	1 75 823	0.124	0.005	0.062	0.067	0.057
	Latvia	5 170	1997–2001	5.8	93	270	0.000	0.000	0.000	0.000	0.000
	Lithuania	2 759	1997–2001	238.0	99	11 781	0.008	0.000	0.004	0.004	0.004
	Poland	178 000	1999–2003	49 534.4	94	2 328 305	1.644	0.062	0.822	0.884	0.760
	Slovakia	3 003	1999–2003	785.4	142	5 578	0.039	0.002	0.019	0.021	0.018

[18] 50% of total biomass of the burned area. 50% is assumed to be the biomass burning efficiency (from Seiler and Crutzen, 1980). Total biomass is the product of area burned and biomass

[19] Sum of prescribe fire and wildfire with prescribed burning

Region	Country	Total Nr of fires over 5 years	Period considered	Average area burned over 5-year period (ha)	Biomass (t/ha)	Biomass consumed by fire[18] (t)	Wildfire without prescribed burning (million tonnes of CO_2)	CO_2 released from: (million tonnes CO_2)			Reduction in CO_2 emissions when prescribed burning is applied (million tonnes CO_2)
								Prescribe fire	Wildfire with prescribed burning	New total wildfire emissions[19]	
Scandinavia	Finland	9 590	1999–2003	615.0	50	15 375	0.011	0.000	0.005	0.005	0.005
	Norway	453	1997–2001	940.4	49	23 040	0.016	0.001	0.008	0.009	0.008
	Sweden	28 803	2000–2004	2 263.4	63	71 297	0.050	0.002	0.025	0.027	0.023
Mediterranean	Algeria	8 300	1996–2000	29 496.8	75	1 106 130	0.781	0.029	0.390	0.419	0.361
	Cyprus	1 274	1999–2003	3 482.6	21	36 567	0.026	0.001	0.013	0.014	0.012
	France	19 873	1999–2003	30 631.0	92	1 409 026	0.995	0.038	0.497	0.535	0.460
	Israel	4 591	1999–2003	3 469.6	3	5 204	0.004	0.000	0.002	0.002	0.002
	Italy	39 289	1999–2003	76 891.0	74	2 844 967	2.009	0.076	1.004	1.080	0.929
	Morocco	1 940	1995–1999	3 118.2	41	63 923	0.045	0.002	0.023	0.025	0.021
	Portugal	140 242	1999–2003	173 802.0	33	2 867 733	2.025	0.077	1.012	1.089	0.936
	Spain	100 737	1999–2003	118 714.8	24	1 424 578	1.006	0.038	0.503	0.541	0.465
TOTAL FOR ALL COUNTRIES							**11.369**	**0.431**	**5.684**	**6.115**	**5.254**

APPENDIX B: Detailed version of Table 4-2

Region	Country	Estimated emissions from wildfires[20] (million tonnes CO_2)	Estimated reduction in emissions from prescribed burning under normal fuel conditions (million tonnes CO_2)	Kyoto targets for European countries (% above/below 1990 levels)	Reported 1990 CO_2 levels of the emissions from LULUCF (million tonnes CO_2)	Amount of emissions reduction required by Kyoto (million tonnes CO_2)	Estimated wildfire emissions of the total reported LULUCF emissions (%)	Reduction in emissions achieved with prescribed burning application (%)
Balkan	Albania	0.053	0.025	-	-	-	-	-
	Bulgaria	0.523	0.243	8	72.996	5.839	1.687	4.136
	Croatia	1.122	0.518	5	8.598	0.429	18.006	120.551
	Greece	0.319	0.148	25	81.065	20.266	0.305	0.726
	Republic of Macedonia	0.087	0.041	-	-	-	-	-
	Slovenia	0.041	0.018	8	-	-	0.383	-
	Turkey	0.285	0.131	8	-	-	-	-
Western Europe	Austria	0.003	0.001	13	49.953	6.494	0.005	0.021
	Belgium	0.002	0.001	7.5	117.65	8.824	0.002	0.011
	Denmark	0.00005	0.000	21	54.597	11.465	0.00008	0.000
	Germany	0.024	0.011	21	1001.616	210.339	0.003	0.005
	Luxemburg	0.00006	0.000	28	-	-	-	-
	Switzerland	0.028	0.008	8	42.729	3.418		0.375
	The Netherlands	0.008	0.004	6	161.781	9.707	0.004	0.038
	United Kingdom	0.006	0.003	12.5	593.235	74.154	0.001	0.004
Eastern Europe	Belarus	0.071	0.032	8	90.629	7.250	0.166	0.454
	Czech Republic	0.019	0.009	8	163.281	13.063	0.016	0.069
	Estonia	0.124	0.057	8	-	-	1.107	-
	Latvia	0.0002	0.000	8	2.094	0.168	0.003	0.053
	Lithuania	0.008	0.004	8	-	-	0.045	-
	Poland	1.664	0.760	6	-	-	0.566	-
	Slovakia	0.039	0.018	8	58.131	4.651	0.103	0.391

[20] Average over five years

Region	Country	Estimated emissions from wildfires[20] (million tonnes CO_2)	Estimated reduction in emissions from prescribed burning under normal fuel conditions (million tonnes CO_2)	Kyoto targets for European countries (% above/below 1990 levels)	Reported 1990 CO_2 levels of the emissions from LULUCF (million tonnes CO_2)	Amount of emissions reduction required by Kyoto (million tonnes CO_2)	Estimated wildfire emissions of the total reported LULUCF emissions (%)	Reduction in emissions achieved with prescribed burning application (%)
Scandinavia	Finland	0.011	0.005	1990 level	35.305	2.824	0.021	0.178
	Norway	0.016	0.008	8	20.157	1.613	0.092	0.466
	Sweden	0.050	0.023	4	34.313	1.373	0.130	1.694
Mediterranean	Algeria	0.781	0.361	8	-	-	-	-
	Cyprus	0.026	0.012	8	-	-	-	-
	France	0.995	0.460	1990 level	367.983	29.439	0.274	1.561
	Israel	0.004	0.002	-	-	-	-	-
	Italy	2.009	0.929	6.5	354.575	23.047	0.524	4.027
	Morocco	0.045	0.021	8	-	-	-	-
	Portugal	0.025	0.936	27	46.727	12.616	3.222	7.415
	Spain	1.006	0.465	15	205.535	30.830	0.310	1.507
TOTAL FOR ALL COUNTRIES						**478.769**		